Jul 1st, 12:00 AM

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iEMSs 2008: International Congress on Environmental Modelling and Software
Integrating Sciences and Information Technology for Environmental Assessment and Decision Making
4th Biennial Meeting of iEMSs, http://www.iemss.org/iemss2008/index.php?n=Main.Proceedings
M. Sànchez-Marrè, J. Béjar, J. Comas, A. Rizzoli and G. Guariso (Eds.)
International Environmental Modelling and Software Society (iEMSs), 2008

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Abstract: Because of the increasing complexity of spatial planning processes there is a need for more powerful and more intelligent planning tools. This involves the development of environmental decision support systems (EDSS), or, in a more general term, spatial decision support systems (SDSS). Their design, implementation, and application have been discussed in many articles within the last 15 years or so. A summary of the most important aspects is given here, which distinguishes between functional and structural requirements of SDSS. With regard to the latter, it is argued that, from an end user's point of view, only a tight coupling or full integration strategy with respect to the involved software components fulfils the functional demands on SDSS. Further, the Land Use Management Support System (LUMASS) is introduced, which was developed in consideration of the functional and structural specifications discussed above. It integrates (i) the commercial GIS package ArcGIS™, (ii) ecological models focusing on soil and watercourse protection, and (iii) the Open Source Mixed Integer Linear Programming System lp_solve [Berkelaar et al., 2004] and follows a tight coupling approach. Finally, a sample application is presented that reveals the optimization of land use patterns with a view to minimizing soil erosion and sediment discharge into adjacent creeks and rivers.

Keywords: Spatial Decision Support System; LUMASS; Ecological Modelling; Land Use Pattern Optimization; Soil and Watercourse protection

1 INTRODUCTION

From the landscape ecologist's point of view, land use management aims at the sparing use of natural resources as well as the sustainable protection of the efficiency of the landscape budget. In the medium or long term, this is achieved by optimizing land use patterns according to environmental standards, e.g. as prescribed by the proposal of the EU Soil Framework Directive and the EU Water Framework Directive. In this context, the Land Use Management Support System (LUMASS) was developed in order to assist scientists and environmental managers in assessing land use impacts on the landscape budget with respect to specified criteria (e.g. minimizing soil erosion). Based on these assessments and additional constraints (i.e. area shares of individual land uses) optimum land use patterns can be generated using the multiobjective optimization module of LUMASS.

The underlying framework for the design and implementation of LUMASS is derived from the SDSS literature covering the last 15 years or so. In the following, the most important aspects are summarized and differentiated according to the functional and structural requirements of SDSS. Subsequently it will be described how LUMASS was designed and implemented to meet the aforementioned functional and structural requirements. Finally the application of the system is demonstrated using an example of the optimization of land use patterns so as to minimize soil erosion and sediment discharge, taking into account the specified area shares of specified land use alternatives.

2 REQUIREMENTS OF SPATIAL DECISION SUPPORT SYSTEMS

2.1 Functional Requirements

In order to identify the functional requirements of spatial decision support systems, it is useful to first take a closer look at the general decision-making process itself. According to Wessels and Wierzbicki [2000, p. 9], there are three vitally important issues that have to be addressed within the decision-making process: “(i) information about the current situation and history; (ii) the relation between basic processes and actions or decisions; and (iii) the decision process.” In the course of a decision-making process, these issues are treated within different phases, which go back to Simon [1960]. In the broadest sense, they may be characterized as follows [cf. Wessels and Wierzbicki, 2000; Makowski and Wierzbicki, 2000]:

Intelligence: The intelligence phase of the decision-making process is devoted to the identification and investigation of the decision problem. Besides data gathering and as accurate a delineation of the decision problem as possible, this phase includes the determination of problem specific evaluation criteria as well as the choice of methods and models for assessing criterion scores with respect to the decision problem.

Design: The design phase involves the development and evaluation of decision alternatives. Therefore, the processes affecting decisions are analysed and different decision alternatives are generated with respect to different magnitudes of preference concerning the evaluation criteria. Finally, each alternative is evaluated in terms of the given criteria.

