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Development of a Web-based Multi-criteria Spatial Decision Support System for the assessment of environmental sustainability of dairy farms

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A B S T R A C T

The assessment of the environmental sustainability of agricultural infrastructures involves the use of multiple evaluation criteria and the analysis of geographical information. A Geographic Information System (GIS) is a computer system capable of assembling, storing, analysing, and displaying geographically referenced information. However, the GIS technology still suffers from several shortcomings due in large part to a lack of capable analytical capacity of supporting spatial decision problems. The most common solution for GIS to evolve into an effective tool for decision support is to couple them with operational research tools and in particular Multicriteria Decision Aid (MCDA). Due to the technological advances in the field of information systems, there is a great need to research how to integrate GIS, MCDA, the Internet, modeling and databases aiming at creating Web Multicriteria Spatial Decision Support Systems (Web MC-SDSSs). A Web MC-SDSS methodological framework is proposed for a fully integrated system of GIS and a specific MCDA method – ELECTRE TRI, through the construction of a Macro written in Visual Basic for Applications (VBA) in ArcGIS software. This macro interacts with a Web Algorithm Server for computing MCDA results. The developed Web MC-SDSS, named ELECTRE TRI in ArcGIS, is applied on a case study analysing the environmental sustainability of dairy farms in the Entre-Douro-e-Minho (EDM) Region.

1. Introduction

Spatial decision problems in agriculture and other areas often require that a large number of alternatives are evaluated based on multiple criteria. Geographic Information Systems (GIS) are a powerful tool for analysing spatial data and establishing a process for decision support. Multicriteria Decision Aid (MCDA) methods can facilitate decision making in situations where several solutions are available, various criteria have to be taken into account and decision makers are in conflict (Dias et al., 2002).

The combination of spatial analysis with MCDA has allowed the creation of Multicriteria Spatial Decision Support Systems (MC-SDSS), whose aim is to formulate and support spatial decision problems. This process involves the use of geographical data, the decision maker's (DM) preferences and the manipulation of the data and preferences according to specified decision rules (Sharifi and Retsios, 2004; Malczewski, 2006).

The integration of MCDA tools in GIS has been used in several projects and studies from different areas over the last twenty years as evidenced by the survey by Malczewski (2006). One of the most remarkable features of the GIS-MCDA approaches is the wide range of decision and management situations in which they have been applied, such as environment/ecology, transportation, urban/regional planning, waste management, hydrology, agriculture, forestry, geology, or site selection. Among some works, we highlight the works of Joerin et al. (2001), Gilliams et al. (2005), Aydin et al. (2010), Marinoni (2004), Eldrandaly et al. (2005), Boroushaki and Malczewski (2008), Vogel (2008), applied in different areas. In these applications the flexibility in representing and analysing spatial information is particularly pertinent as it is assumed that about 80% of the data used by decision-maker (DM) in decision processes are geographically interrelated (Worrall, 1991).

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Current developments in computational speed, storage volumes, World Wide Web (WWW) global access and software integrated development environments (IDE) provide opportunities to develop SDSS exploring both the advantage of information dissemination for DMs and the integration of GIS-MCDA. One of the greatest benefits of using Web Services in spatial decision making is the potential to overcome limited resources in terms of time, data and communication. The web enabled GIS facilitates decision making and serves as a gateway for decision makers and general users to access the system conveniently and effectively.

The typical Web SDSS is a Web-based GIS, where GIS information implemented in World Wide Web environment (Google Maps, and others) and Open Source GIS software is used, where MCDA methods are integrated. In this paper we develop a distinct Web SDSS: a Web-based Multicriteria Decision Aid in GIS software. This Web MC-SDSS integrates an MCDA method which is solved by a Web-based Algorithms Server that contains various MCDA tools, according to a clearly defined communication protocol. This integration uses the ArcGIS commercial software as user front-end. The Web MC-SDSS interface created named *ELECTRE TRI in ArcGIS* is a full integration of the MCDA outranking ELECTRE TRI method and GIS through the construction of a macro written in Visual Basic for Applications (VBA) programmed in ArcGIS 9.3 of ESRI. This interface is capable of: (1) providing mechanisms for the input of spatial data; (2) allowing representation of the spatial relations and structures; (3) applying the analytical techniques of spatial and geographical analysis; (4) providing output in a variety of spatial forms, including maps; (5) performing sensitivity analysis.

The resulting Web MC-SDSS was developed to address a real-world case study of decision analysis to assess environmental sustainability of dairy farms in Portuguese region, although it can be applied to other studies in different areas. Namely, the system was used to classify 1705 dairy farms in the Entre-Douro-e-Minho (EDM) Region according to environmental sustainability criteria. Seven environmental criteria were defined by three experts from Environmental and Zoo-technic areas. The classification allows determining which farms are sustainable from an environmental perspective, which ones are not sustainable, and, as an intermediate category, which ones are barely sustainable.

