

## SYSTEM THEORETIC APPROACH TO SUSTAINABLE DEVELOPMENT PROBLEMS

Vladan BATANOVIĆ

*Institute Mihajlo Pupin, Belgrade,*

*vladan.batanovic@pupin.rs*

Slobodan GUBERINIĆ

*Institute Mihajlo Pupin, Belgrade,*

*slobodan.guberinic@pupin.rs*

Radivoj PETROVIĆ

*Institute Mihajlo Pupin, Belgrade,*

*radivoj.petrovic@pupin.rs*

Received: January 2011 / Accepted: February 2011

**Abstract:** This paper shows that the concepts and methodology contained in the system theory and operations research are suitable for application in the planning and control of the sustainable development. The sustainable development problems can be represented using the state space concepts, such as the transition of system, from the given initial state to the final state. It is shown that sustainable development represents a specific control problem. The peculiarity of the sustainable development is that the target is to keep the system in the prescribed feasible region of the state space. The analysis of planning and control problems of sustainable development has also shown that methods developed in the operations research area, such as multicriteria optimization, dynamic processes simulation, non-conventional treatment of uncertainty etc. are adequate, exact base, suitable for resolution of these problems.

**Keywords:** Sustainability, sustainable development, systems approach, multiple criteria optimization.

**MSC:** 93-99, 90-99.

## 1. INTRODUCTION

The idea of development in general terms had not existed practically until the second half of the twentieth century. However, problems related to the economic growth and social development in general had become very serious in the second half of the past century, so the governments of many states, the United Nations, a large number of institutes and researchers in various science fields were engaged in solving them.

Attempts to solve the development problem using neoclassical economic theory have proven to be inefficient and completely inappropriate for the new global relations established after the end of the Cold War. The tension between the Western and Eastern Blocs, prevalent during the Cold War, was replaced by the conflict between the rich and the poor, i.e. between the developed and underdeveloped countries.

The development problem, which had predominantly meant economic development up to that time, proved to be very complex, general and difficult to the extent that made it insolvable by means of using the available paradigms and methods or by striving to achieve the aims defined in neoclassical economic theory and centralized planning economy. In addition, the notion of development had to be much more complex and comprehensive than something reducible to economic development elements only.

The development problems based on neoclassical economic theory paradigms were intended to maximize welfare based on constrained consumption. The means for attaining such a goal under the stated paradigms were market-oriented reforms. It was found out during the eighties of the 20<sup>th</sup> century that such reforms resulted in an aggravated state of the poor, even when economic efficiency indicators were improved, as well as in widening the gap between the poor and the rich.

The most important negative effects of such a concept of development are:

- *Uneven distribution of development utilities*
- *Negative effects on Nature - environment and existing social structures.*

In addition, the following questions arose: *Is the planetary ecosystem capable of satisfying the higher demand for resources and has its waste absorption capacity been exceeded?*

Such facts led to a conclusion that modernism based on the existing development concept did not contribute to the progress of human society as a whole.

Continuing the general development in the sense of neoclassical economic theory, with today's inequalities remaining existing, is neither sustainable nor worth sustaining.

The stated facts indicate that it is necessary to form a new development concept which should involve, in addition to economic components, the elements of ecology as well as the social elements. Thus, a new vision of development in the 21<sup>st</sup> century should result from a combination of economic, ecological and social perspectives, simultaneously.

To take into consideration all three components of the stated vision in creating the new concept of development, of the so-called *sustainable development*, the following facts have to be born in mind [8]:

*The existing development idea creates a mass consumptive society, which produces social inequalities and affects Nature- environment adversely.*

*The sustainable development concept should prevent the creation of social inequalities, prevent harm to the environment and permit sustaining an efficient economic basis.*

*Sustainable development should permit the preservation of natural capital to provide intergeneration equality. The market mechanism makes the natural capital poorer and devastates it.*

*The sustainable development concept should specify limits to population growth and to the total demand for resources.*

*Sustainable development has to provide social equality in health insurance and free-of-charge education opportunities first of all. What is also crucial is attaining participative democracy in decision making.*

