Chapter 5

Multi-criteria Spatial Decision Support System for Urban Energy Planning: An Interdisciplinary Integrated Methodological Approach

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Additional information is available at the end of the chapter

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Abstract

The present chapter provides an interdisciplinary integrated methodological framework. This framework guides to develop a multi-criteria spatial decision support system (MC-SDSS) to support decision-making processes in urban energy planning (UEP) purposes. The MC-SDSS helps in evaluation and visualization of the results of different UEP scenarios involving the relative stakeholders and decision-makers (DMs) from the early stage of planning. This will help in defining and evaluating energy-saving scenarios taking into account the participation of stakeholders in an interactive way. The meaning of integrating different tools and methods in this framework is due to their complementarity in fulfilling various tasks in the UIEP process. This fact can help to assess, over a short-/long-term period, the mix of measures by analysing meaningful scenarios focused on energy consumptions, environmental impacts and economic and social aspects. The result is the development of a new MC-SDSS, which is an interactive energetic plug-in in GIS environment using CommunityViz. This tool has been applied to a demonstrator case study, related to a medium-sized city of the metropolitan area of Turin. However, the methodology used for delivering the tool can be applied to other contexts due to its flexibility.

Keywords: interactive energy retrofitting scenarios, spatial planning support system: an interdisciplinary integrated methodological approach, geographic information system (GIS)

1. Introduction

Sustainability contests represent a fundamental challenge to traditional urban development practices and concepts. Reducing energy consumption and greenhouse gas emissions from urban infrastructure and building stock towards low-carbon cities requires a supportive planning process. In this regard, the use of appropriate tools and methods in order to address complex interactions of urban integrated energy planning (UIEP) processes is needed [1]. However, there is still not an integrated method to meet the urban integrated energy planning (UIEP) purposes [2]. In the mentioned study, the necessary approaches, which are needed to create the future urban energy consumption paths for scenario analysis, are described. Particularly, the importance of using geographic information system (GIS) for calculating, managing, storing and visualizing data at the urban scale is highlighted.

The chapter discusses in detail the steps design of methodological approach of a new integrated multi-criteria spatial decision support system (MC-SDSS) to evaluate and visualize the results of different UIEP scenarios involving the relative stakeholders and decision-makers (DMs) from the early stage of planning [3]. This will help in defining and evaluating energy-saving scenarios taking into account the participation of stakeholders in an interactive way. The meaning of integrating different tools and methods in this framework is due to their complementarity in fulfilling various tasks in the UIEP process.

The proposed methodology framework is explained in Section 2. Afterwards, Section 3 illustrates the first results of the methodology application. Finally, some concluding and limitation remarks of this study are given in Section 4.

2. Methodology: an interdisciplinary integrated approach

From the literature basing on a compilation of fragmented definitions, the section puts forward a synthetic description of key terminologies used, in order to facilitate and improve the debates on this emerging field [4]. UIEP is defined by [1], as a model-based energy planning process. This is divided into the following four main phases: Phase I, preparation and preliminary analysis; Phase II, detailed urban buildings energy modelling; Phase III, prioritization and decisional process and Phase IV, implementation and monitoring (**Figure 1**).

To address a complex issue of UIEP, which consists of many different planning phases involving multi-sectors and objectives, there is a need for an interdisciplinary approach [5]. In fact, the planning processes in urban energy problems may be not specifically innovative approach; however, its management by means of integrated, cross-sector, multi-criteria and multi-actor approaches is absolutely a novel approach to be resolved [4]. In this vein, many cities should struggle to develop innovative methods to successfully reinforce the collaboration among different research disciplines dealing with energy issues [6].

