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Elsevier Editorial System(tm) for Building and Environment

Manuscript Draft

Manuscript Number: BAE-D-19-00346R3

Title: An interactive Multi-Criteria Spatial Decision Support System for energy retrofitting of building stocks using CommuntiyVIZ to support urban energy planning

Article Type: Original Research Paper

Keywords: Urban Building Energy Retrofitting Planning; Interactive Spatial Decision Support System; Multicriteria; CommunityViz

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Abstract: A major concern for any city is urban energy planning, which is particularly multi-sectoral and multi-actor oriented. This concern is especially critical for the built-up urban zones, which are predominantly responsible for the bulk of energy consumption and carbon emissions. Hence, an interdisciplinary, integrated approach is needed to address this complex challenge. This study focuses on both energy retrofit interventions for existing building stocks and the integration of participative processes in decision-making. It deals with the development of a stakeholder-oriented approach to implementing effective strategies in urban energy planning. This can help define meaningful building energy retrofitting scenarios that focus on energy consumption and environmental impact, in addition to economic and social considerations. A major outcome of this study is the development of a new multicriteria spatial decision support system (MC-SDSS) that is an interactive energy-related plug-in for a geographic information system (GIS) environment, adapted from CommunityViz. The methodology used to deliver the tool can be applied to other contexts and situations due to its flexibility. The new MC-SDSS facilitates the decision-making process for stakeholders who ask "what if" questions and visualise "if-then" scenarios in real time to handle the entire planning procedure adequately.

An interactive Multi-Criteria Spatial Decision Support System for energy retrofitting of building stocks using CommuntiyVIZ to support urban energy planning

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ABSTRACT

A major concern for any city is urban energy planning, which is particularly multi-sectoral and multi-actor oriented. This concern is especially critical for the built-up urban zones, which are predominantly responsible for the bulk of energy consumption and carbon emissions. Hence, an interdisciplinary, integrated approach is needed to address this complex challenge. This study focuses on both energy retrofit interventions for existing building stocks and the integration of participative processes in decision-making. It deals with the development of a stakeholder-oriented approach to implementing effective strategies in urban energy planning. This can help define meaningful building energy retrofitting scenarios that focus on energy consumption and environmental impact, in addition to economic and social considerations. A major outcome of this study is the development of a new multicriteria spatial decision support system (MC-SDSS) that is an interactive energy-related plug-in for a geographic information system (GIS) environment, adapted from CommunityViz. The methodology used to deliver the tool can be applied to other contexts and situations due to its flexibility. The new MC-SDSS facilitates the decision-making process for stakeholders who ask "what if" questions and visualise "if-then" scenarios in real time to handle the entire planning procedure adequately.

Keywords: Urban Building Energy Retrofitting Planning; Interactive Spatial Decision Support System; Multicriteria; CommunityViz

1 INTRODUCTION

One of the primary concerns for cities is urban energy planning (UEP), which is extremely multi-sectoral and multi-actor oriented. Hence, an interdisciplinary, integrated approach is needed to address such a complex challenge [1]. The planning processes for urban energy problems requires the management of integrated, cross-sector, multicriteria, and multi-actor approaches, and this presents a formidable challenge [2].

However, the built environment is a primary concern of UEP with regards to reducing its energy demand, which currently accounts for 60% of the total building final energy use [3]. In Europe, especially, existing building stocks play a key role in energy consumption due to their low energy performance [4]. Because of the complexity of the UEP research field, this study focuses on energy retrofitting of building stock.

Two of the most comprehensive review studies have classified building energy modelling into “top-down” and “bottom-up” [5,6]. In this context, several appropriate bottom-up models were presented by means of statistical [7,8] and engineering analysis [9,10] for building stock at the urban scale.

While many scientific studies have focused on the development of energy efficient residential building stock models, there is a limited number of studies that integrate spatial decision-making processes for future retrofitting alternatives. The development of innovative tools and methods that successfully reinforce collaboration among the different sustainable energy research disciplines is particularly crucial [11].

Multicriteria spatial decision support systems (MC-SDSS) enable users to better understand the decision-making problems they encounter with regards to UEP. It provides users with an adequate interactive convivial environment for performing effective visual decision-aid activity [12]. Consequently, users are able to negotiate, quantify, and communicate preferences, and make more rational and more explicit decisions [2,13]. Visualisation of the output of the evaluation criteria and the alternatives leads to increased robustness of the results and encourages feedback [14–16].

This research was motivated by a dearth of suitable tools, which in combination with a geographic information system (GIS), in the context of UEP, can interactively define real-time building energy retrofitting scenarios by considering the sustainability pillars and the economic, environmental, and social dimensions [17]. This issue remains unresolved in terms of the provision of powerful visualisation tools required in decision-making processes, despite the significant number of studies and tools available for energy planning purposes. For example, the tool by the Management of Energy systems in Urban Environment (MEU) project [18] is a web-based platform that focuses mostly on the development of different energy demands and supply scenarios, including a GIS-based visualisation of the results. It allows annual energy flow, consumption, and related actions to be monitored continuously [19]. UrbanSim is another open source spatial decision support systems (SDSS) tool for scenario development and simulation on a city scale [20]. Another example is the DIMMER Dashboard (district information modelling and management for energy reduction) [21], which is an open platform for existing real-time data processing and visualisation supporting decision-making by energy managers and public authorities that monitor district energy data.

To address the issues mentioned earlier, this study proposes the development of a new MC-SDSS tool. This tool is an interactive GIS environment plug-in adapted from an existing urban planning tool called CommunityViz. The developed MC-SDSS tool can support stakeholders in the energy retrofitting of building stocks planning via participatory and collaborative processes. One of the objectives of this tool is to facilitate the decision-making process for stakeholders who ask "what if" questions and visualise "if-then" scenarios in real time.

The study illustrates the development and use of an interactive map based on multicriteria analysis, representing a decision-making tool for energy retrofitting of building stocks at an urban scale. It addresses the following research questions: "How useful are interactive MC-SDSS tools in supporting the stakeholders in UEP decisions for the built environment?" and "How can their usability be improved?"

The research boundaries were delineated by focusing on thermal energy consumption of existing residential building stocks because these characterise the context of most European cities. The residential building stock of the city of Settimo Torinese, a medium-sized city of the metropolitan area of Turin, was chosen as a case study to develop and test the tool. This city consists of 300 census sections and approximately 3,600 residential buildings with 47,831 inhabitants. It occupies an area of 33 km^2 with 8.55 mm^3 of total heated volume.

This paper is organised as follows: Section 2 describes the selection and evaluation of the decision criteria and illustrates their impact assessment process. Section 3 outlines the modelling approach including the architecture design of the newly developed MC-SDSS. The results and discussions are presented in Section 4, which describes the validation and testing of the developed tool via a series of focus groups that were organised as part of this research, together with relevant stakeholders. Finally, Section (5), includes the concluding remarks and examines the main limitations.

2 DECISION CRITERIA: SELECTION AND EVALUATION

2.1 Selection process of evaluation criteria

The selection process of the criteria was performed in the following steps:

1. Project needs and target definition: residential building retrofitting;
2. Pre-selection: literature, research and development (R&D) projects, normative and standards;
3. Final selection: feedback of stakeholders via a semi-structured workshop.

After collection and elaboration of all the required information and data, a list of decision criteria need to be carefully identified and selected to resolve an urban energy saving problem [22]. Although a large number of criteria does exist for assessment and examination of the energy saving scenario performance, literature suggests it is preferable to select a limited number rather than considering too many [23].

2.1.1 Project needs and target definition

The aim of this research is to create an interactive spatial tool which is able to define a combination of energy retrofit measures that reduce the energy demand of a building (e.g., windows replacement, insulation of the opaque envelope) and the plant system efficiency (e.g., heating, boiler replacement). The key role of the evaluation criteria is to aid decision-makers in making the best energy retrofit decision by providing quantitative or qualitative data. The criteria assess the project within its social, environmental, economic and technical performance for 5 retrofitting measures as shown in Table 1, that emerged from previous analyses provided in Swiss Society of Engineers and Architects-SIA [24]. The Swiss Minergie-P Label has been selected since it corresponds to a zero-energy building. This could be as an example for advanced energy retrofitting refurbishment. The thickness of the insulation required is defined based on the Swiss Minergie-P Label and corresponds to a zero-energy building. This value is derived from the characteristic curve of heat loss with respect to the insulation's thickness and considers that insulation with a thickness greater than 35 cm does not introduce any additional protection.

This work aims to implement the retrofitting measure in Table 1 to create a basic MC-SDSS model. Given that the MC-SDSS can be updated, more solutions can be implemented in the future.