Sustainable development planning, based on the stated guidelines, points to the need for redefining the notion of development, i.e. formulating the definition of *sustainable development*. Several definitions have been offered, depending on whether they are given by economists (welfare maximization based on consumption growth), ecology specialists (development that preserves natural capital is sustainable) or by sociologists (sustainable development is the development which provides for satisfying the basic needs and ensures equality of all individuals, i.e., equality between the present and future generations). An acceptable, although relatively general, definition reads: *Sustainable development is the development which allows the needs of contemporary generations to be satisfied without reducing the possibilities of future generations to satisfy their own needs.*

Considerations and the definition given here indicate the point to the properties which differ the new development paradigm from the existing one based on neoclassical economic theory and massive consumption growth philosophy. The most important properties are:

*Complexity* – consideration has to include development concepts belonging to three fields: economy, ecology and sociology

*Dynamics* – consideration has to include changes of a larger number of variables from three fields over time, i.e. *state* transformation process over time

*Existence of consumption limits* – constraints on the usage of nonrenewable resources are especially important.

*Performance indices* – the addition of ecology and sociology as important development factors has made it necessary to redefine the development indices completely. The existing indices GDP (Gross Domestic Product) and HDP (Human Development Product) have been found unsuitable for evaluating sustainable development performances. GDP includes economic components only and the increase of this index does not result in higher general welfare. HDP, introduced by the United Nations, combines, in addition to GDP, social elements such as: adult literacy, education opportunities, gender inequality, poverty, etc. This index is then defined as a weighted sum of measures of the stated elements. A shortcoming of this index is the fact that it does not consider a single ecological element explicitly.

The concept of sustainable development is based on the assumption that societies and organizations need to manage three types of capital – economic, social and natural which may be non-substitutable and whose consumption might be irreversible

Many authorities in the fields of development think that the term sustainability is obligatory today, but there are development experts who find it absurd, or so vague it

says nothing. Furthermore, they claim that the term is more charming than meaningful. However, sustainable development as a policy approach has gained significant popularity during recent years, especially in international circles.

It is certainly not unexpected that the formidable sustainable problems will give rise to mathematical questions of greater difficulty. What is surprising is that the very construction of a suitable mathematical framework to house these problems and the choice of appropriate mathematical tools to resolve them, are matters which now require considerable care and a certain amount of ingenuity.

In our opinion, it seems rather clear from even a preliminary survey of the sustainability upon which we are embarking, that no single formulation and no single method will be powerful enough or comprehensive enough to treat these many different types of questions that can be asked, or to furnish many different types of answers that are required. What will be necessary is a combination of many different ideas and techniques, skillfully blended.

In what follows, we wish to show that from the properties mentioned, the concepts and methodology contained in the system theory are suitable for the use in planning and managing so complex a process as sustainable development is [5]. The important properties of sustainable development mentioned, such as complexity, dynamics, state, constraints, and new performance indices represent, in fact, problem formulation components for managing complex systems and describing their processes. In our opinion operations research methods represent good, exact, methodological basis which could be used for solving these problems. The great challenge in the study of sustainability is not so much to solve a particular problem by means of a particular method, as it is how to find new methods which can be used to furnish solutions to whole classes of sustainable problems.

## 2. CONCEPTS AND DEFINITIONS OF SUSTAINABLE DEVELOPMENT IN THE LIGHT OF THE SYSTEM THEORY AND OPERATIONS RESEARCH

**State and state transition.** Sustainable development can be defined as the finite-state general system, i.e. by the state transition function and output (read-out) function.

Heuristic definition of state is: *state* is the set of data, giving complete information about the system history necessary for the determination of its behavior in the future, providing the management or control actions are known.

The state transition function is given by expression

$$x^k = f(x^{k-1}, u^k) \quad (1)$$

and system output function is

$$y^k = \varphi(x^k, u^k) \quad (2)$$

where

$x^{k-1}, x^k$  - states in the intervals  $k-1$  and  $k$ , respectively,  $u^k$  - input in time interval  $k$  of the duration  $\Delta t$ .