On one hand, considering the existing research gaps and methodological directions, this study follows an interdisciplinary path. Both technical (e.g. energy modeling) and societal (e.g. an active engagement of relevant actors and interest groups) elements help to perform a proper UIEP, especially from the stakeholders' perspective [7]. On the other hand, this study

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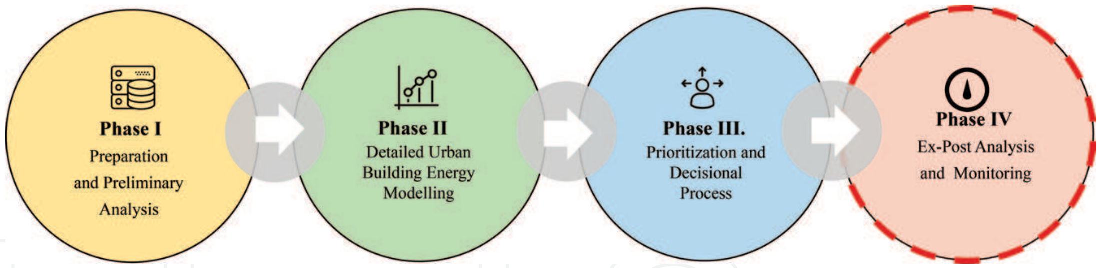

Figure 1. Urban integrated energy planning (UIEP) phases, adopted from [1].

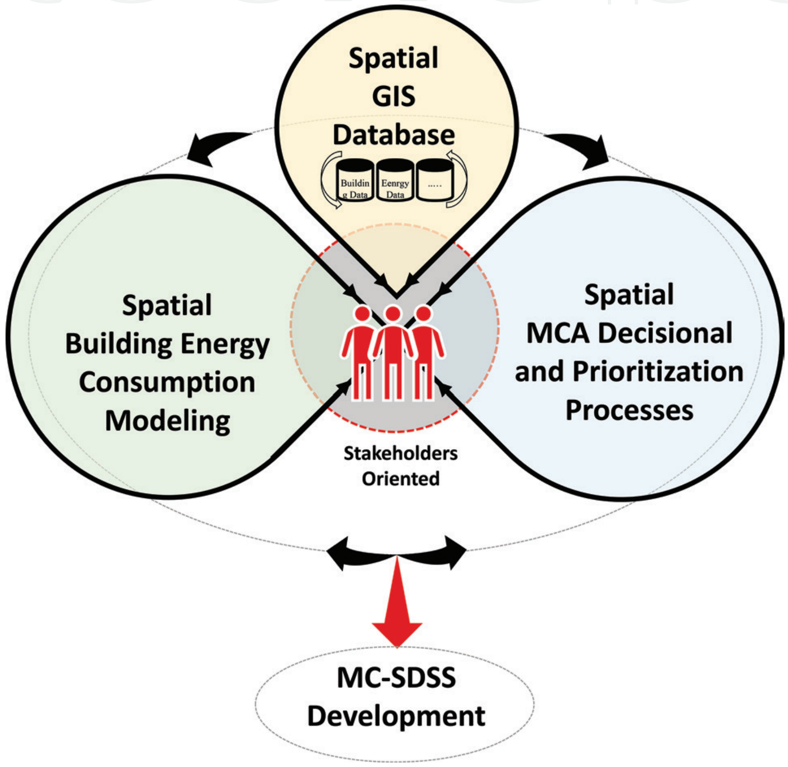

Figure 2. Schematic overview of the three main components of this research.

is fundamentally based on 'multi-methodology integration' defined by [1], in which parts of different methodologies are combined (e.g. statistical, engineering, focus groups, etc.).

In structuring the UIEP, it is important to select different appropriate approaches and to choose them considering the decision context and the type of planning project. Furthermore, it is crucial to analyse how it is possible to implement the interaction among the different stakeholders. As a result, the developed MC-SDSS for UIEP in the built environment uses techniques at the crossroads of three domains (see **Figure 2**):

- Spatial database, which constitutes the GIS platform including all the relative information and data and enables the use of analytical process and outcomes such as the maps, graphs and tables

- Spatial building energy modeling, which develops a bottom-up modeling to evaluate the current and future energy consumption at the city scale concluding a sufficient level of detail
- Spatial decision support system, which is the fact that the decision-makers (DMs) can express and exert their preferences with respect to multiple evaluation criteria and/or alternatives and, consequently, get back feedback in a real time to increase the DMs trust in the outcomes

The integration and combination of this technical know-how allow providing maps of energy, economic, environmental, social and technical indicators resulting from the evaluation of energy-saving scenarios. This provides a supportive tool for the urban actors in the participatory planning processes allowing several stakeholders with different backgrounds and interests to gather and discuss the issues of several urban and regional energy-saving scenarios [8]. In the following section, the integration of theoretical proposed framework and how it is supposed to be applied to the study practice are shown.

