Spatial Development Decision Making and Modeling

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Abstract: **The basic approaches to decision making and sustainable development modeling are considered. Static spatial models include Hägerstrand model, gravity models, transportation models and location models. Dynamics of a sustainable development is considered in the Forrester's system dynamics, in mixed integer programming models of dynamic location. Population dynamics in urban planning models is considered. Multicriteria issues of sustainable development are analyzed. Application of goal programming and other multicriteria optimization techniques are considered. GIS application for the account of the spatial factor is shown. Applying DSS (Decision Support Systems) and multicriteria spatial DSS is analyzed. DSS allow using model and solver bases for sustainable development modeling.**

Keywords: **Sustainable development, system dynamics, spatial-temporal systems.**

SCIENCE AS A FOUNDATION FOR SUSTAINABLE DEVELOPMENT

"Sustainable Development" is currently a topic of great social relevance and one that requires the integration of a challenging array of themes from a variety of disciplines spanning the physical and natural sciences, economics and other social sciences, and the humanities. The classic definition of **sustainable development** proposed in the World Commission on Environment and Development (WCED, 1987) report (so called the Bruntland report) "Our Common Future" [51] is: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". It contains within it two key concepts:

- the concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and
- the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs."

This definition embraces three components: environmental responsibility, economic return and social development and requires that we see the world as a system - a system that connects space; and a system that connects time, i.e., a **spatio-temporal system**.

Sustainable development is a wide concept and has over the years been introduced through many different definitions. Although different in wordings, the definitions have at least three common denominators; they all include a temporal perspective which entails a cross-generational responsibility and they all include a spatial perspective which entails a cross-system application. The temporal perspective indicates that the process is a long-term consideration with a focus on present behavioral modification for future preservation, while the spatial perspective is represented by a systems-approach advocating the dynamic interaction between natural and social systems.

In a report by the Global Environmental Change Programmes (a summary of the conclusions from the workshop "*Sustainable Development - The Role of International Science*", 4-6 February 2002, Paris) is written:

- "Research must move beyond a disciplinary focus to address sustainability issues in the framework of complex dynamical systems".
- "Building and delivering of predictive tools for enhanced understanding and decision-making, such as **system models** at local, regional and global scales".

We can define the difficulties related to the understanding of sustainable development issues due to the extreme complexity and interrelations of the factors, particularly in a log time and global-local perspective. It will also illustrate the necessity for policy makers and stakeholders to define policy and actions, going beyond only locally sustainable and/or environmentally sound, and assess their effective outcomes and impacts.

Amongst the measures developed to indicate sustainability have been economic measures such as genuine savings; ecological measures such as human appropriation of Net Primary Production (NPP), ecological footprints and environmental space; and socio-political measures such as the Index of Sustainable Economic Welfare (ISEW) and quality of life indicators.

In publications Giaoutzi and Nijkamp (1993), Van den Bergh (1996) the issue of **regional sustainable development** has been considered under the three broad headings of **economic**, **social** and **ecological** concerns in a region.

The economic aspects are related to income, production, investments, market developments, price formation etc. The social concerns refer to distributional and equity considerations, such as income distribution, access to markets, wealth and power positions of certain groups or regions etc. And the ecological dimensions are concerned with quality of life, resource scarcity, pollution and related variables. This paradigm advocates a comprehensive decision-making that anticipates and manages scarce resource use, including environment and finance, while developing the regional system.

Information plays a critical role in sustainable development. The ability to identify, implement, and evaluate sustainable development strategies at all levels is inextricably linked to the effective identification, collection, use, and dissemination of information. The principles of sustainable development call for an integration of information about economic, environmental, and social factors in decision making. This information is required to support the identification of objectives, the development of policies or decision rules, and the evaluation of courses of action. While much of the reference to the role of information in sustainable development is directly linked to evaluation and decision making, access to information is also discussed in direct relationship to issues of equity and participation in decision making.