Choice: In the choice phase, decision support methods and models are applied to the problem in order to make the best choice among the given alternatives.

Although the aforementioned approach looks like a sequence of steps to be performed one after another, in reality, it is accomplished in a recursive manner. That is, each phase may itself lead to a complex decision problem with its own intelligence, design and choice phases [Simon, 1960]. Furthermore, at each stage of the process it is possible to return to a preceding one in order to revise it and to repeat the successive stages with modified settings [Janssen, 1996], thus generating decision alternatives or evaluating the weighting scheme of objective functions following an iterative procedure.

Since spatial decision-making may be regarded as a special case of decision-making in general, the aforementioned approach seems to be suitable for spatial decision-making as well. In fact, a multi-stage or multi-level approach is also used in the spatial decision-making literature [cf. Jankowski, 1995; Janssen, 1996; Malczewski, 1999; Poch et al., 2004]. Even if there are some deviations from the above characterization concerning the number of stages and the assignment of tasks [e.g. Jankowski, 1995; Poch et al. 2004], there seems to be a consensus about the essential phases and tasks of spatial decision-making. However, what distinguishes spatial decision-making from non-spatial decision-making? It is the dependence of choices on one or more of the following spatial characteristics of given alternatives: (i) *location*, i.e. the absolute position given by two or three-dimensional coordinates [e.g. Carver, 1991]; (ii) *shape,* i.e. the geometry or contiguity [e.g. Aerts and Heuvelink, 2002]; and (iii) *topology*, i.e. the relative position in relation to other objects [e.g. Tourino et al., 2003].

So, what does this imply with regard to the functional requirements of spatial decision support systems? Generally speaking, the task of (spatial) decision support systems is to provide the user with appropriate methods and tools to support each phase of decision-making [Janssen, 1996; Wessels and Wierzbicki, 2000]. Therefore, the implementation of spatial decision support systems entails the integration of the following capabilities [cf. Fedra and Reitsma, 1990; Jankowski, 1995; Fedra 1996; Djokic, 1996; Malczewski, 1999, Denzer, 2002, Poch et al. 2004]: (i) spatial data management, analysis, and presentation (i.e. GIS), (ii) modelling of spatial processes, and (iii) assisting the user in solving complex spatial decision problems. A more detailed set of distinguishing features of spatial decision support systems is provided by Densham [1993, based on Geoffrion, 1983] as well as by Rizzoli and Young [1997]. Figure 1 shows how the most important of these features are integrated with the 3-phase model of decision-making described above.