2.1. Research framework of MC-SDSS for UIEP

A new MC-SDSS, which is an interactive plug-in of ArcGIS 10.3 (www.arcgis.com) environment helps dynamically analyse the energy retrofitting scenarios based on the stakeholders' preferences over an urban scale. The methodological framework of this study consists of several phases involved in the framework of an integrated urban energy planning according to Mirakyan and De Guio [1]. Hence, it is helpful to break it down into the main elements that frame it to understand the research process steps employed in this study. To this end, in **Figure 3** a schematic flowchart of the methodological approaches is shown.

2.1.1. Phase I: preparation and preliminary analysis

Accordingly, the fieldwork should be started from the quantitative data collection to characterize the building stock and to create a supportive geodatabase. This phase (Phase I) is entitled 'preparation and preliminary analysis'. Phase I is the foundation of all processes and modeling approaches in the next Phases, II and III. Of course, the GIS database can be always updated, and more data can be joined into the framework. In this step, the information characterizes by georeferenced and non-georeferenced data. Therefore, the georeferencing procedure should be performed for those non-georeferenced ones in order to create a strong geospatial database. All the collected data have been then overlapped and integrated into the GIS platform. In this regard, each building polygon has been associated with its available and necessary information. The goal of this phase is to create a 2D-GIS-database platform for the city including the several factors, which may influence the building energy issues. The use of GIS was crucial since it offers the opportunity to characterize the building stocks and to visualize the spatial distribution of a large number of data through its location-based feature and its multiple layers representation.

2.1.2. Phase II: detailed urban buildings energy modeling

Consequently, Phase II intends to perform to model the energy consumption of building stock in a detailed way. First, a bottom-up statistical model has been developed to estimate