Sustainability is defined in the period of time defined by the index-set of time intervals  $k \in K = \{1, 2, \dots, k\}$

The transformation of the state  $x^{k-1}$  to the state  $x^k$  under the influence of the input  $u^k$  is defined by the mapping  $f$ . Output function is defined by the mapping  $\varphi$ .

State is represented by the point in the state space and development is represented by the sequence of states in different moments, also called state trajectory.

An important feature of sustainability is the preservation of values of some state variables, but sustainable development is not the extension of the existing state. The central question is determining which state variables are to be sustained, and which are to be changed. The state variables that have to be sustained are *essential variables* and their values have to satisfy very strong constraints.

From the system theory point of view, sustainable development will be realized if the essential state variables remain in the defined domain or point in state space during the whole time period  $K\Delta t$ .

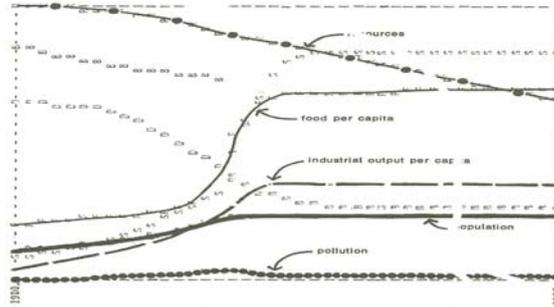
Essential variables  $x_1, x_2, \dots, x_e$  are elements of the set  $X^E \subseteq X$ .  $X$  is the set of all states.

The values of some of these variables, such as the consumption of some nonrenewable resources, some measures of pollution etc. have to be lower than certain determined limits. These constraints define one feasible region to which the state has to belong at any moment of the process. It means that trajectory in the state space, representing sustainable development, has to be located in the feasible region of the state space. The basic idea will be demonstrated on one macro-development example.

It is pointed out, in 'A Report of the Club of Rome', published under the title: *The Limits to Growth* [10], that the restriction of the economic growth is the essential condition for achieving sustainable development.

Figure 1 [10] presents the changes of a selection of state variables in the period between 1900 and 2100 (food per capita, resources consumption, pollution) and inputs (industrial output per capita, population). It is evident that during the whole period, state remains in one point of the state space. The achievement of this sustainable development could be realized [10] by the application of the following measures: resources recycling, equalizing birth rate and death rate, equalizing capital investment in industry to capital depreciation.

The application of the state space concept is especially useful in cases when some regions in the state space have to be escaped. They are primarily the regions where values of the state variables representing the consumption of nonrenewable resources are above the predefined limits, or the regions where the values representing the pollution level are greater than the capacity of environment to absorb waste materials.



**Figure1:** Model of sustainable development (Source[10] )

Sustainable development also needs to meet the requirement of respecting the principle of intergeneration solidarity. This demand represents the necessity to enable the same or better life conditions for future generations and can be described by introduction of some function  $g$  with the property:

$$g(x^k) \geq g(x^{k-1}), k \in \mathcal{K} \quad (3)$$

Similar functions to  $g$  were presented in the literature. Function of the system output can be influenced by a strong subjective component. Some output variables are very often, also the state variables. It could be capital stock expressed in monetary values and can also include ecological and social elements. In the Report of the Club of Rome, the function representing *quality of life* increases when industrial output and food per capita increase and pollution decreases. This expression (3) can also be used for a formal definition of sustainable development [5].

### 3. OPTIMALITY AND SUSTAINABILITY CRITERIA

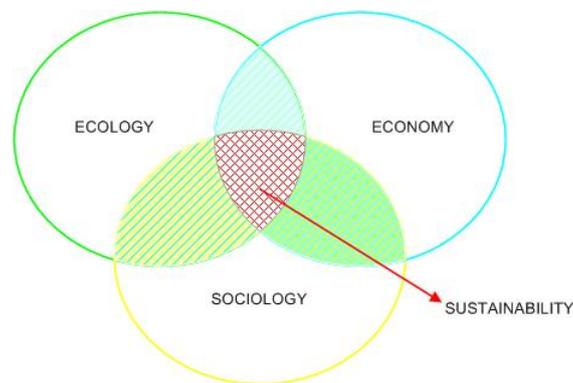
The optimality criterion is among the fundamental concepts in not only operations research, but in a variety of other science disciplines such as system theory and systems management, mathematical optimization theory and mathematical programming, etc. It is generally said that an optimality criterion interprets a value system in each actual problem considered. In some cases, the task of selecting the optimality criterion is trivial. However, in other cases the selection of the optimality criterion turns out to be a complex research problem itself.