SYSTEM DYNAMICS AS A MODELING TOOL FOR SUSTAINABLE DEVELOPMENT

The system dynamics approach applies to dynamic problems (those that involve quantities that change over time) in feedback systems where feedback is defined as the transmission and return of information. System dynamics is an approach to understanding the behavior of complex systems over time. System dynamics is an aspect of systems theory as a method for understanding the dynamic behavior of complex systems. The basis of the method is the recognition that the structure of any system - the many circular, interlocking, sometimes time-delayed relationships among its components - is often just as important in determining its behavior as the individual components themselves.

An early attempt to model sustainable development was undertaken in “Limits to Growth” - models [42]. These models attempted to examine the impact of population growth, and pollution and resource use on planet. The neo-Malthusian conclusion of this early set of models was stated as “the limits to growth on this planet will be reached somewhere within the next one hundred years…even the most optimistic estimation of the benefits of technology in the model…did not in any case postpone the collapse beyond the year 2100” (Meadows et al., [42], pp. 23 and 145). Despite numerous criticisms the system dynamics methodology can be used to build models of sustainable development. The systems dynamic approach to modeling sustainable development is based on the same methodology of difference equations represented as a set of interacting feedback loops.

One of the most innovative approaches to modeling sustainable development at a sub-national or regional scale has been developed in US by Costanza et al. (1990) [16] and Costanza et al. (1997) [17] who have developed a set of system dynamic models which are interconnected to a geographical information system (GIS) to simulate through space and time the changes in wetlands surrounding the Chesapeake estuary. This integration of spatio-temporal processes by interfacing dynamic modeling with GIS represents the cutting edge of such modeling. This approach can be further enhanced by including intelligent front ends or Decision Support Systems (DSS) to the system. These DSS can include optimization approaches as well as neural networks.

Sustainability of development can be modeled with simulation supported by statistical and uncertainty analyses. These models are used to simulate possible scenarios for assessing novel and innovative technologies.

MULTIDIMENSIONALITY OF SUSTAINABLE REGIONAL DEVELOPMENT

Sustainable regional development is multidimensional in nature. Sustainability of regional development is a broader concept that involves multiple criteria. It involves a pattern of economic development that would be compatible with a safe environment, biodiversity, and ecological balance, intergenerational and international equity.

Sustainable regional development is a multidimensional paradigm, including socio-economic, ecological, technical and ethical perspectives. In making sustainability policies operational, basic questions to be answered are sustainability of what and whom? As a consequence, sustainability issues are characterized by a high degree of conflict. The design and development of sustainable development approaches is dependent upon the identification and development of an appropriate information infrastructure to support decision making. This information infrastructure must support the identification of objectives, the development and selection of appropriate actions toward those objectives, and the evaluation of progress toward those objectives.

The characterization of development sustainability in terms of a set of indicators makes very good sense. In fact, development sustainability is an abstract concept that is difficult to conceptualize and measure. These difficulties are due chiefly to the multidimensionality underlying the sustainability. Thus, development sustainability involves economic, ecological and sociological characteristics that are measured in very different units. What we should do in practice within such a complex scenario is to define and measure the different characteristics involved in the sustainability of a particular system in terms of suitable indicators. In general, it seems feasible to operationalize regional sustainability by specifying a set of minimum (or critical) conditions to be fulfilled in any development initiative for a region. These conditions may relate to economic, social and environmental objectives. Such critical conditions are usually not specified via one single indicator, but require multiple criteria. As a consequence, multiple-criteria decision analysis (MCDA) paradigm may be seen as a helpful operational instrument for regional sustainable development policy (Munda, 2005) [49].