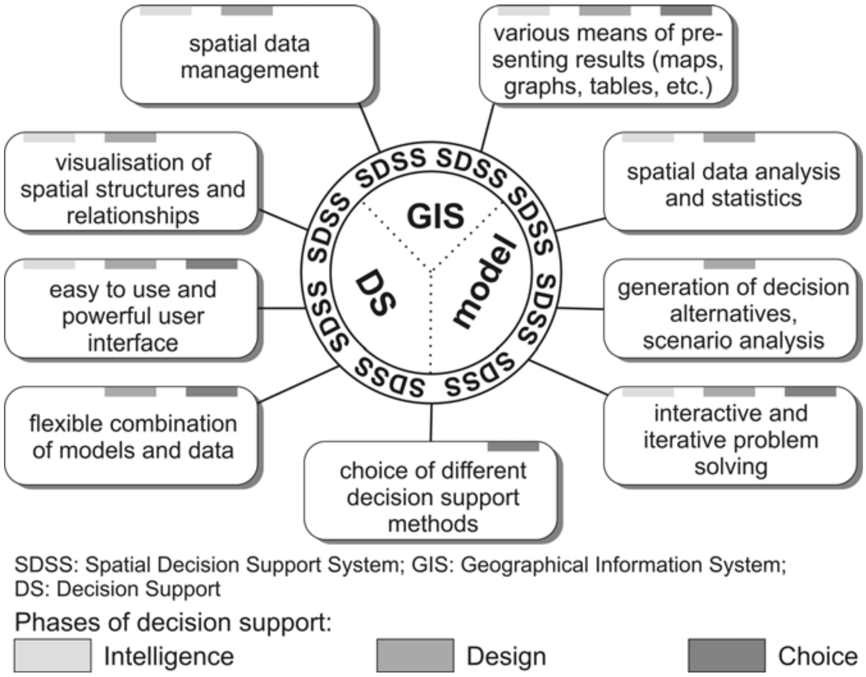

Figure 1. Functional requirements of spatial decision support systems [Geoffrion, 1983; Densham, 1993; Janssen 1996; Rizzoli and Young, 1997; Makowski and Wierzbicki, 2000].

One of the most important features in figure 1 is the ability to carry out the spatial decision-making process in an iterative and interactive manner, thus allowing the user to explore the set of feasible solutions by adjusting inherent model parameters and criterion weights or by preselecting spatial alternatives. Another important feature is the flexible combination of data and models. That is, it should be possible to run different process models on a once configured database in order to analyse the interdependencies of processes and decisions and to develop decision alternatives. Since both of the just mentioned features require some user input and configuration, they also need to have a powerful and easy-to-use user interface providing access to the relevant model parameters as well as to the underlying database. Another subset of important SDSS features comprises the already mentioned capabilities of spatial data management and processing. Here special emphasis should be placed on the methods and tools for analysing spatial structures and relationships as well as their visual representation in the form of maps, tables, graphs, etc.

A review of a random sample of articles dealing with SDSS showed, that the minority of systems integrate all of the aforementioned functional components (i.e. GIS, spatial process models, decision support methods) into the decision making process [e.g. Lam and Pupp, 1996; Joerin and Musy, 2000; Ostfeld et al., 2001; Mendoza et al., 2002a,b; Eldrandaly et al., 2003; Tourino et al., 2003; Li et al. 2005]. The majority of articles focus on either GIS and model integration or GIS and decision support (DS) integration.

2.2 Structural Requirements

In principal, there are three different approaches to the implementation of spatial decision support systems [cf. Djokic, 1996, modified; see also Rizzoli and Young, 1997]: (i) completely new development, (ii) coupling of existing components, (iii) partial new development, reusing existing components. Of these, completely new development is certainly the most flexible, but also the most expensive of the three alternatives [Rizzoli and Young, 1997], and it is rarely described in the literature [e.g. Lam and Pupp, 1996]. Coupling existing software components is much more economical [Denzer, 2005] and minimizes the need for new development. The functionality of the components in question is predetermined by the functional demands on spatial decision support systems as described in the previous section**.** Denzer [2005, p. 1218] considers four different building blocks: (i) models, (ii) geographical information systems (GIS), (iii) decision support systems (DSS), and (iv) data management systems. The challenge of the coupling approach lies in realizing data exchange between the individual components [cf. Johnston, 1990; Djokic, 1996; Reitsma and Carron, 1997; Ungerer and Goodchild, 2002; Eldrandaly et al., 2003; Denzer, 2005]. Depending on the systems involved, different interfaces may be used, resulting in different levels of integration. In general, the literature distinguishes three main types of coupling strategies [cf. Nygeres, 1992, cited in Jankowski, 1995; Fedra, 1996; Ungerer and Goodchild, 2002], which are roughly characterized below. For a more detailed discussion, please refer to the cited articles.

Loose coupling. In loose coupling, the user operates separate stand-alone applications, and data exchange relies on data files (usually in text format) being exported and imported.

Tight coupling. In tight coupling, the user operates separate applications or software components sharing a common user interface. Data exchange is automated and may be implemented by a variety of interfaces such as DDE (Dynamic Data Exchange), COM (Component Object Model), CORBA (Common Object Request Broker Architecture), etc.

Full integration. In fully integrated systems, there is no need for data exchange since the user operates a single application with a single database.