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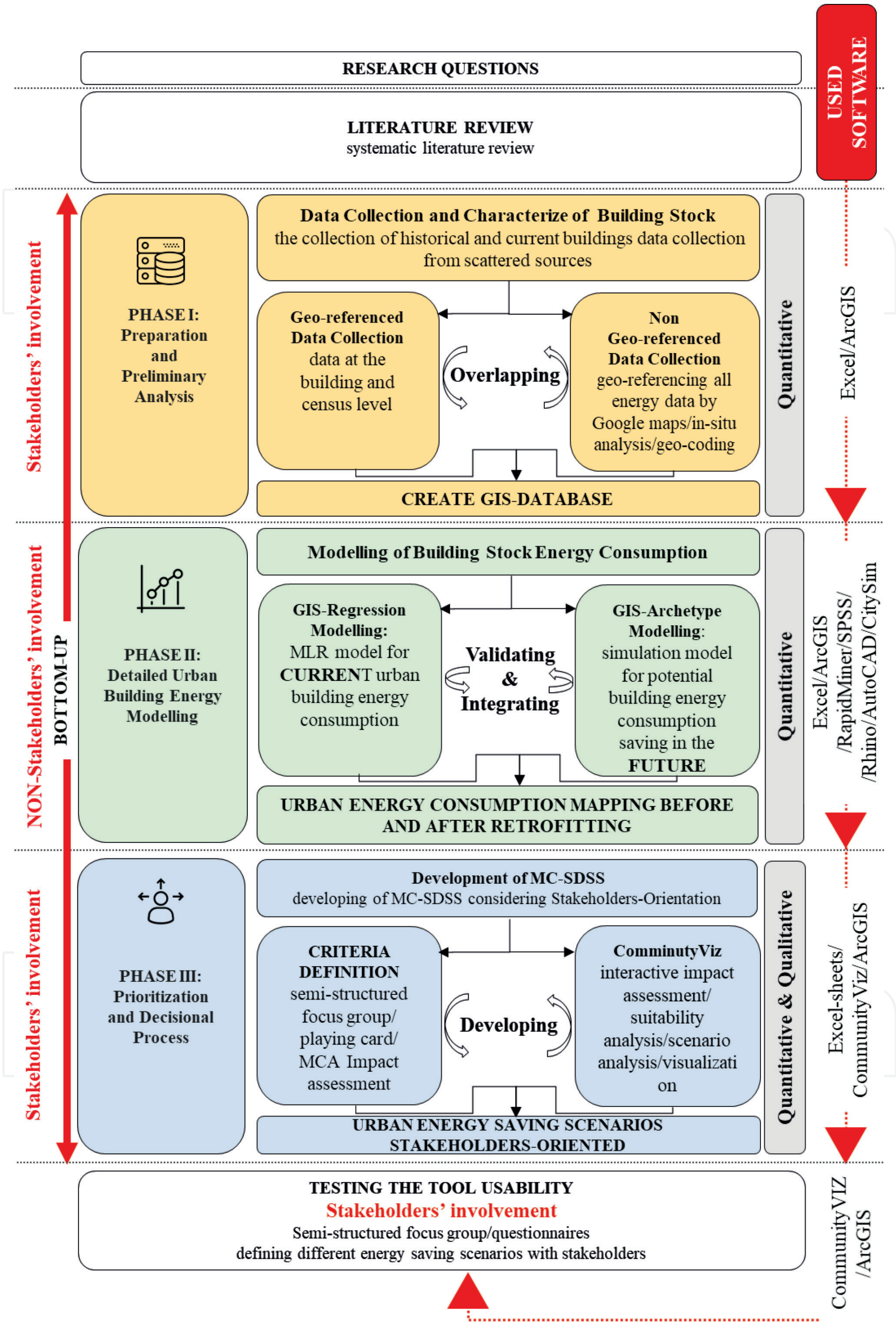

Figure 3. A schematic overview of the methodological approach.

the heating energy consumption for the built environment space heating at the city level. This model is based on the integration of statistical analysis with 2D-GIS to map the current energy consumption of the city [9]. The novelty of the proposed statistical model lies on its simplicity and applicability and the high level of their robustness in the literature. However, these statistical methods rely strongly upon monitored real data. It should be noted that fortunately, the author succeeded to collect a sample of information of energy billings as a data source for modeling purpose and for analysing the link between energy consumption and a wide range of different variables. Moreover, the statistical models are also able to take into account socio-economic effects in the equations [10]. They perform reliable consumption information about the present condition of buildings and for the calibration process of engineering-based models. However, due to the strong dependency of statistical methods on available historical consumption data, these methods are limited to predict the impact of innovative technology options and energy-saving potential after applying renewal solutions.

In counterpart, engineering methods are very detailed models based on traditional thermodynamic relationships and heat transfer calculations [10]. Although the historical data can be used for making a comparison against measured consumption data, these methods can assess energy consumption without any historical information. However, the engineering modeling approaches require a high quantity of information about building structure and parametric input to calculate the energy consumption of a set of reference buildings of the stock based on a numerical model. In this, 3D city models can significantly help [11]. One of the main benefits of engineering-based methods is their ability to predict energy-saving quantity for buildings after renovating solutions application [12]. In this phase, the methodology proposes to simulate the energy consumption of urban areas after applying retrofitting actions. Although the engineering methods are able to predict future conditions, simulating whole cities using energy demand software can be very extensive in terms of computer resources and data collection. The reduction of these time-consuming methods thus still remains to be resolved. Therefore, a new methodology, using city archetypes, is proposed to simulate the energy consumption of urban areas including urban energy planning scenarios. The objective of this part is to present an innovative solution for the simulation of the energy demand of cities by using a simplified 3D-GIS model, designed as a function of the city urban characteristics.