Table 1: Considered retrofitting measures following the Minergie-P renovation.

Code	Retrofit Measures	Considered Measure	Note
b_1	floor	external insulation	35 cm of EPS insulation
b_2	roof	roof thermal insulation	35 cm of EPS insulation
b_3	walls	external wall thermal insulation	35 cm of EPS insulation
b_4	window	triple glazing replacement	U-value = 0.7 ($Wm^{-2}K^{-1}$)
b_5	boiler	condensation	-

2.1.2 Pre-selection

MCDA was previously applied in energy planning with regard to several different issues (e.g. renewable energy planning, energy resource allocation, building energy management) [13,25,26]. In particular, Wang et al. [27] conducted a comprehensive literature review based on 229 articles related to the MCDA criteria for sustainable energy decision-making issues. This study revealed that the energy system efficiency, investment cost, operation and maintenance cost, NOx emission, CO_2 emission, land use, social acceptability and job creation, were the most widely used evaluation criteria in energy planning, energy management, and resource allocation studies. More recently, Strantzali and Aravossis [25] classified the most used criteria with a focus on decision support methods applied to renewable and sustainable energy. They have shown that the investment cost and 52% of CO_2 emissions occupy the first place in all evaluation criteria. This was followed by job creation with 46%, due to its focus on social aspects.

The evaluation criteria can be classified into four main categories: technical, environmental, economic, and social [28]. A first set of criteria for this work was identified on the base of literature review and specifically taking into account the most highly frequent evaluation criteria [23,25], including those that should be affected by energy retrofitting measures (Table 1). Moreover, other existing literature, projects, tools, and standards have been reviewed and analysed, including energy planning [29,30], renewable energy problems [28,31–35], and building and building stock energy management [36–42]. The following three research and development (R&D) projects, SuPerBuildings [43], FASUDIR [44] and INSMART [45], have been considered to pre-select the evaluation criteria for this study. These projects consider many international and European initiatives, standardisation activities on their own, in addition to national building evaluation tools.

The goal of the pre-selection process is to reduce the criteria to obtain a practical but still significant number that is sufficient for conducting a sustainability assessment of urban built environment energy saving projects [46]. To decrease the number of potential criteria, it is necessary to pre-select the most suitable from the set built-up (Table 7 in appendices) [22].

2.1.3 Final Selection

The final list of the criteria was established based on a workshop involving stakeholders. In this workshop, the authors played the role of an analyst, who aided decision-makers without expressing any personal preferences [47]. The workshop aimed to assess the rank and feasibility of the different evaluation criteria that is calculated using the MC-SDSS software tool.

Stakeholder involvement: UEP is a very complex problem that requires a comprehensive vision of urban sustainable energy policies and a significant co-operation between national and local governments [23], involving multiple actors and different sectors [48]. In UEP, the identification of the stakeholders who can affect or can be affected by the recognition of objectives is pivotal [49]; [50]. As reported by Løken [47], stakeholders can be referred to "*everybody that has a just interest in the system*", "*those who have a right to impose requirements on a solution*", or "*who have demonstrated their need or willingness to be involved in seeking a solution.*" Moreover, stakeholders can be categorised into different actors such as political, bureaucratic, special interests, general interests, and experts with different roles including promoter, director, ally, mediator, and gatekeeper [49,51]. In particular, in the public decision problem, the stakeholders' involvement and their identification are significant since their key representatives can be invited to participate in brainstorming sessions [51]. Several innovative methods exist to involve multiple stakeholders and experts in the planning process that was developed and tested in practice, in recent decades. It is necessary to organise the collaborative events for a small group of stakeholders (e.g. focus groups, moderated round tables) or larger groups (e.g. future search conferences, world café) [52,53]. Indeed, in this initial part of the process, accurate and appropriate stakeholder grouping is required for a better perspective of how relationships and communication between them can affect the project outcome and its final application [51]. Furthermore, the stakeholder's involvement is an ongoing and iterative procedure in the entire UEP process and its decision-making. Therefore, their complete involvement from the early phase of planning is necessary. This helps in the collection of the available existing data, determination of the relevant sustainable objectives and the proposal of a common strategic vision [17].

As part of the present work, two workshops were organised, which involved real stakeholders from the early stage of the decision-making process. The significant stakeholders in this case study include the local authorities, local energy provider company, environmental groups, other non-profit organisations, and academic and private experts in the given context [47].

Setting up the workshop: The first half-day workshop was set up with the purpose of selecting and ranking the most important criteria to be further implemented in the MC-SDSS tool. Stakeholder selection was performed with the aim of inviting participants with different backgrounds who were involved in several disciplines. In this regard, a variety of perspectives on the selection, ranking, and evaluation criteria was considered. The invited stakeholders were eight and included all the following categories: architects, representatives of public administrations (i.e., energy and environment), experts in spatial decision support system (SDSS) and in visualisation tools, experts in system building engineering, building administrators and academics.

Describing the workshop: To define the importance of the criteria during this research project, it was decided that the "*Playing Cards*" method would be applied, which is a semi-structured participative procedure [54]. The "*Playing Cards*" method is suitable for supporting group discussions. It allows the stakeholders involved to think and express how they wish to hierarchise the different criteria in a specific context. One of the major advantages of this method is the ease of its application. This approach involves the association of a "*card*" with each criterion. Moreover, the stakeholders have a set of "*white cards*" available, the use of which depends on specific needs. The application of the procedure is very simple:

- The stakeholders are asked to organise the "*cards*" according to the importance of the criteria, providing a complete pre-organisation. If some criteria have the same importance, the stakeholders should build a subset of cards to hold them together;
- Given that the importance of two successive criteria in the ranking can be close, the stakeholders are asked to insert the "*white cards*" between two successive "*cards*" (the greater the difference between the mentioned weights of the criteria, the greater the number of white cards) providing a final ranking of the importance of the criteria;
- The final ranking of criteria is converted into weights according to Simos' algorithms [54]. The fact that the involved stakeholders have to handle the cards to rank them, allows for an intuitive understanding of the aim of this procedure [55]. In the present study, the method is applied directly in a focus group to inform the stakeholders and stimulate discussion. The detailed discussion on the playing card method and the process of evaluation criteria selection is illustrated in Lombardi et al. [22]. The final results associated with the playing cards method is shown in Table 2 [22].

Table 2: Final evaluation criteria derived from Playing Cards method, source [22].

Rank	Subset of Ex-Equo	Number of Cards	Positions	Non-normalised weights	Normalised weights	Total
1	Architectural Impact	1	1	1	1,316	1.32
2	White cards	3	(2, 3, 4)	-	-	-
3	Local job creation	1	5	5	6,579	6.58
4	White cards	1	(6)	-	-	-
5	Reliability	1	7	7	9,211	9.21
6	White cards	2	(8, 9)	-	-	-
7	Socio/economic feasibility + Local emissions	2	10, 11	10.5	13,816	27.63
8	White cards	1	(12)	-	-	-
9	Investment costs	1	13	13	17,105	17.10
10	Payback Period	1	14	14	18,421	18.42
11	Global emissions CO_2	1	15	15	19,737	19.73
SUM			76*			100

*This sum does not include the positions of the white cards (in brackets).

2.2 Criteria Evaluation

This section illustrates the assessment impact methodology of each selected evaluation criterion, with respect to the retrofitting measures developed in **Section 2.1.3**. The evaluation process constitutes the external basis of MC-SDSS, which is then directly integrated into the tool. The evaluation process provides quantitative and qualitative information based on a variety of algorithms that are capable of supporting the decisions of the stakeholders according to “what if” scenarios and provide numeric support for each retrofitting measurement.

2.2.1 Economic criteria evaluation

The economic criteria presented in this research consist of a group of algorithms that were developed for implementation of the MC-SDSS tool. The aim of these criteria was to estimate different costs for the energy retrofitting scenarios. This category of criteria estimates the following costs:

- Existing buildings: fuel costs, operation and maintenance costs;
- Refurbished buildings: fuel costs, operation, maintenance and intervention costs.