With respect to the structural demands on SDSS, only tightly coupled and fully integrated systems are capable of fulfilling the functional requirements of SDSS as described in the previous section. This becomes particularly apparent with regard to the need for flexible combination of data and models and, more obviously, for a common and easy-to-use user interface providing access to all functional components of the SDSS. Among the previously cited articles dealing with SDSS (cf. section 2.1), which fulfil the functional requirements, only some of them also fulfil the structural requirements discussed above [e.g. Lam and Pupp, 1996; Tourino et al., 2003; Eldrandaly et al., 2003; Li et al., 2005]. This implies, that only a minority of SDSS described in the literature seems to be ready-to-use systems tailored to the end-user for use in daily planning processes.

3 THE LAND USE MANAGEMENT SUPPORT SYSTEM (LUMASS)

3.1 Functional Characteristics and Features

In order to implement a SDSS for the purpose of land management or land use management respectively, appropriate models or methods have to be chosen for implementation in accordance with the general functional requirements of SDSS. With regard to the spatial modelling capabilities, land management systems, which are described in the literature, exhibit a broad range of used models. They range from watershed-scale hydrologic models [e.g. Kaur et al., 2004] to noise propagation models [e.g. Joerin and Musy, 2000]. In fact, due to the environment’s complexity, there exists no generic model for assessing the infinite variety of spatial processes. Hence, only specific models may be implemented, which cover the decision problem at hand.

LUMASS was developed primarily as a planning tool in the area of soil and watercourse protection. It focuses on model-based prediction of soil erosion risks on agricultural land and on estimating the erosion related transport of sediments into the surface water. Additionally, it offers further modelling capabilities for assessing land use impact on the landscape budget (cf. table 1). To be applicable as a tool for supporting decisions in the planning of concrete measures, it was designed with the following additional requirements in mind: (i) it must be possible to carry out query, calculation and assessment operations at the level of individual parcels, (ii) the system must have flexible parameter settings for land use and cultivation scenarios, and (iii) the geometry of parcels and other areal and linear landscape elements must be freely changeable (e.g. roads, ditches, erosion prevention strips) via the user interface.

For the purpose of spatial data processing, analysis and presentation, LUMASS is implemented as an extension to the commercial GIS package ArcGIS™. Thus, LUMASS provides the user with the functionality of a full featured geographical information system.

The decision support methods of SDSS, which are tailored to land management, predominantly focus on the following issues: (i) resource allocation among existing parcels (i.e. spatial alternatives) [e.g. Janssen, 1996], (ii) resource allocation including the generation of new spatial entities [e.g. Aerts and Heuvelink, 2002; Tourino et al., 2003], and (iii) site selection (i.e. generation of suitability maps) [e.g. Joerin and Musy, 2000]. Typical decision support methods used to address the aforementioned decision problems may be summarized as follows (in the same order): (i) linear programming, (ii) search heuristics (e.g. simulated annealing), and (iii) multicriteria analysis.

With regard to LUMASS, the challenge is to allocate the specified land use options among the existing pattern of parcels with a view to minimizing landscape impacts (e.g. minimizing soil erosion and sediment discharge) whilst taking into account specified area shares of land use options. For this, LUMASS provides the module "Multiobjective Optimization", which provides the user with an easy-to-use user interface for specifying the optimization problem. It maps the spatial allocation problem into the linear program format required by the underlying solver library (lp_solve) [Berkelaar et al., 2004]. If a solution is found by the solver, LUMASS displays the optimization result as a polygon layer within the ArcMap™ GIS environment. Due to the generic implementation of the optimization module, it may also be utilized for any areal related resource allocation problem in general. Thus, other criteria besides those focused on here (e.g. socioeconomic criteria) may be taken into account within the optimization procedure.

Table 1. Functional components and features of LUMASS.