In fact, the methodology framework combines both the statistical and engineering approaches to obtain a more robust prediction of the urban energy consumption. The framework is performed in order to reduce time-consuming processes of energy demand simulation and assessment and for designing urban energy-saving scenarios. A spatial distribution of urban building energy consumption in 2D/3D visualization provides spatial decision support system (SDSS) tool in order to identify where the energy consumption is mostly concentrated to make the better decisions.

2.1.3. Phase III: prioritization and decisional process

Phase III of the study follows 'a mixed methodology' that combines qualitative and quantitative approaches [7]. Qualitative research refers to semi-structured focus groups formed in which the qualitative data such as stakeholders' opinion are collected through discussions and questionnaires. Particularly, the use of focus groups by stakeholders in this study has the following implication: it reflects the 'mixed methodology' choice for Phase III with the use of qualitative (semi-structured focus groups, questionnaires, playing card) and quantitative (building stock energy data, costs, etc.) data collection and analysis methods.

Regarding the definition of evaluation criteria, several methods exist in the literature [13]. The present study proposes a participative approach in order to define the evaluation criteria through the multi-stakeholders workshop including semi-structured focus group organized involving relevant stakeholders [14]. The definition of evaluation criteria side by side with the real local stakeholders leads to have trustable results that grantee the robustness of planning process. A vast number of available MCDA approaches make it necessary to carefully select the most appropriate method for each specific decision context. In this framework, the 'playing cards' is chosen [15] due to some reasons. First, it is a simple and intuitive method and easy to be understood, even by non-experts in the field of decision processes [16]. Second, they can help DMs in managing values that cannot be quantified without difficulty, involving qualitative judgments. Finally, the technical parameters involved in the playing card methodology can be interpreted easily, allowing a simplification of the problem. Lombardi et al. [14] describe the main the procedure of 'playing cards' method and its results.

Subsequently, each of the selected criteria from the workshop has been analysed and assessed to be implemented in a new MC-SDSS tool (see Section 3). Two main instruments, Interactive Impact Assessment (IIA) and Suitability Analysis (SA), are modeled and adapted in order to develop a new MC-SDSS. Several dynamic attributes and indicators were modeled and coded using CommunityViz as a planning support system (PSS) tool [17]. This PSS tool is selected as a base for further modeling processes due to its several strengths. It helps in analysing and understanding the potential alternatives and their impacts through visual investigation and scenario analysis. Moreover, this tool is interactive and provides dynamic feedbacks on changing the assumptions and viewing the influences of changes on the future scenarios on the fly. Furthermore, it engages stakeholders in participative and collaborative decision-making processes through visualization in real-time approach. All the above strengths lead to stronger consensus and better decisions in resolving complex problems. The detailed methodological procedure developed for supporting this phase of research is under progress of publication.

This methodological approach provides a significant innovative progress in the research field that is developing an interactive plug-in tool for UIEP in the GIS environment. In this regard, finally, the second workshop is organized to test the usability and validate the tool from the real stakeholder point of view. For evaluation purposes, this workshop is included in two semi-structured focus groups. This step attempts to understand the weaknesses and strengths of the mentioned framework. In this workshop, the questionnaires also were designed for analysing the stakeholders' feedbacks about the developed tool. Within the use of this GIS extension, public administrative users, such as urban energy planners, policymakers and built environment stakeholders, can plan, design and manage low-carbon cities. This plug-in will provide the stakeholders with the ability to visualize interactively and explore a range of possible future-saving scenarios.

3. Methodology application

The present section illustrates the interface of the developed MC-SDSS tool based on the methodology framework explained in the previous section (Section 2). As mentioned before, this tool is an interactive plug-in in GIS environment, which has been adapted from an existing urban planning tool called CommunityViz. The developed MC-SDSS tool supports the stakeholders in urban energy planning through participatory and collaborative processes. It helps make better decisions by expressing the stakeholders' preferences and their conflicting objectives.