2.2.1.1 Investment Cost

The investment cost incurs all the costs related to the purchase of building material, connection to the supplier, technological installation, in addition to manpower and set up of the cost for each individual element of the renovation project (building envelope and energy systems) [31,56]. The investors consider the investment costs and the subsequent benefits [47]. Many studies consider investment costs as the most important criterion to evaluate energy saving interventions [29,30,33–35,38,57]. Indeed, Wang et al. [23] reported that this criterion is the most widespread economic criterion that is used to assess energy problems. To apply the investment costs method for an energy refurbishment project in buildings, the model evaluates different retrofit strategies including initial investment, operation and maintenance costs during the calculation period. The analysis period of the calculation (τ) was set equal to 30 years for residential buildings, by following Regulation n. 244/2012 precepts [58]. Generally, these methods are previously evaluated based on principles of economics, the net present value (NPV) criterion, and traditional discounting [59]. The following steps have been executed, which are shown in

Table 3:

- The initial investment cost (C_I), which refers to all costs associated with the delivery of the building or the building element to the customer, ready to use [58]. All retrofit measure prices were found by referring to the Italian Regional databases “*Pricelist of the Piedmont Region*” suggested by Becchio et al. [56]. Typically, from Italian literature, manpower and setup costs are assumed to be 30% of the investment costs [60];
- Annual costs (C_a), which refers to the sum of the periodic costs or replacement costs or running costs paid in a specific year [58]:

- Running costs (C_r) considers annual maintenance costs (C_m), operational costs (C_o) and energy costs (C_e).
  - C_m and C_o are calculated as percentages of the related initial investment cost according to the indicative data given in Annex A of EN15459 [61]. Normally, operation and maintenance costs are considered at 0% for envelope components and 2% for energy system components from [61].
  - (C_e): energy prices were assumed to be constant during the calculation period including energy taxes. Energy tariffs were determined as: (Natural Gas = 0.072 €/kWh+22% VAT = 0.093 €/kWh) and (District Heating for space heating = 0.076 €/kWh +22% VAT= 0.097 €/kWh).
- Replacement costs (V_n), were quantified according to the lifespan of the components installed in the buildings that need to be replaced. The lifespan of each component is determined on the basis of the values provided in Annex A of the European standard [61].

- It was necessary to specify that the calculation of the maintenance and replacement costs were performed by NPV. NPV refers to the difference between the present value of cash inflows and the present value of cash outflows [62]. The NPV of costs refers to the starting year of the calculation period and relies on the discount rate (R_d) in the calculation process. R_d was set to 3% in line with the study performed by Copiello et al. [63]. The NPV factor was used to adapt the future costs to the moment when the economic assessment is performed.

Table 3 summarises investment cost assessment with respect to the aforementioned procedure.

Table 3: Investment cost assessment for individual retrofitting measures in the MC-SDSS geodatabase.

Code	Lifespan (year)	Price of measure	Manpower costs	C_m	V_n	C_I *	$C_{f,\tau}(j)$ **	Unit
b_1	50	72.56	22	0.00	0.00	94	94	(€/m^2)
b_2	50	48.97	15	0.00	0.00	64	64	(€/m^2)
b_3	50	40.88	12	0.00	0.00	53	53	(€/m^2)
b_4	30	392.23	118	0.00	0.00	510	510	(€/m^2)
b_5	20	1878.82	564	957.47	1312.95	2442	4713	(€/piece)

* C_I (€/m2) is the initial investment cost at the year τ=0.

** $C_{f,\tau}(j)$ (€/m2/y) is the final value of component j at the end of the calculation period.

2.2.1.2 Pay Back Period (PBP)

Payback period (PBP), simple or discounted, is another popular criterion that represents the number of years required to compensate for the sum of the investment capital. This criterion gives immediate insight to investors in the event that there is a preference to shorten the payback period [30]. PBP is assessed by dividing the overall investment costs and the annual saving of the energy running costs (C_r). For the PBP calculation, the following steps have been executed [64]:

- The total investment costs (C_I) of the energy retrofitting measures is automatically calculated by MC-SDSS each time a specific scenario is defined. Based on the number of buildings to be retrofitted, the amount of C_I will be changed (e.g. C_I *(€/m2) * transparent retrofitted area (m^2) = total investment for that specific retrofit application €*).

- The yearly savings in C_r (€) was calculated by subtracting the energy running costs of the retrofitted building from the energy running costs of the original building.

(C_r) Yearly saving in energy running costs (€) =

Building C_r energy original-Building C_r energy retrofitted

- PBP is calculated based on a static reduction in the annual running costs C_r and the current costs to install a C_I measure.

$$PBP = CI/Cr$$

2.2.1.3 Socio-economic feasibility

Socio-economic feasibility is an important criterion because it evaluates the level of economic willingness and the capacity of the inhabitants to invest in retrofitting solutions [60]. This criterion was introduced by Mutani and Vicentini [65] and measures the ability of people to invest; even if the designed retrofitting packages are appropriate in terms of energy performance. They reported that the socio-economic feasibility is characterised by different variables as follows (Figure 1):

- (f_a): age factor is the percentage of the probable active population in the range of 25–69 year olds with respect to the total population. Naturally, population range has a higher interest in investing in energy related renovation.
- (f_{em}): employment factor is the percentage of the employed population and total active people in the range 15–74 years old. This factor can therefore express the initial economic ability of people to invest, as well as their ability to pay their bank-funded loans.
- (f_p): property factor is the percentage of buildings occupied by the owner's families and the total number of buildings (only residential). This factor has an influence because the owners have an increased interest to requalify their own buildings from an energy perspective compared to the tenants.
- (f_f): family factor is the percentage of 1–2 component families in the total number of families. This factor indicates the eventual occupancy presence schedule in dwelling stock.
- (f_{gm}): gender factor is the percentage of the male gender to the total population.
- (f_{ed}): education factor is the percentage of graduates (high school diploma or higher education level) with respect to the total population. The educated population may have a higher awareness of detrimental environmental impacts and energy technologies.
- (f_{pc}): period of construction is the percentage of buildings built before 1960 in the total number of buildings. f_{pc} represents the older buildings that need to be retrofitted in regard to energy usage.
- (f_o): buildings occupation factor is the ratio of an occupied building to a total ones. f_o represents the occupied buildings, which consequently, may consume more energy.

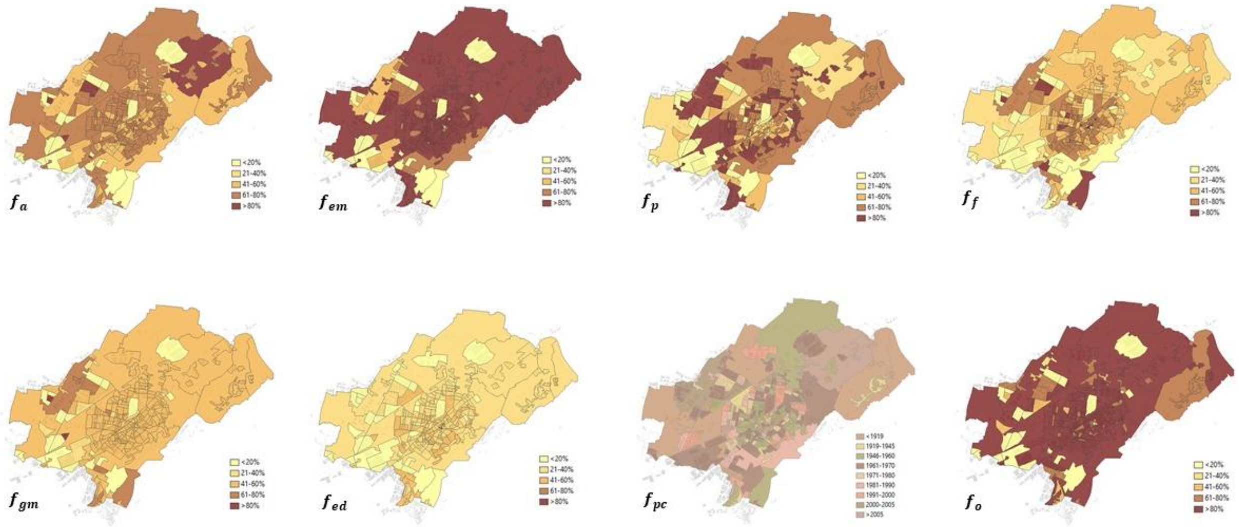

Figure 1. Mapping for Settimo Torinese by GIS.

Obviously, when the aforementioned factors are higher, the feasibility of renovation interventions is more probable [66]. This criterion will not be considered as a "*major*" criterion, due to the lack of disaggregated data, but as a visualisation criterion. Although the aforementioned criteria impact the decisions of DMs, they will not be involved in the calculation phases.

2.2.2 Environmental criteria evaluation

2.2.2.1 Global CO_2 emissions

As previously mentioned, this criterion was ranked first in the preference of stakeholders. It has been reported by several researchers [29,31–33,35,38]. The building's energy system CO_2 emission is undoubtedly a criterion that should be assessed for the sustainable development of cities. The assessment methodology for global emissions is based on the conversion coefficients [67]. The assessments will be directly performed internally in MC-SDSS.