Consequently, it seems a practical approach (Nijkamp, P., & Ouwersloot, 1997) [50] to describe environmental considerations and concerns mainly in terms of **reference values or threshold conditions** (limits, standards, norms) on resource use and environmental degradation (or pollution). This is in agreement with popular notions like carrying capacity, maximum yield, critical loads, environmental utilization space, maximum environmental capacity use and so forth. Usually optimization-based techniques are designed to create only single best solutions to problems. However, due to the presence of considerable system uncertainty and to the possibility that opposition from a dominant stakeholder can actually eliminate any single (even an optimal) solution from further consideration, environmental policy-makers faced with difficult and potentially controversial choices prefer to have the capability of selecting from a set of alternatives. MCDA has emerged as a powerful tool to assist in the process of searching for decisions which best satisfy a multitude of conflicting objectives, and there are a number of distinct methodologies for multicriteria decision-making problems that exist. Thus, Mendoza et al. (2002) [45] recommend the use of some qualitative multi-criteria methods for the assessment of indicators of forest sustainability. Bousson (2001) [9] applies a multi-criteria methodology (ELECTRE) to the choice of the most preferred management alternative according to several criteria.

Belton and Stewart (2002) [4] define MCDA as "an umbrella term to describe a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter". This general definition outlines three dimensions of MCDA, namely: (1) the formal approach, (2) the presence of multiple criteria, and (3) that decisions are made either by individuals or groups of individuals. MCDA approaches have been classified in a number of ways (Mendoza & Martins, 2006) [46]. One of the first categorizations makes a distinction between multi-objective decision making (MODM) and multi-attribute decision making (MADM). The main distinction between the two groups of methods is based on the number of alternatives under evaluation. MADM methods are designed for selecting discrete alternatives while MODM are more adequate to deal with multi-objective planning problems, when a theoretically infinite number of continuous alternatives are defined by a set of constraints on a vector of decision variables

The general classification of MCDA methods is suggested by Belton and Stewart [4] and classified MCDA methods into three broad categories:

1. **Value measurement models**: "numerical scores are constructed in order to represent the degree to which one decision option may be preferred to another. Such scores are developed initially for each individual criterion, and are then synthesized in order to effect aggregation into higher level preference models";
2. **Goal, aspiration or reference level models**: "desirable or satisfactory levels of achievement are established for each criterion. The process then seeks to discover options which are closest to achieving these desirable goals or aspirations";
3. **Outranking models**: "alternative courses of action are compared pairwise, initially in terms of each criterion in order to identify the extent to which a preference for one over the other can be asserted. In aggregating such preference information across all relevant criteria, the model seeks to establish the strength of evidence favoring selection of one alternative over another".

Land-use planning has also been analyzed including the integration of MCDA methods with Geographic Information Systems (GIS) (Malczewski, 1999) [39].

In many cases, the concept and measurement of the sustainability of a regional development is based upon an aggregation process of several indicators of different type and, consequently, expressed in very different units. Within this generally accepted scenario, this aggregation procedure can be done with a method based upon goal programming (GP) [33] with zero-one decision variables that turns out to be a powerful tool for determining the sustainability of development. The proposed procedure flexibly determines the "most sustainable" system from a set of feasible regional development plans in terms of several indicators of sustainability, as well as ordering or ranking the systems considered. GP technique has been widely used in the development of forest plans since the work by Field (1973) [25]. Thus, the works of Davis et al. (2001) [19] and Buongiorno & Gilles (2003) [10] include several applications of this method in forest resources management.

Some of limitations of the traditional MCDA methods when dealing with the complexity of natural resources management were summarized by (Rosenhead, 1989)as follows: (1) "comprehensive rationality", which unrealistically presumes or aspires to substitute analytical results and computations for judgement; (2) the creative generation of alternatives is deemphasized in favor of presumably objective feasible and optimal alternatives; (3) misunderstanding and misrepresenting the reasons and motivations for public involvement; (4) a lack of value framework beyond the typical "utilitarian precepts".

In view of the above limitations, a more flexible, robust, and broad approach to MCDA application to natural resources management is needed, one that is able to deal with ill-defined problems, with objectives that might be neither clearly stated or accepted by all constituents, with unknown problem components, and with unpredictable cause-and-effect relationships. A transparent and participatory definition of the planning and decision problems would also be desirable.

