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Towards a New Integrated Spatial Decision Support System in Urban Context

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Abstract

The current growth of urbanization rate indicates that this trend is not going to stop, and therefore, it stresses the necessity of actions for mitigating the local and global pollution. Moreover, most of the actual stock is characterized by low energy performances since it pre-dates the energy regulation. The paper aims at addressing this issue by proposing the integration of Building Simulation (BS) approach, Multi-Criteria Analysis (MCA)methods and Geographic Information System (GIS)tool for developing a newMulti-Criteria Spatial Decision Support System (MC-SDSS)in urban context. The BS of relevant building archetypesallows to identify different resolutions of energy data: hour-by-hour data can be useful for demand-side management or renewable integration while aggregated data can be used for load forecasting and retrofit simulations. TheMCApermitschoosing between different building renovation alternatives by considering both qualitative and quantitative criteria.Moreover, the GIS support the method by creating geo-referenced databases.The methodpurposes in giving a comprehensive view to address the complexity of urban building energy planning; due to its flexibility, it can be applied to several urban areas. Three main phases characterize the study: i. overview of relevant existing techniques; ii. description of the integrated proposed method; iii. discussion and future application. The method can provide relevant feedbacks for ranking complex design energy options.

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*Keywords:*Geographic Information System (GIS);Building Simulation (BS);Multi-Criteria Spatial Decision Support Systems (MC-SDSS); Urban Energy Planning

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1. Introduction

The current growth of urban realities implies the implementation of proper planning strategies to avoid congestion in cities and to guarantee the same level services to citizens. The realization of new methods to properly drive the pattern toward the decarbonisation of energy sources is an urgent challenge to be faced (Lombardi, 2015; Lombardi & Gruning, 2016). According to Loorbach (2014), this challenge represents a "fundamental power shift away from powerful elites controlling resources, money and power towards diverse and distributed forms of collaboration between professionals and citizens".In Europe there are a number of case studies representing "anticipatory experiences of energy transition" (AEs).These are about 1500 cases but 90 have been deeply analyzed by the recent EU MILESECURE-2050 project (http://www.milesecure2050.eu/en/public-deliverables), which have developed environmentally sustainable ways of producing, consuming and transporting energy. Energy transitions are situated in current high-carbon societies, against the background of vested interests and influential societal structures. Currently, European contexts are insufficiently geared towards empowering individuals and facilitating local initiatives. All urban stakeholders play a role in this transition; in particular, researchers and practitioners should investigate and develop methodologies and tools for supporting decision makers and politician to fulfill their activity. Taking into account the guidelines provided, decision makers should implement the planning strategies in order to match the environmental goals and simultaneously improving or maintaining the life-style level of citizens.At once, the urban end-user should have a pro-active role in modifying their energy use profiles and attitudes, being aware of their role in the community.Despite much effort in research on the topic on Smart city and energy efficiency, currently, there is no an appropriate tool or a decision support system which is able to support this activity (Lombardi & Cooper, 2009; Brandon, Lombardi, & Shen, 2016). This paper proposes a novel methodology to integrate three different methods to achieve aMulti-Criteria Spatial Decision Support System (MC-SDSS)that enables to share heterogeneous data and can contribute to the strategies definition at two different levels: i. the individual inhabitant can visualize and understand the energy consumption and the refurbishment potential of its buildings; ii. the decision makers can collect precious technical information at the aggregated level for promoting short and long-term energy planning guidelines.

The proposed MC-SDSSis developed by scaling up the BSoutputs at the urban level by means of GIS tools and then by integrating Multi-CriteriaAnalysis (MCA).The thermal/electric load patterns as well as multi-criteria scenarios results can be geo-referenced on different maps considering the time-periods. This is crucial for identifying critical areas in terms of energy consumptions.The proposed methodology can thus contribute to tackle difficulties in terms of spatial decision making. The paper is organized as follows:Section 2 describes the MCA background;Section 3 introduces the new presented methodology;finally, Section 4 provides concluding remarks and discusses the concept of the potential of future application.