This paper is divided into five sections. Sections 2 and 3 offers a brief literature review regarding the Multicriteria Spatial Decision Support Systems, characterizing their types and directions of integration of MCDA and GIS as well as integrations available in GIS software and the development of Web MC-SDSS. In Section 4, the case study with description of problem and the criteria involved as well as the characterization of the chosen method, ELECTRE TRI, is presented. In Section 5, we introduce the MC-SDSS approach, enhancing the type of developed integration of GIS-MCDA, as well as the created architecture of MC-SDSS. Finally, in Section 6 the conclusions that have been drawn from the study are presented encouraging the opportunities for expanding the work.

2. Multicriteria Spatial Decision Support Systems

Finlay (1994) defines a Decision Support Systems (DSS) broadly as "a computer-based system that aids the process of decision making." The basic idea of DSS is to provide a computer-based framework that integrates database management systems with analytical models and graphics to improve the decision-making process. Spatial Decision Support Systems (SDSS) are a class of computer systems in which the technologies of both GIS and DSS are applied to aid decision makers with problems that have a spatial dimension (Walsh, 1992).

GIS and MCDA are currently the two most common decision support tools employed to solve spatial decision-making problems. Some authors consider GIS itself as a form of SDSS. However, GIS is widely recognised as a computer based system that combines spatial database management, geo-statistical analysis and mapping but not more than that (Laaribi et al., 1996; Van der Meulen, 1992; Malczewski, 1999). GIS can provide the decision makers with spatial information but it does not provide any type of preference modelling for decision support. Conventional MCDA techniques are mostly non spatial in nature and are subject to the assumption that the area under consideration is spatially homogeneous. This assumption makes such techniques unrealistic as, in many cases, performance criteria vary across the space.

In recent years, to avoid the limitations of each system (GIS and MCDA) in the area of spatial decision support, the idea of integrating GIS with different MCDA modelling has emerged in different areas of application such as: land suitability (Marinoni, 2004; Santé-Riveira et al., 2008), route location (Jankowski and Richard, 1994), risk-based in natural hazards (Chen et al., 2001), bank branch closures (Zhao and Garner, 2001), land management (Joerin and Musy, 2000), and location of undesirable facilities (Ferretti, 2011).

Abel et al. (1994) have identified three major advantages of integration: enhancing the evolution of GIS, improving the desired level of usability, and enriching approaches to problem solving. Therefore, both GIS and MCDA can be made more useful and complete through their integration and the effort to combine the strengths of these technologies would be mutually beneficial to both communities as well as those participating in decision-making processes (Parks, 1993). The integration of decision making techniques designed to handle multicriteria problems within GIS can provide users with a valuable extension of the functionality of GIS (Carver, 1991; Goodchild, 1992).

MC-SDSS integrate GIS based data processing and analysis techniques as well as MCDA. MC-SDSS provides a consistent framework that allows combining spatial data and decision maker's preferences according to a selected decision rule. MC-SDSS tools offer unique capabilities for automating, managing and analysing spatial decision problems with large sets of feasible alternatives and multiple conflicting and incommensurate evaluation criteria.

The way the two components are integrated depends on (Ascough et al., 2002): (1) the MCDA models incorporated into the MC-SDSS system (e.g., multiobjective versus multiattribute decision analysis techniques; (2) the decision making philosophy behind the design strategy (e.g., a system for supporting a single-user versus collaborative decision making); and (3) specific types of decision problems concerned (e.g. environmental problems, planning problems, location, etc.).

Operationally, the integrated GIS-MCDA approach starts with the problem identification, where the capabilities of the GIS are used to define the set of spatial alternatives and the set of criteria. Then, the overlay analysis procedures are used in order to reduce an initially large set of alternatives into a small number of alternatives which are easily evaluated by using a multicriteria model. Finally, the drawing and presenting capabilities of the GIS are used to present results (Chakhar and Martel, 2003). There is a large literature on GIS-MCDA integration available (see Malczewski, 2006).

MC-SDSS can be classified according to the extent of integration and the direction of integration of GIS and MCDA. Integration indicates the degree to which functions of software can be controlled directly by one another. It refers to the physical and logical connection between the software packages in the system. There are four possible modes of physical integration of GIS and multicriteria analysis tools (Goodchild, 1992; Chakhar and Martel, 2003; Jankowski, 1995; Malczewski, 1999, 2006, 2010; Chakhar and Mousseau, 2008): (i) no integration, (ii) loose integration, (iii) tight integration, and (iv) full integration. The first mode was dominant until the late 80s, when GIS and multicriteria analysis were used independently, without any connection between them. The other