A number of authors (e.g. (Rosenhead, 1989) and (Checkland, 1981) [15]) proposed an alternative paradigm, known as "soft systems" methods to address what these authors described as wicked, messy, ill-structured or difficult to define problems. According to (Rosenhead, 1989) , these alternative paradigms are characterized by attributes such as: (1) search for alternative solutions, not necessarily optimal, but which are acceptable on separate dimensions without requiring explicit trade-offs; (2) reduced data demands through greater integration of hard and soft data including social judgments; (3) simplicity and transparency; (4) treatment of people as active subjects; (5) facilitation of bottom-up planning; (6) acceptance of uncertainty guided by attempts to keep options open as various subtleties of the problem are gradually revealed. An excellent review of these "soft methods", or sometimes referred to as soft-operations research methods, can be found in (.

In general, soft systems approaches give less emphasis on generating solutions; instead, they give primacy to defining the most relevant factors, perspectives and issues that have to be taken into account, and in designing strategies upon which the problem can be better understood and the decision process better guided. They are also more adequate for addressing complex problems dominated by issues relevant to, and influenced by, human concerns and their purposeful schemes (Mendoza and Prabhu, 2002) [45]. By doing so, they recognize the intrinsically complex nature of social systems and consequently attempt to avoid prematurely imposing notions of objectivity, rationality, mechanistic and predictable causality among relevant components of the problem.

Two characteristic features that are central to the soft systems approach are facilitation and structuring. Facilitation aims to provide an environment where participants or stakeholders are properly guided and discussions or debate are appropriately channeled. Structuring, on the other hand pertains to the process with which the management problem is organized in a manner that stakeholders or participants can understand, and hence, ultimately participate in the planning and decision-making processes.

This need led to the development of approaches that formally analyze qualitative decision problems such as: artificial neural networks (see (, (Moisen & Frescino, 2002) [48] and (Liu et al., 2003) [36]), knowledge bases ((Reynolds et al., 1996) [57] and (Reynolds et al., 2000) [59]), and expert systems (Store & Kangas, 2001) [64]. Two applications in particular of these new approaches, developed as decision support systems, are the Ecosystem Management Decision Support System (EMDS) developed by Reynolds (1999) [58] and CORMAS (Common-pool Resources and Multi-Agent Systems) developed by Bousquet et al. (1998) [8].

DECISION SUPPORT SYSTEMS (DSS)

DSS can be used by decision makers as an effective technique in examining and visualizing impacts of policies, regional development strategies, emission reduction measures, and climate change within an integrated and dynamic framework. In (Cai, Y. P. et al., 2009) [11] an interactive decision support system (UREM-IDSS) has been developed based on an inexact optimization model (UREM, University of Regina Energy Model) to aid decision makers in planning energy management systems. Optimization modeling, scenario development, user interaction, policy analysis and visual display are seamlessly integrated into the UREM-IDSS. In (Handbook, 2005) [55] the current status and future directions of model-based systems in decision support and their application to sustainable development planning is comprehensively examined.

A **spatial decision support system** (SDSS) is an interactive, computer-based system designed to support a user or a group of users in achieving a higher effectiveness of decision making while solving a semi-structured spatial decision problem (Malczewski, 1999) [39]. The concept of SDSS has evolved in parallel with DSSs (Marakas, 1998) [41]. The first MC-SDSS have been developed during the late 1980s and early 1990s (Malczewski, 1999) [39]. Early research on MC-SDSS is especially devoted to the physical integration of the GIS and MCDA. According to (Densham, 1991) [20], a SDSS should (i) provide mechanisms for the input of spatial data, (ii) allow representation of spatial relations and structures, (iii) include the analytical techniques of spatial analysis, and (iv) provide output in a variety of spatial forms, including maps. A typical SDSS contains three generic components (Malczewski, 1999) [39]: a database management system and geographical information systems (GIS), a model-based management system and model base, and a dialogue generation system. Today's spatial decision support systems rely on a GIS component. Cowen (1988) [18] defined GIS "as a decision support system involving the integration of spatially referenced data in a problem solving environment". A GIS system is composed of a geographical database, an input/output process, a data analysis method, and a user interface. Such modern GIS techniques have been instrumental in developing interactive modes between quantitative modeling and spatial mapping (Giaoutzi & Nijkamp, 1993) [30]. Especially when regional development plans have a bearing on land use, GIS may offer a powerful analytical tool for spatial sustainable development.