2.2.2.2 Local NO_X emissions

NO_x produces toxic pollution that adversely affects the health of individuals. Moreover, air pollution can also harm the built environment, climate and vegetations [68]. This also implies that there is an indirect impact on the social health of communities [29]. The assessment methodology for local emissions is based on the conversion coefficients [67]. The local emission assessment will be directly performed internally in MC-SDSS.

2.2.2.3 Local PM_{10} emissions

PM_{10} emissions are caused by fuel burning and heavy industrial processes and are very harmful to human health. These emission cause lung diseases, heart attacks and arrhythmias, cancer, atherosclerosis, childhood respiratory disease and premature death [68]. During an initial workshop, stakeholders were specifically asked to consider a criterion related to the health of the local community. Therefore, this criterion has been associated with the geodatabase of the MC-SDSS tool and was calculated based on specific conversion coefficients [67].

2.2.3 Technical criteria evaluation

2.2.3.1 Reliability

Generally, in literature, the reliability of retrofitting measures can be assessed using both quantitative and qualitative evaluation methods [32,33]. The retrofit measures that are considered for this study are widely available and are, thus, mostly reliable. However, some of these measure performances depend on the context, while others are independent of context [69]. For this investigation, the reliability criterion is determined according to Dall'O' et al. [69] in qualitative terms: high, medium, low, and none. Only the b_4 and b_5 measures present lower performances and the b_1, b_2, and b_3 situations have almost the same level (Table 4).

Table 4: Qualitative evaluation of the reduced performance.

Retrofitting Measures	b_1	b_2	b_3	b_4	b_5
user interaction	none	none	none	high	low
risk of breaking	none	none	none	none	low
dependence on weather effects	none	none	none	none	none
score	4	4	4	3	3

2.2.4 Social criteria evaluation

2.2.4.1 Local job creation

For stakeholders, an increase in local job creation was fundamental to ensure that the community was healthy from a socio-economic perspective. Since the focus of this study is limited to the local level, the manpower needed for each retrofit solution is only considered based on the installation and maintenance phases. Indeed, the job creation criteria do not meet the required manpower to produce building materials or machinery [69]. Again, this criterion can be qualitative or quantitative. As shown in Table 5, a quantitative approach is performed for each measure based on man-day assessment according to Dall'O' et al. [69] and a national reference [70].

Table 5: Manpower in the installation and maintenance of the measures developed for 100% of the potential in thirty years.

Retrofitting Measures	b_1	b2	b_3	b_4	b_5
N. of interventions	1.0	1.0	1.0	1.0	1.0
N. installations in thirty years for installation	1.0	1.0	1.0	1.0	1.0
N. of workman per team	7.0	7.0	7.0	3.0	2.0
Days for installation	3.0	3.0	3.0	3.0	3.0
MAX man-days for installation	21.0	21.0	21.0	9.0	6.0
man-day euro/m2	594.3	401.1	334.8	1376.7	4396.4
N. of interventions	1.0	1.0	1.0	1.0	1.0
N. maintenance in thirty years	0.0	0.0	0.0	0.0	1.5
N. of workmen for maintenance	5.0	5.0	5.0	2.0	2.0
Days for maintenance	4.0	4.0	2.0	1.5	3.0
MAX man-days for maintenance	20.0	20.0	10.0	3.0	6.0

man-day euro/m2	0.0	0.0	0.0	0.0	87.9
Tot.	41.0	41.0	31.0	12.0	12.0

2.2.4.2 Architectural impact

This criterion evaluates the visual outcome that may be created by the application of some retrofitting measurements for a city, which is an important social aspect [31]. When retrofit measures lead to aesthetic improvement of the city, this criterion has a higher value. Five scores of impact are presented in Table 6 according to the study conducted by Dall'O' et al. [69], with reference to specific measures. This criterion adopts an ordinal scale to rank the strategies, from the best to the worst. In all cases, the considered retrofitting measures achieve positive (b_1 and b_4) or neutral (b_2, b_3, b_5) scores as they improve the aesthetic outcome of the city.

Table 6: Architectural impact criterion.

Positive	great positive impact	b_1	1
	positive impact	b_4	2
Neutral	no impact	b_2, b_3, b_5	3
Negative	little negative impact	-	4
	negative impact	-	5

3 MODELLING APPROACH

The modelling approach consists of two main integrated tools: interactive impact assessment and suitability analysis of CommunityViz 360 that are used to build a new MC-SDSS. These two integrated tools are modelled and adapted using different functions, such as Advanced Formula Editors, to achieve the target of this investigation. Advanced Formula Editors helps in creating formula providing access to additional predefined functions. The modelling approach is depicted hereafter.

3.1 CommunityViz

CommunityViz is an ArcGIS-based extension decision support system (http://www.communityviz.com), that was created for urban planning processes. This tool is able to integrate different types of data, such as scripts, numbers, 2D maps, 3D visualisation, and rasters in real time and multidimensional environments [71]. CommunityViz consists of two main components: (*i*) Scenario 360 for mapping and analysis, and (*ii*) Scenario 3D for visualisation. CommunityViz Scenario 360 adds interactive analysis and decision-making tools to the ArcGIS platform. As an interactive tool, it facilitates an improved understanding of complex problems such as UEP for the stakeholders [23]. Stakeholders can define different decision scenarios and visualise the on-the-fly environmental, economic, technical, and social effect of changes [71]. Many presentation features are available that allow for the exchange of information with users including maps, alerts and charts. From this perspective, stakeholders can ask "*what if*" questions and visualise "*if then*" scenarios in real-time, and discuss them very effectively and quickly [72].

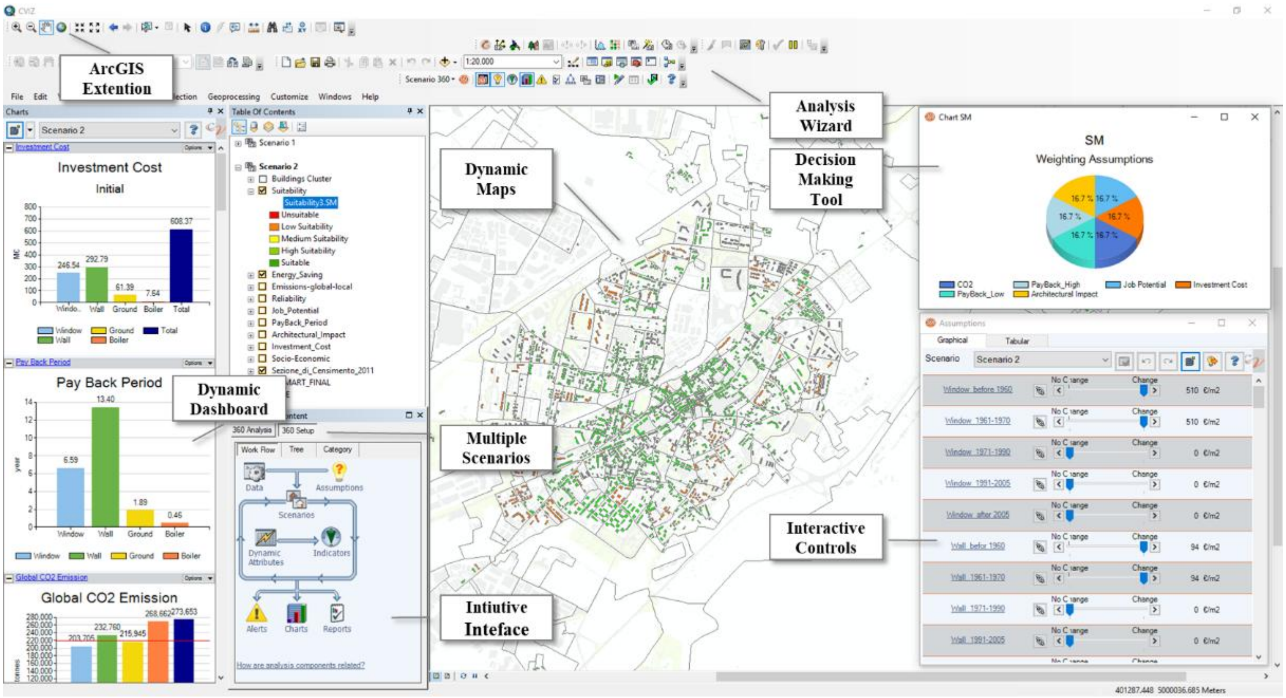

Figure 2: CommunityViz Interface; the case study of Settimo Torinese, source [73].

The selection of the CommunityViz Scenario 360 is due to the following:

- Helping to analyse and understand the potential alternatives and their impacts through visual investigation and scenario analysis;
- Creation of a real-time experiment with different scenarios by changing assumptions quickly and observing the influences of the changes;
- Engaging stakeholders in participative decision-making processes through visualisation and interactive media [74].