3.1. An interactive MC-SDSS tool

All the phases were integrated in order to create a new MC-SDSS tool. This tool uses CommunityViz, which is an ArcView modular GIS-based decision support system developed by the Orton Family Foundation (http://www.communityviz.com). The above-said tool is able to integrate different types of data such as scripts, numbers, 2D maps, 3D visualization and raster in a real-time and multidimensional environment [17]. CommunityViz encompasses two main components as extensions to ArcGIS: (i) Scenario 360 to map and analyze and (ii) Scenario 3D to visualize. Conceptually, Scenario 360 can be described as a spatial spreadsheet allowing for calculations on spatially related data and formulas that call standard GIS functions [18]. Since each formula, assumption and dependency is viewable and editable, there is not any 'black box' element to a model defined in Scenario 360 [18].

CommunityViz Scenario 360 adds interactive analysis tools and a decision-making framework to the ArcGIS platform with which stakeholders can understand the planning processes easily.

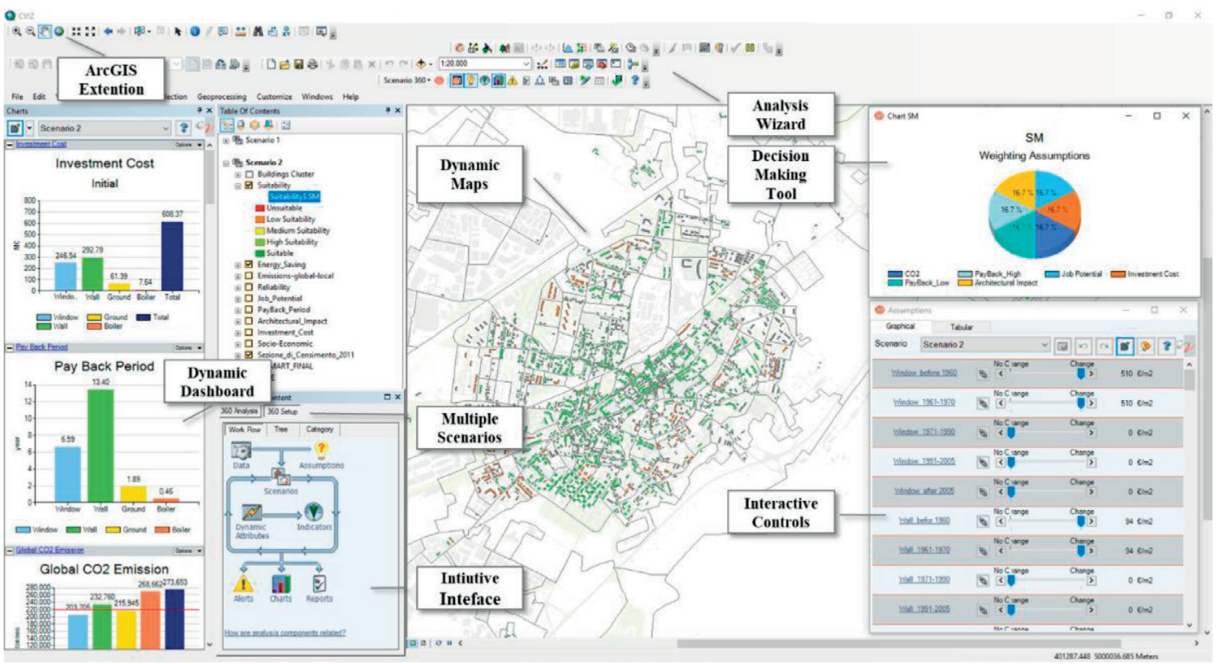

Figure 4. CommunityViz interface; the case study of Settimo Torinese.

Stakeholders can define different decision assumptions and visualize on the fly how the changes may affect environmentally, economically, technically and socially the future scenarios. This dynamic process helps urban actors to negotiate in order to make better decisions [17]. Moreover, it helps facilitate an understanding of the complex problems such as UIEP [19]. Within this tool, many presentation features are available to assist in sharing information with the users including maps, alerts and charts. In these views, stakeholders can ask 'what-if' questions and visualize 'if-then' scenarios in a real time and discuss it very quickly and effectively [20].