In a formal sense, an optimality criterion is a function or a functional in various forms and the central task of optimization is to determine the extreme value (or values) of the optimization function or the optimization functional. Most often this task is complex and the OR literature abounds in methods for determining the extremum or extrema, or at least, the values close to optimality criterion extremum/extrema.

The first decades of OR development are characterized by insisting, in both theory and practice, on the existence of a single optimality criterion. It is regarded that even when several optimality criteria appear to exist, they have to be synthesized to a single criterion function (functional). This results not so much from believing that it is

possible to interpret a value system in terms of a single performance measure, but rather from the need to avoid methodological difficulties faced when treating a problem with more than one optimality criterion. The development of OR has made it possible to overcome former mathematical difficulties, and multicriteria optimization theories have undergone a very intensive development.

Great progress has been recorded in the interpretation of value systems in planning and management tasks. A recent idea is that, apart from interpreting a value system in terms of several optimality criteria, it is of utmost importance to 'cover' all important aspects of the system environment managed by optimality criteria. This has given rise to a suggestion that optimality criteria be threefold in nature: sociological, economic and ecological. This is illustrated by the three well-known circles that form 7 subsets by intersecting. One circle symbolizes sociological criteria, the second an economic and the third an ecological criterion.



**Figure 2** Threefold Nature of Optimality Criteria

Figure 2 shows four intersections. The intersection of all three circles is a subset symbolizing the field

- *Sustainability* - [2, 1]

The intersections of each of the two circles symbolize the following fields:

- *Viability*, economic and ecological criteria - [11, 7]
- *Equitability*, sociological and economic criteria - [12, 4]
- *Bearability*, sociological and ecological criteria - [3, 13]

Sustainability criteria are defined on an abstract level as the mapping of input, control (or management action) and output on the vector space with real numbers as vector components.

$$I \times U \times Y \times \rightarrow V^R \quad (4)$$

The mapping in (4) is not necessarily in analytical form. In solving problems in practice, very often there is a tendency to describe sustainability criteria in some appropriate analytical forms. Two analytical forms are in frequent use.

The first form is time discrete expressions where the sustainable criteria functions are generally the vector functions of all discrete time state variables and all discrete time control variables,

$$F_c = F_c(x^0, x^1, \dots, x^K, u^1, \dots, u^K), c = 1, \dots, C \quad (5)$$

where  $x^0$  is initial state of the system,  $k$  denotes discrete time interval and  $C$  is the number of criteria in the vector sustainability function.

The second very common form of the sustainable criterion is vector functional as,

$$F_c = \varphi_c[y(t_f)] + \int_{t_0}^{t_f} f_0(u, y) dt, c = 1, 2, \dots, C. \quad (6)$$

where  $t_f$  is the final time and  $C$  is the number of associated functionals.

In the following, we will present the evolution of a typical OR problem over a five-decade period as an example to illustrate how OR has converged to the field referred to as *Sustainability* today. Firstly, we shall consider a conventional OR task – economic allocation of electric energy production to thermal generation units in an electric power system. During the fifties and sixties of the previous century, energy production distribution to thermal generator units was treated as a strictly economic task with only one optimization criterion – energy production costs. Hundreds of papers addressing this issue, from purely theoretical to very practical ones, were published. Very diverse problem statements were treated – daily, weekly and annual dispatching, dynamic and non-dynamic versions, deterministic and stochastic variants, but all of them had only one optimization criterion – production cost or expected production cost which was to be minimized.

During the eighties and nineties, operations researchers started paying attention to the ecological aspects of these problems as well. CO<sup>2</sup> and NH<sup>3</sup> emissions of powdered matter increase in the temperature of generator cooling water fed to river flows began to figure as optimization criteria. Production allocation tasks became complex multicriteria optimization problems.