Component	*Features*
Modelling Analysis and assessment of landscape processes	Simple and complex relief parameters (e.g. specific catchment area)
	SCS curve number (e.g. direct runoff per parcel, cascaded direct runoff)
	Soil erosion by water (USLE/RUSLE approach)
	Surface matter transport including localization of discharge points
	Soil water budget (e.g. groundwater recharge, usable field capacity)
	Soil compaction (including pressure propagation within the profile)
	Additional soil parameters (e.g. effective rooting depth)
GIS	Input, output, analysis, visualization, etc.
DS	Multiobjective optimization of areal resource allocation

3.2 Structural Characteristics and Integration

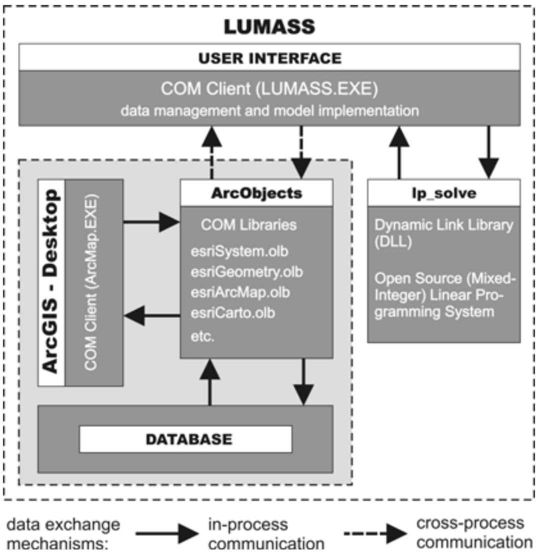

Figure 2. Structural components of LUMASS.

In order to fulfil the general functional requirements of SDSS as described in section 2.1, LUMASS follows a tight coupling strategy (cf. figure 2). It integrates five different software components and applications: (i) the LUMASS user interface, (ii) the ArcMap™ GIS application, (iii) the ArcObjects™ libraries, (iv) the geographical database, and (v) the Open Source Mixed-Integer Linear Programming System lp_solve [Berkelaar et al., 2004]. In this the LUMASS user interface, which is implemented as Visual C++® ex-ecuteable, plays the key role in integrating the aforementioned soft-ware components. On the one hand, it serves as central user interface for configuring the spatial database and model specific parameters and for modelling the spatial allocation problem. Further, it implements the logic of the integrated spatial process models. On the other hand, it manages the bidirectional data exchange between the LUMASS user interface and the ArcMap™ GIS application as well as the communication between the LUMASS user interface and the lp_solve library. For the communication with the GIS, the LUMASS user interface utilizes the ArcObjects™ COM (Microsoft Component Object Model) interface to access the spatial data, which is actually loaded into the ArcMap™ GIS application. Since the decision support component lp_solve is available as dynamic link library (DLL), the data exchange with the LUMASS user interface is implemented on the Visual C++® level.

4 LAND USE OPTIMIZATION USING LUMASS

The application of the LUMASS module "Multiobjective Optimization" is demonstrated using a rather simple but comprehensible optimization problem. The task is to optimize the land use pattern of the investigation site (cf. figure 3) with a view to minimizing the overall soil erosion. Therefore, two scenarios, which differ in the area shares allotted to the land use alternatives (cf. table 2), are investigated.

Table 2. Scenario definition of the sample application.

Scenario [1)]	WW-WB-R (c-factor: 0.072)	Winter wheat (c-factor: 0.115)	Maize (c-factor: 0.505)	Pasture (c-factor: 0.004)
1	$\geq$ 40	$\geq$ 20	$\geq$ 6	$\geq$ 9
2	$\geq$ 35	$\geq$ 15	$\geq$ 6	$\geq$ 20

[1)] the values represent the specified area shares as percentage of the area of the investigation site
ww: winter wheat, wb: winter barley, r: rape

Here, the disposition to water driven soil erosion of each land use alternative is expressed in terms of the c-factor. A high value denotes a high disposition to soil erosion and vice versa. Then for each optimization criterion (here: soil erosion), each spatial alternative has to be evaluated with respect to the given land use alternatives. In case of LUMASS, the integrated soil erosion model is used to assess the criterion scores as input for the optimization module. Figure 3 (left) maps the results of the model run in terms of a winter wheat–winter barley–rape rotation, indicating the parcel specific potential erosion risk.

