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Design and development of a generic spatial decision support system, based on artificial intelligence and multicriteria decision analysis

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ABSTRACT

A new integrated and generic Spatial Decision Support System (SDSS) is presented based on a combination of Artificial Intelligence and Multicriteria Decision Analysis techniques. The approach proposed is developed to address commonly faced spatial decision problems of site selection, site ranking, impact assessment and spatial knowledge discovery under one system. The site selection module utilises a theme-based Analytical Hierarchy Process. Two novel site ranking techniques are introduced. The first is based on a systematic neighbourhood comparison of sites with respect to key datasets (criterions). The second utilises multivariate ordering capability of one-dimensional Self-Organizing Maps. The site impact assessment module utilises a new spatially enabled Rapid Impact Assessment Matrix. A spatial variant of General Regression Neural Networks is developed for Geographically Weighted Regression (GWR) and prediction analysis. The developed system is proposed as a useful modern tool that facilitates quantitative and evidence based decision making in multicriteria decision environment. The intended users of the system are decision makers in government organisations, in particular those involved in planning and development when taking into account socio-economic, environmental and public health related issues.
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1. Introduction

Decision makers increasingly rely on SDSS to address multicriteria, semi structured spatial decision problems. The concept of SDSS is mostly limited to domain specific applications [1]. However, certain spatial decision problems are common to many application areas. For example site selection, site ranking and site impact assessment problems are faced commonly in different environmental applications, public health risk assessment, land use planning, resource allocation, geoenergy initiatives and development of new facilities etc. These spatial decision problems have some common traits, i.e. they are multicriteria in nature and they combine a certain degree of both soft and hard information. Hard information is represented by quantitative and qualitative data, whereas soft information is comprised of decision maker's preferences, priorities and judgements [2].

Although the above mentioned spatial decision problems are common to many application areas, it is hard to find a generic SDSS in literature that can readily be utilised. Sugumaran and Degroote [3] discussed the possibility of developing a generic SDSS that can be useful in many application areas. Some of the commercial and open source GIS software such as IDRISI, ArcGIS, SAGA and ILWIS provide a variety of modelling techniques and an underlying mechanism for software customisation to serve the purpose of a generic SDSS [3]. For example, ArcGIS model builder provides a mechanism to combine different geoprocessing components together. Despite these customisation features, it requires deeper understanding of the structure of different modules and/or relevant programming/scripting knowledge to develop generic decision support tools from such existing software. Spatial Analysis and Decision Assistance (SADA) and Decision Support System for the Requalification of Contaminated Sites (DESYRE) are two freely available and frequently used decision support tools used for environmental and public health risk assessment. SADA provides a comprehensive decision support environment for site specific human health and ecological risk assessment [4]. DESYRE provides integrated management and remediation of contaminated sites, providing features for site characterization, socioeconomic constraints and risk assessment [5]. Both SADA and DESYRE provide site specific risk assessment features but lack in other commonly faced decision problems, e.g. site selection, site ranking or spatial knowledge discovery.

On the other hand, a number of other SDSS have been presented in the literature for domain specific applications related to

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site selection or site risk assessment. For example, Escalante et al. [6] presented an SDSS to evaluate crop residue energy potential to analyse the potential and geographic dispersion of biomass production. A set of biomass points was generated through the transport municipal network. Neighbourhood analysis was used to assign biomass potential to each study point. Fuzzy AHP and multicriteria decision analysis has been used for the assessment of each biomass point for the selection of most suitable sites for anaerobic digestion plants [6]. A hybrid multicriteria SDSS has been developed for the identification and prioritization of suitable regions for construction of solar power plants in Iran. This SDSS considers economic, environmental, technical, social and risk criteria in MCDA models to rank and prioritise cities for the solar projects in Iran [7]. Zanuttigh et al. [8] developed an SDSS for the management of coastal risks including assessment of erosion, flood risk, socio-economic and ecological vulnerability. This system allows the user to set up multiple scenarios by assigning different weights within the multi criteria risk analysis and to compare different options subsequently [8]. Comino et al. [9] presented a multicriteria SDSS for the assessment of environmental quality of the Pellice river basin in Italy. The model has been developed in IDRISI and has the capacity to assess the environmental quality of the study area in terms of “naturalness” and "pressures". An economic evaluation of the ecosystem services has been performed using the system. This evaluation compares the percentage of area covered under key landuse classes in comparison with the environmental quality classes considered [9]. Gorsevski et al. [10] introduced a prototype SDSS to facilitate the group decision making for wind farms site suitability in Northwest Ohio. The framework integrates environmental and economic criteria in the analysis using fuzzy set theory, Borda count and Weighted Linear Combination (WLC) methods. The criterion maps created by participants are aggregated to produce a group solution using Borda count method. Sensitivity analysis has also been performed to check the sensitivity of the model against the weights assigned to different criterion [10]. Fayetteville shale gas SDSS has been developed to analyse and assess the impacts of water consumption for hydraulic fracturing [11]. The system is used by the regulatory agencies and producers, to study the potential impacts on the environmental flow components of the river. Fayetteville shale gas SDSS utilises the Soil and Water Assessment Tool (SWAT) as its underlying modelling unit to analyse changes in hydrological patterns in the study area as a result of Shale gas exploration [11]. Ruiz et al. [12] have presented the design and construction of a multicriteria SDSS for the identification of sustainable industrial areas incorporating socio-economic, physical–environmental, infrastructures and urban development factors. The SDSS uses fuzzy logic and weighted score for the construction of the multicriteria decision model. This tool has been applied in Cantabria region, Spain for the identification of suitable areas for sustainable industrial areas [12].