Multicriteria spatial decision support systems (MC-SDSS) can be viewed as part of the broader fields of SDSS. The specificity of MC-SDSS is that it supports *spatial multicriteria decision making*. Spatial multicriteria decision making refers to the use of MCDA. Web-based MC-SDSS is an active research topic which will be the subject of considerable additional interest in the future (Carver, 1999) [12].

A number of frameworks for designing MC-SDSS have been proposed including Diamond & Wright (1988) [21], Carver (1991) [13], Eastman et al. (1995) [23], and Jankowski et al. (1999) [35]. Despite differences in GIS capabilities and MCDA techniques, the generic framework contains three major components: a user interface, MCDA models (includes tools for generating value structure, preference modeling, and multiattribute decision rules), and spatial data analysis and management capabilities.

MC-SDSS have been developed for a variety of problems, including land use planning (Diamond and Wright, 1988) [21], (Thill, J.-C. & Xiaobai, Y., 1999) [65], (MacDonald & Faber, 1999) [38], water resource management (Bender and Simonvic, 1995) [5], habitat site development (Jankowski et al., 1999) [35], health care resource allocation (Jankowski and Ewart, 1996) [34], land suitability analysis (Eastman et al., 1995 [23]; Fischer et al., 1996 [26]), MULINO, the prototype of a DSS software (mDSS) for the sustainable management of water resources at the catchment scale (Giupponi et al., 2004) [31].

SPATIO-TEMPORAL INFORMATION SYSTEMS

Recently, the interest has been focused on dynamic applications with geographic reference. These applications are commonly called as spatio-temporal applications and examine phenomena, which occur in specific regions and change over time (Stefanakis & Sellis, 2000) [63], (Egenhofer, M.J., & Golledge, 1998) [24], (Frank, 1992) [29]. Current GIS technologies have limited capabilities in modeling and handling complex spatio-temporal phenomena. A framework with enhanced capabilities in both representation and reasoning of geographic data is proposed in (Ratsiatou & Stefanakis, 2001) [56]. A unified model for spatial and temporal information is proposed in (Worboys, 1994) [66]. The semantic data model proposed in (Yazici et al., 2001) [67] utilizes unified modeling language UML for handling spatiotemporal information, uncertainty, and fuzziness especially at the conceptual level of database design. Bibliography on spatio-temporal databases is in (Al-Taha et al., 1993) [2]. In (Parent et al., 1999) [52] spatio-temporal conceptual models are discussed. Examples of spatial, temporal, and spatiotemporal applications include land management, weather monitoring, natural resources management, environmental, ecological, and biodiversity studies, tracking of mobile devices, and navigation systems. Paper (López et al., 2005) [37] contains many recent references on spatio-temporal databases. A comparative review (Pelekis et al., 2004) [53] is followed by a comprehensive description of the new lines of research that emanate from the latest efforts inside the spatio-temporal research community. Spatial information systems can be categorized into four main groups (Abraham & Roddick, 1999) [1]: Geographical Information Systems (GIS), which result from the automation of cartography and deal with digitized maps displaying geographic or thematic information, Automated Mapping/Facilities Management (AM/FM) systems which automate the management and maintenance of networks such as telephone lines or power grids, Land Information Systems (LIS, also known as cadastral systems) which manage information such as the details of land parcel ownership, and Image Processing systems which process remote sensing images acquired by aircraft and satellites.