When solving the optimization problem according to scenario 1 (cf. table 1), it becomes evident that the optimization procedure assigns the land use alternatives that exhibit a relatively high disposition to soil erosion to those parcels showing a relatively low potential erosion risk and vice versa. When the area shares are adjusted in accordance with scenario 2, the optimization module produces a similar land use pattern (cf. figure 3, right), except that the overall area of parcels providing a relatively high potential erosion risk has decreased in size due to the higher percentage of pasture.

5 CONCLUSIONS

Many articles have been published covering different aspects of the design and implementation of SDSS. Together, they provide valuable clues of functional and structural demands on the development of SDSS. However, only a limited number of SDSS fulfil these strict requirements. The introduced land use management support system (LUMASS) was developed in accordance with the functional and structural requirements of SDSS, thus representing a ready-to-use planning tool even for smaller private planning offices as well as for agricultural consulting agencies. With respect to its modelling capabilities, it includes rarely found methods such as the localization of non-point source sediment discharge. Furthermore, it assists the user in finding an optimum land use pattern with a view to minimization of landscape impacts whilst taking into account specified area shares of specified land use options. The sample application with the objective of minimizing soil erosion and sediment discharge in the investigation area showed plausible results for both, the modelling component as well as the optimization module.

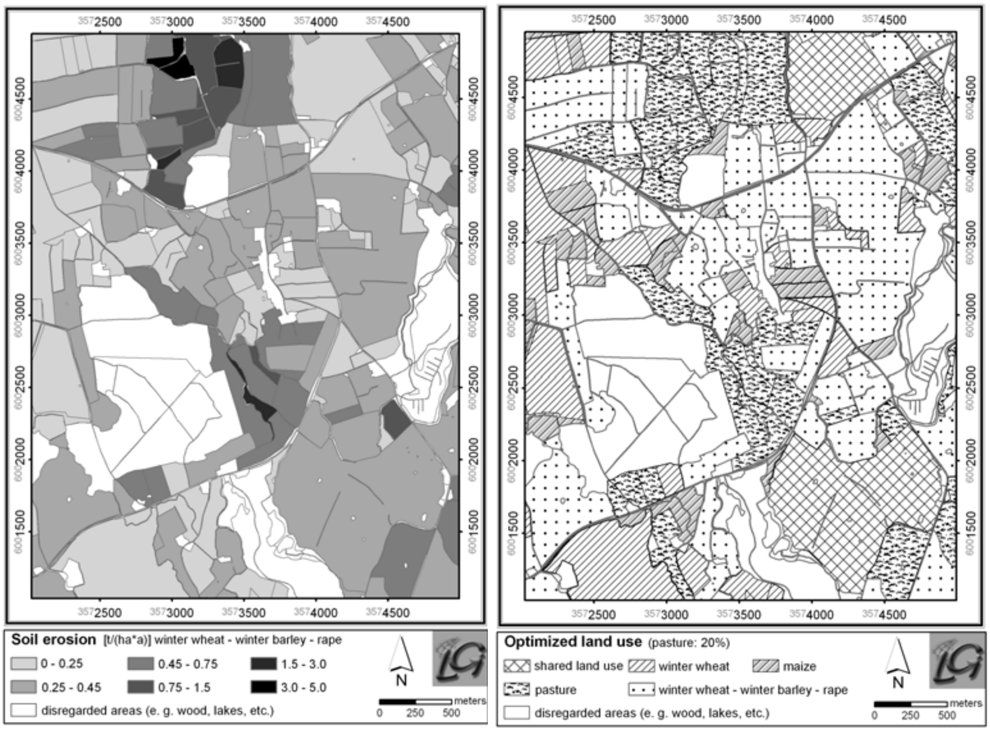

Figure 3. Left: soil erosion modelled for a winter wheat-winter barley-rape rotation; right: land use pattern optimized to minimize soil erosion and taking into account the given area shares (scenario 2).

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