2. Overview of relevant existing techniques

In this section, an overview of existing multi-criteria decision support analyses, especially, the spatial one is provided. The aim is of introducing background theory that leads to the proposed integrated methods within which the building simulation is coupled with spatial decision support system methods.

2.1.Multi-Criteria Analysis (MCA)

A decision problem could be determined when a number of actions are available to be chosen by a group or an individual to perceive a difference between a current and a required state; thisdepends on the uncertainties of the alternatives'selection. As known, traditional decision analyses generally lead to minimize costs and maximize profits.MCA can help the decision makers to generate better decisions when there is more than one criterion(Bogetoft & Pruzan, 1997).Particularly, the application of MCAsto sustainable and smart energy planning has fascinated the decision makers' attention for a long time (Lombardi & Giordano, 2012). This method can resolve the difficult situation of energy management problems (Dall'O', Norese, Galante,& Novello, 2013). Energy planning is anappropriate field for MCA methods because it is subject to many sources of uncertainty, long time frames and capital-intensive investments along with featuring multiple decision makers and many conflicting criteria (Zhou, Ang, & Poh, 2006). The complexity in the planning of local energy systems is discussed in more detail in the work conducted by Catrinu et al. (Catrinu, Bakken, & Holen, 2004). Noticeably, different methods lead to various results, so it should be chosen the most suitable method that reflects the decision makers' targets in the best possible way. The method should be understandable and easy to use (Hobbsa & Horna, 1997). If decision makers do not comprehend what is happening in the method leads to the unreliability of results for them. One of the key non-academic texts in the MCA field is conducted by the UK Department of Communities and Local Government (DCLG) which produced a MCA techniques guide in 2009, where this manual introduces the best use of MCA, providing the practical techniques and guidance (DCLG, 2009).Particularly, this paper is focused on Multi-Criteria Decision Analysis, or MCDA. It is one of the most appropriate systemsto solve complex decisions that are characterized as a choice among alternatives. There are many classifications of MCDA methods, which exist in the literature. According to the classification of Pardalos, Siskos and Zopounidis (1995), methodological approaches can be divided into four principal categories, considering both characteristic development of the models and processes: Multiobjective Mathematical Programming (MMP); Multiple Attribute Utility Theory (MAUT) (e.g. AHP); Outranking Relations (ORT) (e.g. ELECTRE and PROMETHEE family); Preference Disaggregation Analysis(PDA).

The choice of the methods strongly depends on the specific problem formulation (Løken, 2007).In the case of urban planning, which is the main focus of this study, several decision making problems are faced (Finco & Nijkamp, 1999): the different scale of data and information that may be difficult to analyse and compare; a large set of - often conflicting - objectives or targets has to be taken into account; the uncertainty and quality of the available data and information, the available time for the decision making process. Therefore, this method should be appropriated since generally there is more than one decision maker in the relevant process who wants to include many conflicting objectives in the system. Pohekar and Ramachandran (2004) performed a comprehensive review of the multi-criteria application to sustainable energy planning, classifying different methods according to the application areas (Pohekar & Ramachandran, 2004). From their study is observed that the Analytical Hierarchy Process (AHP) accounts for 20% of the identified studies, followed by ELimination Et Choix Traduisant REalité(ELECTRE) (15%), and Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE, 10%).

Although a decision-making procedure could be harmed by advantages, the lack of a common language among the different stakeholders and urban actors is one of the most difficulties in this context. This is vitalsince planning assessment is generally based on both quantitative and qualitative values, expert's opinions and judgment. Moreover, training and experience are needed to use these methodssince one of its weaknesses is that it is reliant on decision makers' opinions and judgment which may change depending on the decision making's context (e.g. time, place, speakers, etc.).