The following main modules may be utilized for integrated analysis modeling sustainable regional development:

1. a base of mathematical models and/or meta-models for simulating population dynamics;
2. a base of mathematical models and/or meta-models for simulating land use changes as affected by alternative policy/management scenarios;
3. a base of mathematical models and/or meta-models for the simulation of environmental impacts associated to land use changes producing quantitative indicators to be used by the multi-criteria analysis;
4. MCDA models (includes tools for generating value structure, preference modeling, and multiattribute or multiobjective decision rules); and
5. GIS/spatio-temporal information system for the management and description of spatio-temporal variability.

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Oleg Ščerbina, Jelena Šembeļeva, Jēkabs Trušiņš. Ilgtspējīgas telpiskās attīstības modelēšana un lēmumu pieņemšana
Ilgtspējīga attīstība ir saistīta ar sistēmu, kas apvieno telpu un laiku, jeb telpas-laika sistēmu. Rakstā dots pārskats par galveniem paņēmieniem ilgtspējīgās attīstības modelēšanā un lēmumu pieņemšanā. Sistēmdināmika ir sistēmu teorijas metode, kas pēta un modelē kompleksu sistēmu uzvedību laika gaitā. Reģionālā ilgtspējīgā attīstība aptver reģiona ekonomisko, sociālo un ekoloģisko struktūru. Ilgtspējīgas attīstības dinamika tiek ņemta vērā Forestera sistēmas dinamikas pieejā, kā arī dinamiskās izvietošanas jauktās programmēšanas modeļos. Statiski telpisko modeļu vidū ir modelis Hägerstrand, gravitācijas, transporta un izvietošanas modeļi. Aplūkota iedzīvotāju dinamika pilsētu plānošanas modeļos. Analizēta ilgtspējīgas attīstības daudzkriteriālā problēma, vērtējot iespējas izmantot mērķtiecīgo programmēšanu un citas daudzkriteriālās optimizācijas metodes. Aplūkoti priekšlikumi par telpisko risinājumu atbalsta sistēmu, kas ir interaktīva datorbalstīfa sistēma, kas veicina sasniegt augstāku lēmumu efektivitāti telpisko problēmu risināšanā. Analizētas iespējas izmantot ĢIS (ģeogrāfiskās informācijas sistēma), kas dod iespēju ievērot telpisko faktoru. Telpisko lēmumu piņemšanas sistēmas un GIS integrēšana paredz: mehanismus telpisko datu ievadīšanai, telpisko attiecību un struktūru reprezentāciju, telpiskās analīzes izmantošanu un dažādu telpisko risinājumu, tai skaitā kartografiko, izvadi. Apskatīta lēmumu pieņemšanas atbalsta sistēmas (DSS) un daudzkriteriālās telpiskās DSS izmantošana, kas ļauj izmantot modeļus bankās un ilgtspējīgas attīstības modelēšanas risinājumus.

Олег Щербина, Елена Шембелева, Екабс Трушиньш. Принятие решений и моделирование устойчивого развития.
Долгосрочное развитие связано с системой, которая обьединяет пространство и время. В статье рассматриваются основные подходы к принятию решений и моделированию устойчивого развития. Долгосрочное региональное развитие охватывает экономическую, социальную и экологическую структуру региона. Динамика устойчивого развития учитывается в подходе системной динамики Форрестера, в моделях смешанного целочисленного программирования динамического размещения. Статические пространственные модели включают модель Hägerstrand, гравитационные модели, транспортные модели и модели размещения. Системная динамика является методом теории систем, которая исследует и моделирует поведение комплексных систем в течении времени. Рассматривается учет динамики населения в моделях планирования городов. Анализируется многокритериальность задачи устойчивого развития, рассмотрены возможности применения целевого программирования и других методов многокритериальной оптимизации. В статье показаны возможности использования ГИС (географических информационных систем) для учета пространственного фактора. Интеграция системы принятия пространственных решений и ГИС предусматривает: ввод пространственных данных, репрезентацию пространственных отношений и структур, использование пространственного анализа и вывод пространственных решении, в том числе и карт. Анализируются возможности использования систем поддержки принятия решений (СППР) и многокритериальных СППР с учетом пространственного аспекта, позволяющих использовать банки моделей и решателей для моделирования устойчивого развития.