Figure 2 illustrates the interface for Scenario 360 modelled for the case study of Settimo Torinese.

3.2 Architecture model design of a new MC-SDSS for energy retrofitting of building stocks using CommuntiyVIZ

The aim of this section is to illustrate the process by which CommunityViz Scenario 360 is modelled, coded, and adapted for energy retrofitting issues of building stock. The design and implementation of a modelling approach is an iterative process. Two main integrated tools were modelled and adapted using different functions, such as Advanced Formula Editors [75].

The target of interactive impact assessment is to create different dynamic energy saving scenarios considering the five selected retrofitting measurements (i.e., b_1, b_2, b_3, b_4, b_5), as illustrated in Table 1. Moreover, the building stock is divided into 5 macro-clusters considering the building types and age classes [76].

The aim of the suitability analysis is to understand the ability of a system to meet the needs of stakeholders. Using this tool, stakeholders can better understand whether their defined scenario would enter into a suitable range or not. They can also associate different weights to each criterion to observe the changes in suitability.

According to retrofitting assumptions, a series of relative algorithms presented in **Section 2.2** that are capable of assessing indicators over a short time period, have been developed. The developed algorithms assess the following indicators at the district level both for each retrofit measure and for the total value, considering all the measures: total energy consumption (GWh), energy saving reduction (%), initial investment costs (M€), investment cost (€/m^2), PBP (year), CO_2 emissions (tonnes), CO_2 emissions (tonnes/GWh), local NO_X emissions (tonnes), local PM_{10} emissions (kg), job potential (man-day), architectural impact (rank), and reliability of the retrofitting measure (rank).

3.2.1 Interactive impact assessment

Figure 3 illustrates the architecture design flowchart of the interactive impact assessment function for the new MC-SDSS. The aim of this step is to create different energy saving scenarios and visualise the relative impact assessment in real-time.

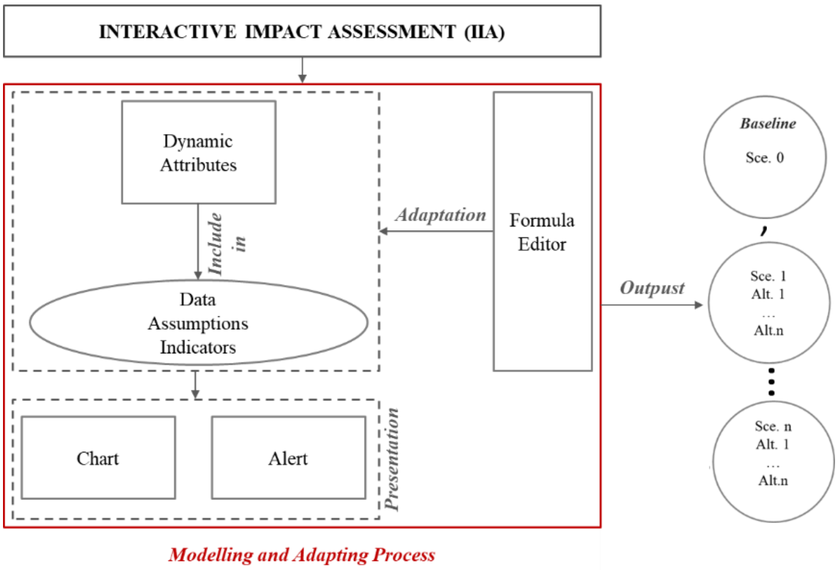

Figure 3: Architecture of MC-SDSS design: modelling and adapting process.

The modelling process starts with the creation of Formula-based GIS dynamic attributes. Dynamic attributes are automatically updated when changes are made in the analysis. In fact, Scenario 360 improves the quantitative capabilities of ArcGIS by formula-based spreadsheet-like calculations that are performed on geospatial data [77]. Formula-based GIS data attributes create dynamic analysis providing rapid changes of geographic and numeric inputs as well as an automated recalculation of maps and quantitative outputs [78]. It is possible to very easily write Scenario 360 formulas directly using the Formula Editor wizard due to its similarity to Excel formulas. Indeed, formula editor does not only assist in the structuring, editing, and display of the formulas, but also continuously syncs all components of the model [75]. When the new "*Dynamic Attribute*" or "*Indicator*" needs to be created, the Formula Editor wizard constructs the most common types of analysis formulas [79]. These values are dynamically controlled and updated. A formula is linked to each dynamic attribute, which specifies how the attribute should be calculated. A relative value is calculated for each feature within the data layer. As an example, a snapshot of the Formula Editor showing the formula that calculates the total amount of investment cost for wall insulation retrofitting is shown in Figure 4.

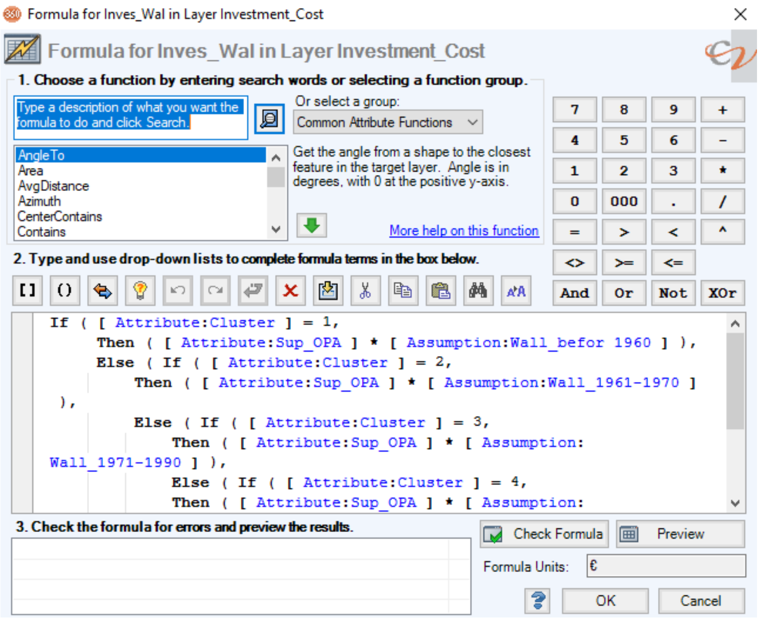

Figure 4: A snapshot of Scenario 360 Formula Editor Interface, an example of an investment cost wall insulation formula.

The dynamic attributes change based upon:

- Data: dynamic data layers create new or add existing layers to Scenario 360 analysis geo-database. An important feature of Scenario 360 is that it provides dynamic data on the features of a map that can be quantified using formulas. Therefore, when one aspect changes, the software recalculates the entire analysis. Dynamic data is used for geo-designing, which implies experimenting with alternatives and visualising the impacts of changes in real-time.
- Assumption: slider bars or tables let assumptions change 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 [75]. Figure 5 shows a user-friendly interface for modifying assumptions that facilitates sensitivity testing [75]. The stakeholders can visualise the consequences of their changes in real-time.
- 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.

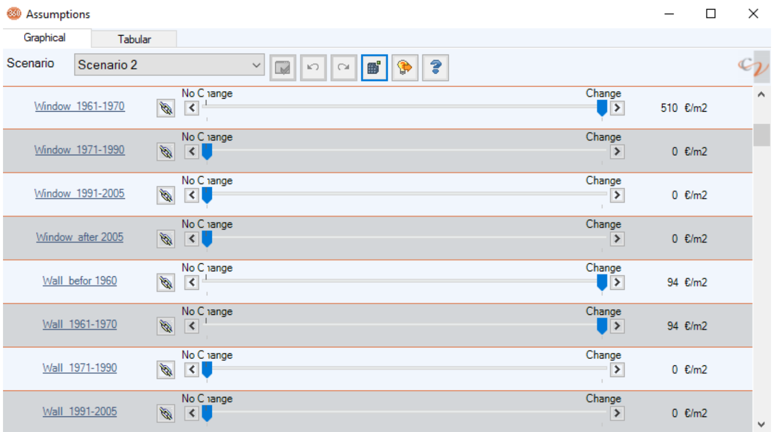

Figure 5: Representative CommunityViz assumption sliders for retrofitting actions that are applicable to the Settimo Torinese building cluster.

Finally, it is possible to visualise all the changes in dynamic charts and alerts. Alerts appear when the outcomes do not meet the specific target value based on related normative or on the requests of stakeholders. Once the modelling process is finished (e.g. formulas are coded and linked, dynamic attributes are created etc.), the scenario creation and analysis phase is initiated.