2.2.Multi-Criteria Spatial Decision Support Systems (MC-SDSS): integrating GIS and MCDA

Almost about 80% of the decisional analyses datahas beenestimated to have a geographic nature (Worral, 1991). The spatial data and information is crucial to manage the territorial planning process. Due to the complexity of decision-making problems, appropriate approaches or methodsto support decisions and empower stakeholders are needed (Lombardi & Ferretti, 2015).Different approaches have been conducted by numerousresearchersin order to integrate the environmental values into the planning and urban design (Wang, Yu, & Huang, 2004). Brandon and Lombardi (2011) have classified these approaches based on their ability to tackle the whole life cycle management of an urban project.A list of these methods and tools is also provided in Lombardi and Cooper (2009). They aim is the identification and the assessment of both the technical andthe spatial aspects of the built environment. Although they are useful to guide the urban planning/design process according to environmental principles, they are not able to deal with all the complex issues involved in a planning design process. Furthermore, these systems are not able to describe the urban dynamics as a network distribution of issues at the different scales.

Although the existing tools and methods are very efficient to manage and store the data and information (e.g. visual and geo-referenced information system, decision support systems, virtual reality tools, etc.), there is still a lack in structuring problems tools. Therefore, it is needed to integrate and communicate among the stakeholders based on astructured support. In this sense, the collaboration based on Spatial Decision Support System (SDSS) and Multi-criteria seems more appropriate to tackle the problem (Lombardi & Ferretti, 2015). McHarg (1969) was the first who has used the maps to make decisions; this concepthas been later developed in GIS (Charlton & Ellis, 1991).To analyse this kind of systems, GIS is a strong and useful digital tool for supporting the analysesand management of big data; it offers a spatial model structured according to several layers and geo-referenced data (Azzena, 1995). Although the built-environment is the largest cultural, social, physical and economic capital of most societies, the lack of data has blocked the long-term scenarios development (Lomas, 2009). By using GIS, the data will be geo-referenced and each item will belocated in a proper system of coordinates.

Thereupon, there are many opportunities to make decisions in order to achieve a better level of sustainability of areas, and supporting suitable urban planning. On the other hand, GIS visualization could be expanded for building related environmental data by associating it to building stock (e.g. energy consumption can be associated to group of buildings) (Jones, Lannon, & Williams, 2001; Delmastro, Mutani, Pastorelli, & Vicentini, 2015). Various sources can be integrated to make available better information on which can make decisions for sustainable urban planning (Nghi & Kammeier, 2001; Mutani & Vicentini, 2013). Accordingly, the results presented in the urban energy maps are beneficialto have a broad overview of the energy performances of cities (Torabi Moghadam, Mutani,&Lombardi, 2016). The most widespreadknownprocess of the decision-making has been presented by Simon (1960) and then it is adjusted to territorial planning by Sharifi and Rodriguez (2002).

The decision making process is divided into four phases: intelligence, design, choice and review. The Intelligence phase provides the decisional context analysis for identifying the problems or the opportunity for those problems that is requested to make a decision. Design phase provides and generates the analyses of the possible alternatives actions; it is based on the problem comprehension process, utilizing the planning models that generate the solution for those alternatives and verify their feasibility. The design phase involves the standardization and weighting of all the factors being considered in the analysis. In the phase of Choice, the most advantageous alternatives will be selected from those available. Detailed analysis and implementations is the final phase to review, taking into account the past experiences and feedbacks. Several complex conditions are required in order to integrate GIS and MCDA systems and to afford better solutions; however, they can be considered separately problem-solving tools. Fig. 1. illustrates how both GIS and Multi-criteria are involved in the Multi-criteria spatial analysis methodological step-process (Malczewski, 1999). The flowchart (Fig. 1.) refers to the model based on four decisional process phases of that has been introduced by Simon (1960). This framework illustrates that GIS plays a significant role in the initial phase, while in the subsequence one (decision maker's preferences) multi-criteria techniques give an important contribution. In fact, as said before, GIS could be considered as a database facility management for supporting the decisional process as well. A detailed analysis of the state of the art of MC-SDSS can be found in Ferretti (2013);(Lombardi & Ferretti, 2015). The final section highlights the potentialities of the application of a new MC-SDSS toll the urban and regional planning level.