CommunityViz Scenario 360 is selected for this study due to its several strengths. It helps analyze and understand the potential alternatives and their impacts through visual investigation and scenario analysis. Moreover, it creates a real-time experiment with different scenarios, changing the assumptions quickly and viewing influences on changes. Furthermore, it engages stakeholders in participative and collaborative decision-making processes through visualization and interactive media [21]. All aforementioned strengths lead to stronger consensus and better decisions in resolving complex problems.

Figure 4 shows the interface of Scenario 360 modeled for the case study of Settimo Torinese. Particularly, the tool consists in building dynamic attributes, which are changeable based upon:

- Data: dynamic data layers create new or add existing layers to the Scenario 360 analysis geodatabase. An important feature is that it provides a dynamic data about features on a map that can be performed by formulas. Therefore, when one aspect changes, the software recalculates the entire analysis.
- Assumption: slider bars or tables let change assumptions during analysis. Using the assumptions, the stakeholders can express their preferences and decisions. When an assumption is changed, all associated formulas with that assumption are automatically recalculated within the scenario.
- Indicators: formula-driven analysis results that are updated automatically while the analysis is performed. Indicators can show the outcome of one or several dynamic attributes.

The stakeholders can experiment their preferences and decisions altering the slide bars. Consequently, they can visualize and analyse the impact of their decisions over different energy retrofitting scenarios. The impact of different scenarios is then visible through different charts, maps and indicators. The tool provides the ability of comparison among different scenarios and indicators.

4. Conclusion

This chapter summarizes the overall conclusion and relative limitation for each phase of planning. In particular, this work creates a link between energetical, economical, societal, technical and environmental performances of retrofitting interventions. The research boundaries were delineated by focusing on existing residential building stock since they characterize the context of most European cities. The relative available data of these buildings were first collected and georeferenced from various sources. Based on the created geospatial database, the building energy consumption patterns were statistically modeled to map the current energy patterns over the entire city. Afterwards, the archetype model of the city was created in order to speed up and ease the future energy-saving simulations by applying the retrofitting solutions. The geospatial database was used as the object of multi-criteria analysis assessments. Finally, an interactive MC-SDSS was created to support the DMs in defining energy-saving scenarios in real time.

4.1. Phases I and II

As illustrated in **Figure 3**, to model the energy consumption over the entire city, a large number of historical data are needed. The most challenging issue was related to collecting and integrating the built environment data and information since the data are significantly scattered among several entities at the local level, and there is a lack of interoperability among the data sources. Actually, this section reports that one of the main barriers to developing a robust and detailed analysis is correlated with the data collection procedure. Especially in Italy, information about building stock and their energy performances are derived from different regional and local authorities, and they are not often homogeneous. Therefore, in order to set up an effective energy planning at the local scale, it is crucial to improve the quality of data availability and management. Data availability of buildings' energy consumption will hopefully improve in the future thanks to smart metering and real-time data monitoring following recent open data policy. To this end, a supportive GIS database where all the scattered information and data were georeferenced is first created.

Referring to the energy consumption modeling at the urban scale, this framework proposed a geospatial statistical modeling. Generally, statistical methods estimate the energy consumption based on a historical data. The model succeeded to estimate the energy consumption of most existing buildings, where the monitored data was not available. However, due to the strong dependency of statistical models on existing available data, these methods are not able to predict the impact of the future refurbishment solutions. Therefore, there was a need to simulate the future city energy performances. However, the simulation of the whole city may be extremely time-consuming.

Therefore, Phase II within the research framework in **Figure 3** proposed a novel engineering methodology to accelerate the urban area energy consumption simulations, including urban planning renovation scenarios. The energy demand of cities, as well as the microclimatic conditions, was calculated by using a simplified archetype 3D model designed as a function of the city urban characteristics. By the proposed archetype modeling approach, this method shows that the number of buildings to be simulated can be drastically reduced with no particular influence on the accuracy of the results. On one hand, the main advantage of an engineering-based method is the capability of predicting energy savings for buildings after the application of renovation measures. On the other hand, these methods are very detailed models based on thermodynamic relationships and heat transfer calculations. As a general remark, the historical data can be used for the comparison against measured consumption data.