Scenarios: As previously mentioned, the aim of the project was not to create specific scenarios. The notable innovation is the ability of the tool to facilitate working on the future scenario definition, together with stakeholders, using interactive impact assessment and suitability analyses. This section describes some examples of defined scenarios and the methods used to model them.

The first step in establishing future scenarios was to create a "baseline" scenario 0 [80] as shown in Figure 6. Setting up a baseline analysis is a significant aspect in determining the future opportunities that exist and the location of the hot-spots. Obviously, this scenario represents the baseline conditions in which no new retrofitting, modification, or investment are planned. As shown in Figure 6, the results are visible on maps and charts. In the baseline scenario, some indicators such as CO_2 emissions (tonnes) and energy consumption (GWh) are used to indicate the current value of the city. This means that some values do not start from zero given that they already exist in the current state. This description of current conditions can commonly be compared to different future scenarios (e.g., from Scenario 1 to scenario n). An additional so-called indicator "*Active Action Control*" shown in Figure 7, is created to control the active assumptions, especially when there are several assumptions to be considered. Actions in Figure 7, is activated when the retrofitting solutions are applied to each building clusters. Using this indicator, the analyst and stakeholders can easily control the assumptions considered for each scenario.

Figure 6: "*baseline*" scenario 0 without any retrofitting action.

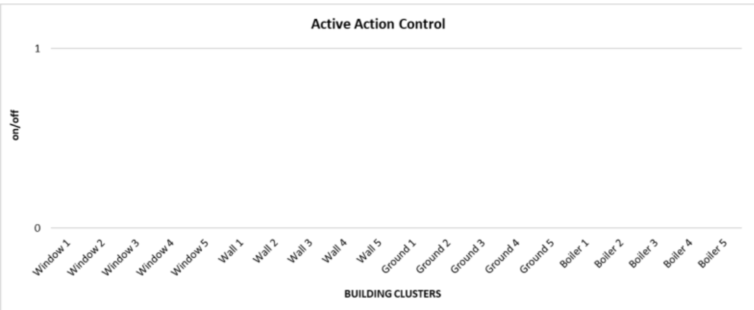

Figure 7: Active Action Control for the assumptions of "baseline" scenario 0; there are no retrofitting actions.

Future Scenarios: In the next step, it is possible to create different scenarios by modifying the assumptions and data (Figure 8). These scenarios can be evaluated by indicators, alerts, and selected thresholds. In fact, it is possible to establish the thresholds as a target for created scenarios; for example, achieving a minimum of 20% energy consumption or CO_2 emission reduction. An alert appears on the chart indicating that a pre-set threshold has not been met. In this case, there is a 20% energy consumption reduction. If the scenario meets the requested threshold, it could be acceptable. In this case, certain scenarios can be discarded immediately when they do not reach the 20% energy saving target.

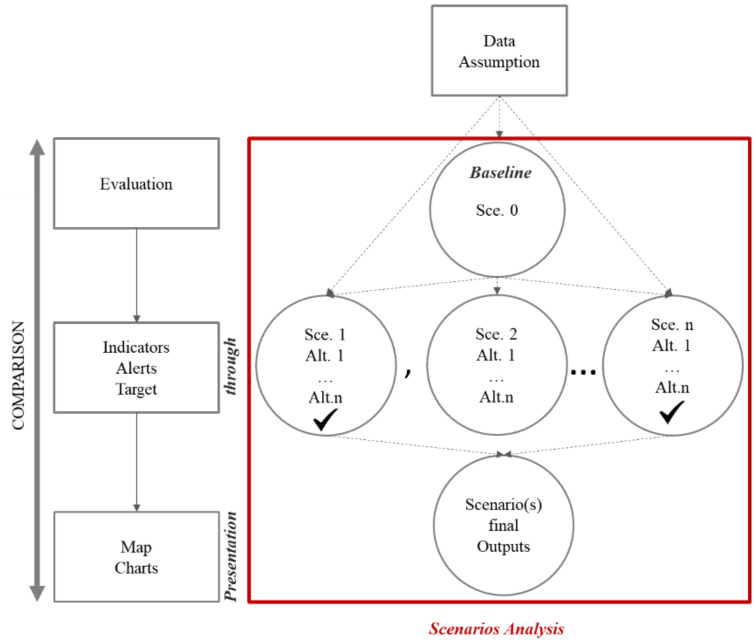

Figure 8: Schematic flowchart of MC-SDSS design; scenario analysis.

The results of different scenarios can be displayed by maps and charts in real-time. As an example, Figure 9 and Figure 10 demonstrate the changes from "*baseline*" scenario 0 to scenario 1, named "*expert-oriented*". The "*expert-oriented*" scenario is defined by experts (forming an internal focus group) with the aim of creating a scenario characterised by moderate energy performance. This scenario is performed as an example to non-expert stakeholders. In scenario 1, the selected technologies were chosen according to the experts' perspective. They suggested the replacement of the glazing windows of older buildings (clusters 1 and 2). Likewise, they improved the floor and roof thermal insulation of clusters 1 and 2 (building aged between 1961-1970). Finally, the experts decided to substitute the boilers for the buildings built between 1971-1990 (cluster 3). This decision was made because the boilers of the older buildings have already been replaced after their 20-year lifespan.

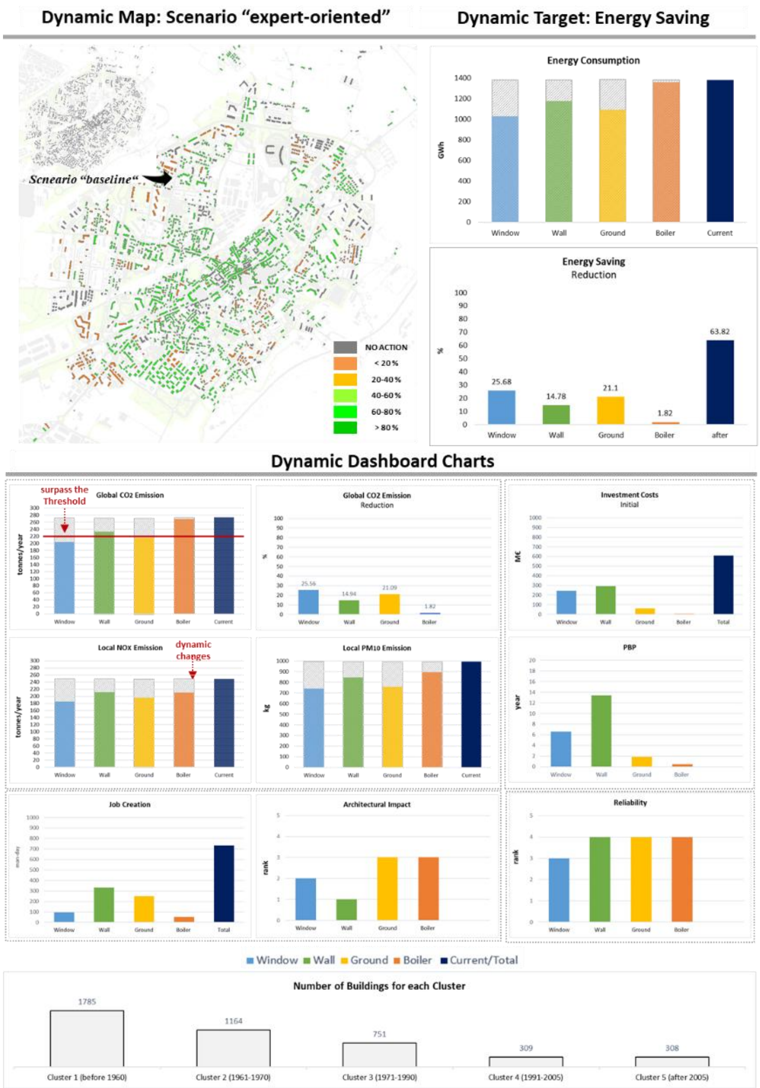

Figure 9: “*expert-oriented”* scenario 1 in CommiuntyViz; maps and charts.

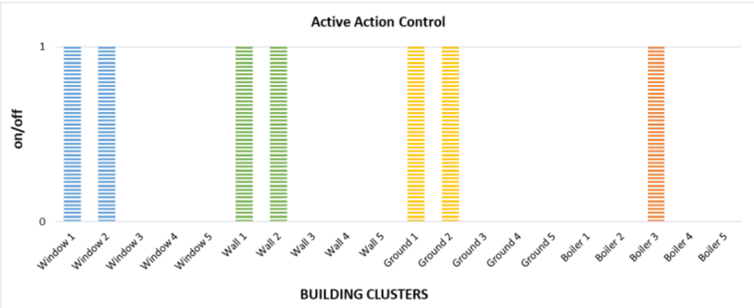

Figure 10: Active Action Control for assumptions for “expert-oriented” scenario 1.