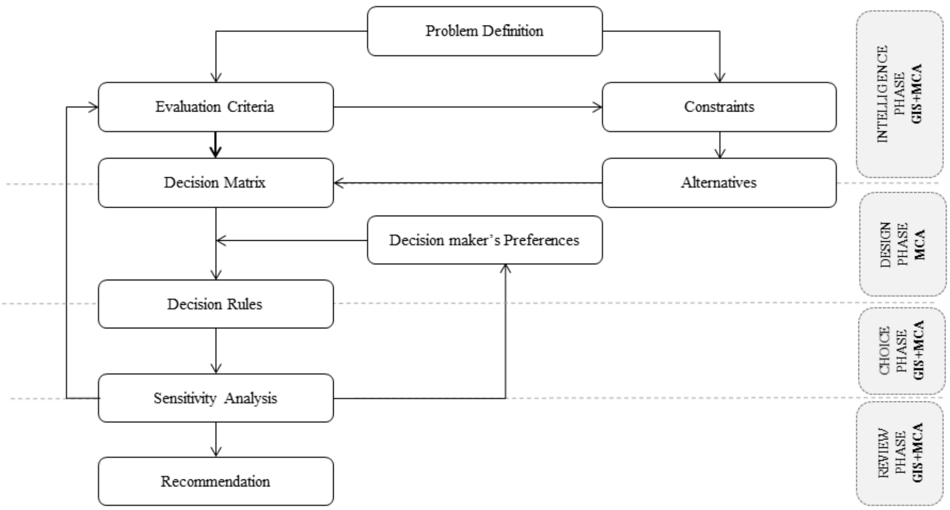

Fig. 1. Decision flowchart for spatial multi-criteria analysis, Source: (Malczewski, 1999; Simon, 1960)

2.3. Building Simulation (BS) and Reference Buildings

BS tools have been widely used for designing buildings able to satisfy all energy and operational requirements of the occupant. Generally, there are three main approaches for building energy simulation (Harish & Kumar, 2016): i. forward approach, the so called “White-box” models in which output variables are predicted according to input variables and their effect on the model parameters within a defined structure of the models (e.g. TRNSYS, EnergyPlus, DOE-2). This approach requires high quantity and quality of input data and provides high resolution of output results; ii. data driven approach, the so called “Black-box” models in which the models are based on regression techniques and are driven by both input and output data; parameters are estimated with artificial learning techniques;iii. “Grey-box” approach which consists in formulating a physical model for representing the structure of the building and identifying the important parameters (key parameters in an aggregated form); this last approach is mainly used for remote control and fault detection diagnosis, but not for the whole building energy use analysis.

The purpose and level of available input data drive the choice of the model. In the case of urban analysis, due to the lack of data and, mostly, to the high computational cost, it is clearly not possible to analyze every single building independently. It is thus necessary to define a set of Reference Buildings (Corgnati, Fabrizio, Filippi, & Monetti,2013) that are representative of the average building stock in terms of functionality and energy performances.

Reference Buildings are usually identified by taking into account the most energy-consuming service and data availability. Considering the Reference Buildings’ distribution, the procedure is extendable to every urban area with similar climatic characteristics.The number and the level of detail of each Reference Building strongly depends on the contest: there are areas with rich punctual building information (TABULA, 2012) and others with only few available data (Delmastro, Lavagno, &Mutani,2014).Once the Reference Buildings are identified, the characterization of the building stock can be easily defined with the support of GIS tool (Mutani & Vicentini, 2015).

This step is crucial for assessing urban energy consumption and their retrofit potential. When real energy consumption data are available, the typical energy consumption of Reference Buildingscan be assessed (Black-box approach); contrarily,if data are not accessible, buildings simulation softwareisone of the best ways to evaluate the energy performances of the stock.Nevertheless, White box models applied to Reference Buildings needs to be used for the estimation of the renovation potential of buildings.It is well known that buildings' actual energy performance frequently does not meet the expectations simulated at the design phase mainlydue to the occupant presence and behaviour(Torabi Moghadam, Soncini, Fabi, & Corgnati, 2015;2014). Thus, dynamic energy simulation tools are still unable to replicate the actual dynamics that govern energy uses within single buildings scale. Monitored data, if available, can be helpful to enhance the quality of the analysis.

The previous sections, both revising existing evaluation tools in MC-SDSS and BS, are used for creating the basis to develop an innovative and integrativemethod to facilitate and scale up the solutions for decision makers and stakeholders.