4.1.1. Limitations

This study suggests first a spatial data collection and then an integrated procedure of urban energy modeling approaches based on the data collected (i.e. statistical and engineering). This faces several barriers including:

Regarding the data collection

- The energy consumption data is not usually open source; thus, a huge effort was needed to collect the data from different entities and to ask the collaboration from local stakeholders.
- The georeferencing procedure of data could be also a challenging issue. In many cases, the necessary information related to the buildings are associated with the building number (as points) rather than the building polygon. The tricky issue is that these points are sometimes situated between two or three buildings having the same distance. Thus, it is not easy to understand that the data belongs precisely to which building.

Regarding the statistical modeling approach

- A vast amount of historical available data is needed. For many regions, it is almost impossible to have a monitored data in terms of energy performances.
- The intrinsic limitation of statistical methods concerns the microclimate effects, which were not taken into account in the present work. In fact, a microclimate model that would give a single value for the whole city for air temperature would not significantly improve the results of the current model presented in this work.

Regarding engineering modeling approach

- The need for high-level detailed thermo-physics data of the buildings in the city.
- Setting up the simulations can be a tedious task requiring a lot of time and expertise.
- The simulations themselves are very time-consuming, and they require high-performing processors in order to perform the entire city.

4.2. Phase III

As illustrated in **Figure 3**, a MC-SDSS has been developed to support the stakeholders with different backgrounds and preferences. The tool is an interactive plug-in in ArcGIS environment. MC-SDSS is able to help participants in a user-friendly way to define energy refurbishment scenarios. Moreover, the tool gives an opportunity to generate the suitability maps, with which the stakeholders can analyze the grade of the suitability of their decisions. The development of MC-SDSS is based on an existing tool, named CommunityViz. Originally, CommunityViz is a software used to support urban planning purposes. Within this research, CommunityViz was adapted and modeled to support UIEP. Two main integrated instruments, Interactive Impact

Assessment and Suitability Analysis, were modeled. The main difficulty was to adapt the tool to energy urban planning, considering many complex aspects of this issue. Modeling of all retrofit dynamic attributes and the type of connection between all the attributes was another difficulty of this part. The modeling design process is quite complex. The model should chain all the data, attributes and indicators. This means that once the stakeholders change one parameter, others will change automatically in their proposed scenario. The participants are able to rapidly experiment different energy renovation scenarios and change the assumption. This creates an effective interaction between the stakeholders. They can visualize very complex problem of energy-saving scenarios simply by different dynamic colorful maps, charts and indicators.

4.2.1. Limitations

This study suggests the development of a new MC-SDSS, which can define dynamic retrofitting scenarios side by side with stakeholders. This faces several barriers including:

- The need for the tool that to be open source
- The difficulty of the workshops to be time-consuming involving real stakeholders
- The difficulty of the inclusion of conflicting point of views and then aggregation of stakeholders' preferences in a participative decision-making context

The proposed framework will help urban actors to develop energy planning projects, guiding them in the choice among a considerable number of existing planning approaches. The main advantages of the developed MC-SDSS in the field of urban energy planning can be summarized as follows:

- To allow the participative processes
- To give a visualization opportunity for the decision process in specific areas
- To consider multiple criteria (e.g. economic, environmental, technical and, particularly, social aspects)
- To manage and store a very large amount of georeferenced data and to illustrate results requested by users according to different spatial forms (e.g. maps, graphs)
- To show the distribution of buildings' geometrical characterization and buildings' energy consumption

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Conflict of interest

The authors declare no conflicts of interest.

Other declarations

The present chapter is emerged from the 3 years research of PhD thesis of Sara Torabi Moghadam under the supervision of the Professor Patrizia Lombardi and co-supervision of the Professor Guglielmina Mutani in order to illustrate the methodological framework used to create an interactive MC-SDSS.

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