Comparing scenarios: After creating different scenarios, it is possible to compare them with each other and also with the “*baseline*” scenario 0 using maps and charts. As an example, the comparison between scenario 0 “*baseline* “and scenario 1 “*expert-oriented*” is shown in Figure 11. It is possible to compare many scenarios at the same time. When comparing different scenarios, side-by-side maps, charts, and results table are available.

Figure 11: The comparison between "*baseline*" scenario 0 and "*expert-oriented*" scenario 1 through analysing maps and charts.

3.2.2 Suitability Analysis

The output of scenarios become input for the suitability analysis (Figure 16 appendices). After stakeholders have selected their eventual preferred scenarios, they then need to know the extent of their suitability. Suitability modelling identifies a continuum of best or worst retrofitting scenarios. The modelling and adapting process is similar to the interactive impact assessment procedure; however, weights are added that play a key role in the suitability analysis. According to Lieske and Hamerlinck [77], "*CommunityViz suitability model meets the requirements for planning methods, including increasing insight to a decision situation, the ability to quickly handle changing inputs, transparency, and making values incorporated in a decision process explicit*".

Indeed, CommunityViz is a powerful tool for modelling and spatial MCA, which was built on a weighted linear combination (WLC) model [77]. WLC is one of the best-known analytical methods for GIS-MCA [81]. It links the weight values to each criterion and automatically updates the model when there are changes in either weight or geographic data inputs. Firstly, the evaluation criteria are normalised to a specific numeric in the range 1 to 100. Then the numeric range is combined with a weighted average to create a composite score for each decision scenario based on WLC [77]. Of course, the weights represent the importance of each evaluation criterion. For each decision scenario, a score is calculated for each criterion by multiplying the weight by the normalised value of that criterion. Scores are summed for all evaluation criteria to provide an overall suitability score [77]. The scores are calculated for all the scenarios and the ones with the highest values may be chosen. The results are visually represented in maps where the scores are displayed with a gradient colour ramp as: Unsuitable; Low suitability; Medium suitability; Suitable and High suitability (Figure 12). Generally, the suitability model creates two kinds of evaluation criteria scores: raw and standardised. A raw evaluation criterion score is calculated using a formula-based dynamic attribute [77].

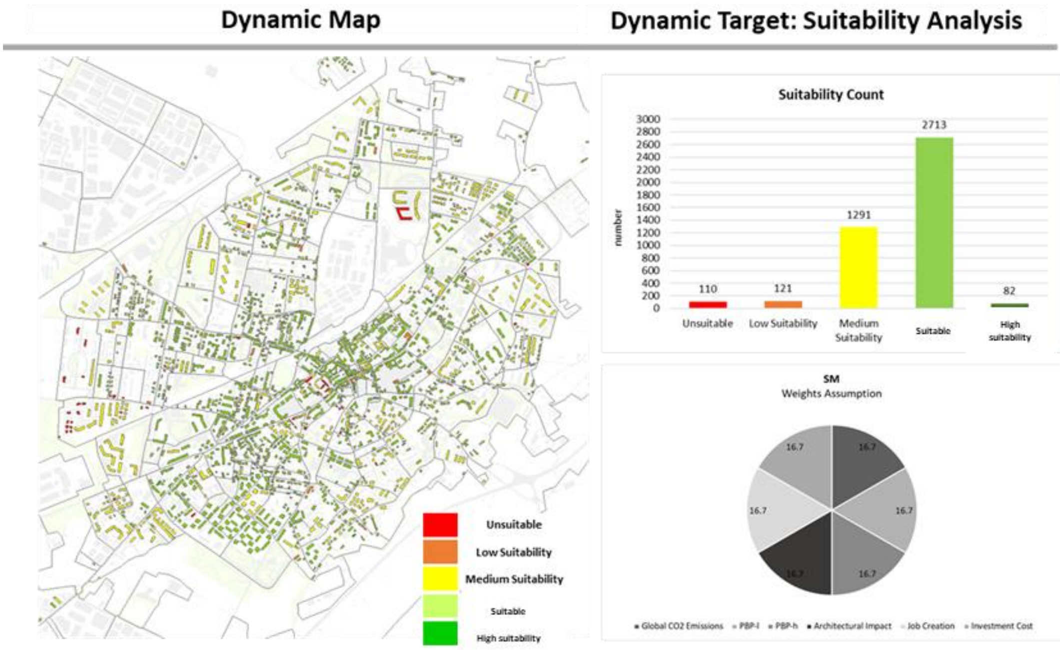

Figure 12: Suitability modelling, “expert-oriented” scenario 1 same weights.

Stakeholders can easily change the weights of the evaluation criteria using the graphical display of value (Figure 17 in appendices). Consequently, MC-DSS recalculates the suitability analysis by considering the new weights. The new results are displayed again in maps and charts (Figure 18 in appendices). A zero-weight is inserted when stakeholders do not want to provisionally or permanently consider some criteria in the analysis. This interactive approach aids in the discussion of the importance of each criterion. Moreover, it provides a supportive method for dealing with conflicting preferences and supports sensitivity analysis. It permits SDSS-based suitability analysis to be used as a thinking tool in retrofitting scenario selection [77]. After the scenarios are selected, they are analysed and also compared as was explained in the previous section. Again, the comparison between different suitability scenarios is possible.

4 RESULTS AND DISCUSSION

In Section 3.2, the basis of MC-SDSS is modelled and adapted for the case study of Settimo Torinese. Afterwards, the second workshop was organised to test and assess the usability of the developed tool for urban energy planning.

4.1 Testing and validation of MC-SDSS

In this second workshop, scenario 1 was presented to the participants as an example to provide them with information and guideline on how to define scenarios. During the workshop, two focus groups were formed to test the tool. Indeed, the focus groups provide a more natural environment as opposed to an individual interview because the participants influence and are influenced by each other [82]. As the MC-SDSS tool is still a demo version, receiving opinions from stakeholder and DMs was the best option to improve the tool [1].

4.2 Results of the validation process of MC-SDSS: through the 2nd workshop design

Setting up the workshop: The second half-day workshop was set up with the purpose of assessing the usability of the developed MC-SDSS tool. The stakeholders involved in this workshop were the same as those in the first workshop with the addition of a district heating (DH) provider and the environmental representative of the Municipality of Turin (9 participants in total). Initially, a brief introduction to the progress of the research project and the structure of the workshop organisation was presented to the participants. Moreover, the MC-SDSS tool, its functionality and practical applications have been presented.

Describing the workshop: The workshop was structured into three main steps to facilitate the understanding and working with the interactive energy-related plug-in (

Figure 19). Moreover, these three steps reduce the learning curve for the workshop process for the participants. At the end of each step, evaluations took place (i.e. questionnaires). The stakeholders were asked to fill out the questionnaires regarding the usability of the tool for each step. All participants were asked 17 questions about the usability of the tool. A limited number of invited stakeholders was targeted due to the complexity and specificity of the workshop's topic. Therefore, high levels of concentration and expertise were required to fulfil the objective of the workshop, which was to improve the tool and its usability.

Step 1: this step included a two-hour interactive focus group to define different energy saving scenarios utilising the interactive impact assessment tool of MC-SDSS. In this step, the facilitator (author) worked together with the stakeholders. As previously indicated, initially, the facilitator showed the already created scenario, so-called "*expert-oriented*" scenario 1 to the stakeholders to give them a better understanding on the use of the tool. "*expert-oriented*" scenario 1 represents moderate investments in building renovations that leads to moderate emission reduction. The choice of strategy depends on the willingness to invest with respect to achieving emissions target [83]. Thereafter, different scenarios were defined by directly modifying and experimenting with the sliders (assumptions) by the stakeholders. The stakeholders changed the assumptions several times and they were notably interested in the rapid changes in the results based on their decisions. When this step was completed, the participants were asked to fill out a questionnaire and given approximately 30 minutes to evaluate its usability. The major activities performed in this step are as follows:

- Demonstrating how to use the tool for defining different scenarios;
- Experimenting with the energy refurbishment assumption to achieve different energy saving scenarios in real-time;
- Questionnaire compiling.

The double-display facilitated the negotiation task, giving the participants a better understanding and perspective of the scenarios related to their proposed changes [72]. Additionally, a better understanding increased the participants' interaction. Indeed, the workshop provided an opportunity for more discussions on each participant's own practices, relative to their daily work.