3. Proposed methodological approach

The ongoing transition toward the decarbonisation of energy production implies the realization of new tools/models/researches for supporting this process. The transition involves all the urban stakeholders: practitioners should provide proper technical guidelines and indications (e.g. the strategic mix of clean energy technologies to be promoted, the meaningful benchmark values, etc.) for supporting decision makers in defining the policy framework;decision makers have to implement the indications in order to i. guarantee a constant or improved level of energy services and well-being to citizens, ii. overcome costs and infrastructures barriers, iii. enhance the coordination with local, national and regional decision makers, iv. create action plans; at the same time, end-users should be aware and pro-active of their role in changing energy consumption patterns. Finding synergies between GIS and MCDA methods is a great opportunity for enhancing urban energy planning; in fact, it allows combining geo-referenced data and decision makers’ preferences in order to obtain useful information for the decision process.In this paper, the authors propose a new MC-SDSS model where heterogeneous data are commonly shared through a GIS platform accessible to final users for supporting i. citizens to understand the energy consumption of their building and ii. decision-makers to promote short and long-term buildings energy planning at the urban scale (see Fig. 2.).

Each component provides a fundamental contribution to the final model.

The BS approach is extended through GIS to a district/urban level in order to simulate the energy usage and future renovation possibilities. The buildings simulation allows understanding energy consumption with different resolutions (from hourly to annual) for assessing the energy profiles of several users' typologies. Therefore, different refurbishment interventions can be simulated. Moreover, this analysis is preliminary for studying how to match renewable energy distributed on a large scale and the urban demand. Both input data -such as an envelope system, equipment loads, occupant behaviour, climate data, lighting and etc. to simulate the energy usage (e.g. Heating and Cooling consumption, ACH) - and output results of the scenarios analyses – optimized energy systems configurations, distribution of retrofit measures etc.- are collected into geo-referenced databases.

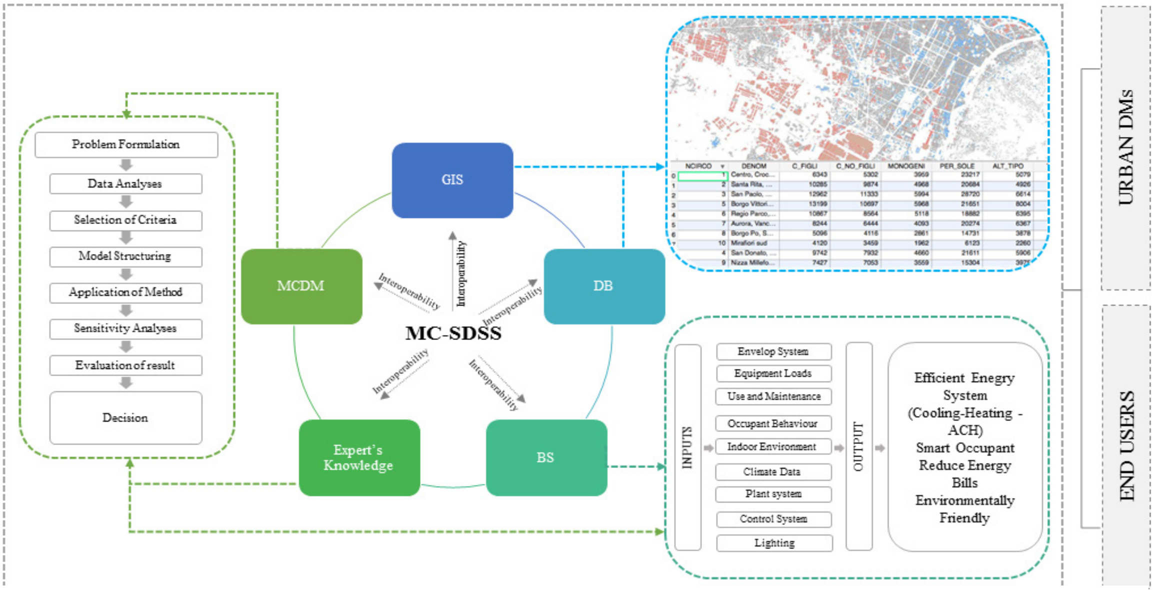

Fig. 2. Conceptual scheme of integrated proposed method, Source: Author's own elaboration.