The review presented above suggests that although a number of SDSS have been developed specifically for site selection or site risk assessment, but they do not offer a holistic decision support environment, i.e. they are limited to a specific decision problem or they are domain/application specific. It is hard to find a generic system that can tackle these frequently occurring spatial decision problems in one system, is not domain specific and is not limited to a given study area. Therefore there is a need for an integrated and holistic approach. This can be achieved by designing and developing a generic SDSS with an adequate model base to assist the decision makers tackling multicriteria decision problems in different domains. Furthermore, it is envisaged that using open source Geoinformatics technologies and a modular development approach can ensure the easy adoption and further extension of the capabilities of the system.

This paper presents the design, development and verification of such an integrated and generic SDSS based on a number of Artificial Intelligence (AI) and Multicriteria Decision Analysis (MCDA) techniques. The system can be applied in a variety of applications in environmental, socioeconomic, geotechnical and public health domains. Analytical modules can be used independently or in combination with each other as per the application requirement. The system also provides features for spatial knowledge discovery and geo-visual analytics to gain evidence based information for a given geographical region. The intended users of the system are decision makers in local and national government organisations, consultants and researchers.

2. SDSS architecture design

Architecture of the developed SDSS consists of three main components: (I) Geodatabase, (II) Model base and (c) Graphical User Interfaces (GUI) based on the SDSS architecture presented by Malczewski [2]. Geodatabase is used for spatial data management, Model Base provides analytical capability and GUI are utilised in decision making process by the user. The system design is independent of the study area and the underlying spatial data in Geodatabase. Therefore, the system can be applied independent of geographical location, subject to the availability of the data. Because of the modular design, any new analytical modules can be added to the model base without any architectural changes.

McIntosh et al. [13] identified key challenges and made recommendations in Environmental Decision Support Systems (EDSS) development and its successful adoption to help facilitate the achievement of desirable social and environmental outcomes. One of the main challenges exists in relation to ensuring EDSS longevity and financial sustainability. A recommendation to overcome this challenge was to focus on EDSS development that is relatively easy and inexpensive to use and update. This can be achieved by employing open source software technology which enables easy model expansion and reusability to reduce development costs [13]. The .Net based open source spatial library DotSpatial has been used for the development of current SDSS in order to read, manipulate and visualise spatial data [14]. The analytical modules in the Model Base have been developed using Microsoft .NET C# programming language and DotSpatial library. The GUIs were developed using .Net Windows Forms. In order to cover the most commonly faced spatial decision problems, several analytical modules have been developed using MCDA and Artificial Neural Networks (ANN) techniques. As shown in Fig. 1, the analytical modules designed and implemented in the system are divided into three main categories in accordance to their functional similarity and include:

1. Site selection and ranking: The analytical modules developed are:
   a. Analytical Hierarchy Process (AHP) based site selection tool.
   b. Self-Organizing Maps (SOM) based site ranking tool.
   c. Site ranking by neighbourhood analysis tool.
2. Impact assessment and prediction: The analytical modules developed are:
   a. Rapid Impact Assessment Matrix (RIAM) based site impact assessment tool.
   b. General Regression Neural Network (GRNN) based regression and prediction tool.
3. Spatial knowledge discovery: The analytical modules developed are:
   a. SOM based correlation finding tool.
   b. Parallel Coordinate Plots (PCP) based geo-visual analytics tool.

Technical detail of these analytical modules is covered in Section 4 and verification is provided in Section 5. A schematic di-

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