The sociological component was added to energy production allocation problems in the first decade of this century. A performance measure involving some social aspects became one of the candidates for optimization criteria. This is how a classical OR task has transformed into a multicriteria optimization problem, the solution to which may be referred to as sustainable management, because it takes into account the economic, ecological and sociological performance measures and objectives.

From the OR perspective, sustainability means multicriteria optimization in both conceptual and methodological sense. Numerous multicriteria optimization methods are available for selecting sustainable strategies/management. As is well known, one of the key problems in multicriteria optimization is the issue of determining the relative importance of single optimization criteria. It is natural to approach this issue in a hierarchical way: first to determine the relative importance of criteria groups (sociological, economic, and ecological) and in the following steps, the relative

importance of each criterion within each group. The known Analytical Hierarchy Process (AHP) could be a guide through this procedure.

We wish to underline a fact well known in OR – individual (expert) subjectivity in determining the relative importance of criteria is unavoidable. This is why we have to be careful in interpreting the results we obtain – sustainable strategies/management which inherently contains subjectivity.

### 3. CONCLUSION

The concepts and methods developed in the theory of the large scale systems control and operations research area, are very suitable for and applicable to the important problems of sustainability and determination of sustainable strategies. Use of the state space concept is especially useful because it enables the exact statement of the sustainability and sustainable development problems. Some important features of sustainability can be accurately treated, using state space concepts.

Primarily, it is very simple using state space concept, to define feasible regions i.e. to define the regions where values of the state variables representing the consumption of nonrenewable resources are greater for the defined limits, or the regions where the values representing the pollution level are greater than environmental capacity to absorb waste materials. It is especially useful in the cases when some regions in the state space have to be avoided.

Secondly, it is shown that the concepts of viability, equitability and bearability are closely related to the optimization criteria in OR.

A large number of system analysis and management methods developed in OR over the past few decades are well suited for use in the problems of determining sustainable strategies/management. We mention four groups of such methods that have a key role in the selection of sustainable strategies/management: (1) multicriteria analysis and multicriteria optimization methods, (2) forecasting methods, (3) simulation methods (4) non-conventional treatment of uncertainty. We will go one step further and claim that a real, optimal sustainable strategy/management cannot be determined without appropriate application of the stated OR methods.

### REFERENCES

- [1] Adams, W.M., "The future of sustainability, rethinking environment and development in the twenty first century", Report IUCN, 2006.
- [2] Allen, W., "Learning for sustainability", *Sustainable Development*, 2007.
- [3] Bookchin, M., *The Ecology of Freedom*, Stirling Press, 2005.
- [4] Diclos, J.Y., *Horizontal and Vertical Equity*, The New Palgrave Dictionary of Economics, 2008.
- [5] Galloppin, G., "A systems approach to sustainability and sustainable development", UN Publication, Santiago, Chile, 2003.
- [6] Guberinić, S., Matejić, V., Mikić, and O., Petrović, R., "Sistemi, upravljanje sistemima, sistemske discipline, tehnike i metode", Institut „Mihajlo Pupin“, Beograd, 1970. (In Serbian)
- [7] Hanley, N., Shorgen, J., and White. B., *Environmental Economics in Theory and Practice*, Palgrave, London, 2007.
- [8] Harris, J., "Basic principles of sustainable development", Tufts University, Medford MA, USA, 2000.

- [9] Luc, F., "Protégé l'espace humaine contre elle-meme", *Revue de Deux Mondes*, 10 (2007), 75-79.
- [10] D. Meadows, D. Medows, J. Randers, and W. Berens III, *The Limits to Growth*, Universe Books, New York, 1972.
- [11] Pearce, D., "An intellectual history of environmental economics", *Annual Review of Energy and Environment*, 27 (2002) 57-81.
- [12] Peyton, Y., *Equity in Theory and Practice*, Princeton University Press, 1994.
- [13] Steiner, R., and Nanser, M., "Human ecology", *Ecology Review*, 15 (2008).