The GIS enables to visualize the buildings in the urban maps, the results of building simulations to understand the retrofit options, the results of multi-criteria scenarios analysis and critical areas in terms of energy consumptions.This integration provides a graphical database able to improve the mapping, visualization, collection and management of data about building distribution and their consumption. Once the baseline energy map is ready to be analyzed, several multi-criteria analyses can be integrated and continuously updated into the database and the maps. It is possible to start the MCDA process and formulate the problems definition. For each decisional problem (e.g. reducing pollution, locating new facilities etc.) it is required to define the criteria (in accordance with decision makers' preferences) and their description to structure a robust model. For making decisions at urban scale is needed to consider and define different kind of criteria both qualitative and quantitative related to the decision context (e.g. environmental, social, economic, etc.), and it is crucial to implement the experts' opinion and judgment. In fact, the method requires the contributions of several experts to achieve the coherent and unique result.

With respect to traditional MCDA applications, the GIS integration implies the spatial representation of criteria data and the geographic siting of alternatives. Spatiality of criteria can be related to various aspects depending on the involved decision makers, the objective of the study and the type of alternatives: decision makers can belong to different territories; alternatives can be sited in different areas (location problems); the goal of the study can be different in different spatial context (e.g. district of a city). In such framework, weights are associated also in accordance to spatial units.The spatial criteria can be represented on maps.

The final decision depends on the spatial distribution of the alternatives. Some criteria may need a punctual spatial resolution (e.g. a single buildings), or more aggregated (e.g. group of buildings or a street) while others do not need at all (e.g. total investment cost of a new district heating network). A MC-SDSS problem can be seen as a map of tables (every location has a specific performance matrix) or as a table of maps (a map is created for each alternative) (Van Herwijnen & Janssen, 2001).

Once all the maps are created, the MCDA approach allows generating a suitability map of alternatives in which the performances of alternatives are spatially reflected (Ferretti, 2013).The coupling of GIS and MCDA can be performed in multiple ways: i. no integration: GIS and MCDA are sited on different hardware platforms and the transfer of input and output data is realized off-line; ii.loose coupling: GIS and MCDA are executed on the same hardware and data transfer is realized online by ASCII text manually executed by the operator; iii. tight Coupling: GIS and MCDA are executed on the same hardware and data transfer does not require an operator; iv: full integration: a single program that include both GIS and MCDA is created (Malczewski, 2006). The Loose coupling and Tight coupling are the most widespread approaches.

4. Discussion and future application

This study has provided a general overview of MCDA current techniques and proposes their integration with GIS and BS. The novel MC-SDSS method generates a common platform based on GIS data in which heterogeneous results are commonly shared and visualised by different users and for different purposes. The service is thought to be developed into an academic project framework and to be freely offered to interested consumers.

This paper has illustrated the importance of MC-SDSS as a way for solving problem in the energy filed at the urban scale. This method combines and transforms spatial geo-referenced data and building simulation data into a decision. The future implementation of the method implies to solve the several difficulties of SDSS, for instance the proper coupling of GIS and MCDA methods, as discussed in Section 3.Evidently, all of the data is not entered simultaneously; therefore, systems' interoperability is required so that data can be communicated from upstream systems for downstream use (International Facility Management Association, 2013). The presence of both qualitative and quantitative aspects related to the sustainable development is a challenge for the building sector; as a matter of facts, it is required to integrate heterogeneous data and information inside the urban spatial framework with the aim of setting up an integrated knowledge of the territory. Another challenge will be the integration of BS results as it involves users to continuously update and improve the reliability of simulation results. Data sharing between these approaches it is not simple because is characterized by different level of information. Moreover, by integrating GIS and BS it will be possible to link individual building models together with the energy urban network optimizing the energy demand and supply at district/urban scale. This will provide further benefits in decision making since allows reducing carbon intensity in energy demand and supply simultaneously, optimizing the overall energy system.

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