One of the scenario examples defined by stakeholders was "*stakeholder-oriented*" scenario 2 (

Figure 20 in appendices). Finally, they could compare different scenarios. In this specific scenario, they replaced the glazing of most older buildings (clusters 2, 3 and 4) and isolated the walls and floors of clusters 2 (building age 1961–1970) and 3 (building age 1971–1990); while, they preferred not to renovate the energy system (Figure 21 in appendices). This decision was made to examine the impact of the refurbishment of the envelope system, which leads to a significant reduction in energy consumption. In this workshop, the different scenarios were defined not to find the "*best*" performance scenarios, but to test the usability of the tool. Therefore, just one of the defined scenarios among the others (from "*expert-oriented*" scenario 1 to "*stakeholders-oriented*") scenario 2 is hereby recalled to illustrate the potentiality of the tool as well as its functionality.

At the end of step 1, each individual participant completed a questionnaire, which had two primary objectives:

- To understand how the stakeholders experienced the process of energy saving scenario creation.
- To collect their suggestions to improve the tool.

Additional goals included the collection of opinions on the utility of the assumptions, indicators, and attributes. They also sought to evaluate the clarity of the charts and maps and the potential barriers to planning practice [1]. The aim was to address any weaknesses to improve the tool for future experiences. The ultimate goal was to apply the stakeholders' requests in the future development of a new MC-SDSS tool for planning practices. The questionnaire of step 1 was divided into three main macro-sections:

- Questions regarding the considered "*Retrofitting Measure*";
- Questions regarding created "*Indicators*":
- Questions regarding the emerged "*Map of Results*".

The question types of each macro-section are shown in appendices (Table 8, Table **9** and Table **10**):

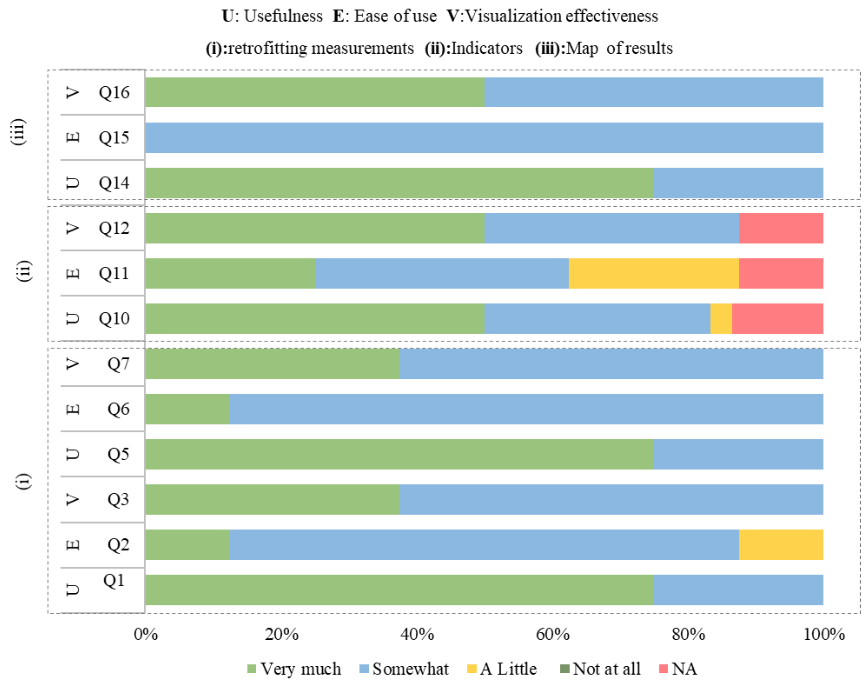

Figure 13: Summary of the answers received in step 1.

The questions regarding the retrofitting measure simulations and their usability were designed in the first nine questions (Figure 13). Generally, the participants expressed very positive views regarding the usefulness of the tool (U: Q1, Q5: 75%). Moreover, the answers to 2 and 6 (E) indicate that the MC-SDSS tool was sufficiently easy to use. However, approximately 13% of respondents reported that the simulations were not easily understood. They encountered difficulties in understanding how the simulations were previously calculated. 37% stated that the results were visualized in a very effective way and 63% in a sufficiently effective way (V: Q3, Q7). Regarding the indicators, 58% of the participants noted that they were very useful (U: Q10), while just 4% indicated that the indicators had little use. Q10 was also separately analysed (Figure 22 in appendices). An interesting outcome from this figure is that the participants were sufficiently satisfied with the created indicators. This is due to their effective participation in the development of the MC-SDSS tool from an early stage. Indeed, in the first workshop, the same stakeholders were asked to define their preferred criteria and indicators. However, it is evident that the stakeholders identified two qualitative indicators, in particular, architectural impact and reliability, that were not very useful to them, while most of the quantitative indicators seemed to be very useful. One participant did not provide an answer to the indicator question, stating that the allotted time was not enough to evaluate all the indicators. Q14 to Q16 were about the maps of results and their presentation. The tools were useful and easy to understand by the stakeholders. Regarding the presentation of maps, a stakeholder who was an expert in visualisation stressed the focus on the colour grade of the maps.

By listening to the recording during the discussion, some important points emerged. Several respondents expressed that they needed more options for retrofitting measurements (i.e., photovoltaic panel, district heating, etc.). In particular, they determined that it was necessary to implement more energy system retrofitting. They also insisted on enlarging the number of clusters to improve the overall flexibility for applying retrofitting actions. They intended to regroup the buildings into more than thirty clusters instead of five, considering all their ages and typologies. Currently, five clusters of buildings were identified.

They also suggested the consideration of the renovation ratio of the buildings. However, the data regarding the renovation status is not yet available for addition to the tool. Moreover, the stakeholders strongly recommended the addition of back-costing objectives. This required fixing an objective for energy saving (e.g., 20% for all scenarios) and defining the different scenarios that can always achieve that target. Currently, "what-if" scenarios could be defined with different energy saving targets, however, the different alerts and thresholds were set to give the indications. Another interesting discussion was related to installing the sensors to obtain real-time data instead of historical information. However, this requires a huge effort in terms of costs and time.

Step 2: In step 2, the stakeholders could visualise the suitability maps of the scenarios that were created in step 1. Likewise, in this step, the side-by-side collaboration of the facilitator and stakeholders were requested. After step 2, another brief questionnaire regarding the usability of the tool was provided to the participants. Again, major activities were performed in this step as follows:

- Demonstrating how to use the suitability maps;
- Experimenting with the changes in the weights and observation of their real-time impacts;
- Questionnaire compiling.

In this step, the participants were asked to change the weights using sliders. Consequently, the participants made a comparison between different suitability maps based on different distributed weights. Again, at the end of step 2, each stakeholder was asked to fill out a questionnaire, which had two primary objectives:

- To understand how the stakeholders experienced the process of suitability analysis.
- To collect their suggestions to improve suitability modelling in MC-SDSS.

Additional objectives included the collection of opinions on the clarity of the charts and maps of suitability [1]. As previously indicated, the aim was to improve the tool. The questionnaire associated with step 2 had only one macro-section: (*iii*) Information regarding the emerged Maps of Results.

Regarding the suitability maps, the participants were asked four questions (Figure 23 in appendices). Most of the respondents stated that the suitability maps were very useful. This is because they needed to visualise an aggregated evaluation of their decisions. Moreover, they wanted to examine the impact of changes made to weighing on their decisions. For approximately 50% of the stakeholders, the complexity level of the generated suitability maps was perceived as simple; while 50% perceived them to be very complex. Approximately 85% of the respondents stated that the emerged results of suitability were presented and visualised in an effective manner. Specifically, during the discussion, the participants stated that the suitability map was significantly useful. This tool aided the DMs to analyse their decisions by visualising a unique map.

Step 3: Finally, the workshop survey was designed in step 3 to analyse the general evaluation of the workshop organisation [1]. All participants were asked 13 questions about the session evaluation survey. Their answers are evaluated in Figure 14. The participants shared a very positive general opinion about the process. Specifically, most of the participants (88%) stated that the session resulted in useful results (Q1). A total of 50% of the stakeholders felt that the results of the session were based on correct assumptions, and consequently, they were confident that the group solution they reached was correct (22). Furthermore, 88% of the participants expressed satisfaction with the session in their response to Q3. Q4 explored the usefulness of the workshop in increasing the information regarding UEP. As many as 63% of the respondents stated that the session provided better information. Based on the answers to Question 5, 63% of stakeholders stated that the session was extremely useful in terms of understanding the opinions of the other stakeholders, while 25% thought it was useful enough, and 1 participant did not provide an answer. Seventy-five percent of the respondents also stated that they would probably use the tool in their daily planning practice (Q6). Questions 7 to 9 explored how the participants achieved a shared vision problem (Q7; 50%) and the goals (Q8: 50%) and solutions (Q9; 25%). 75% had a strong sense of being part of a group during the session (Q10).

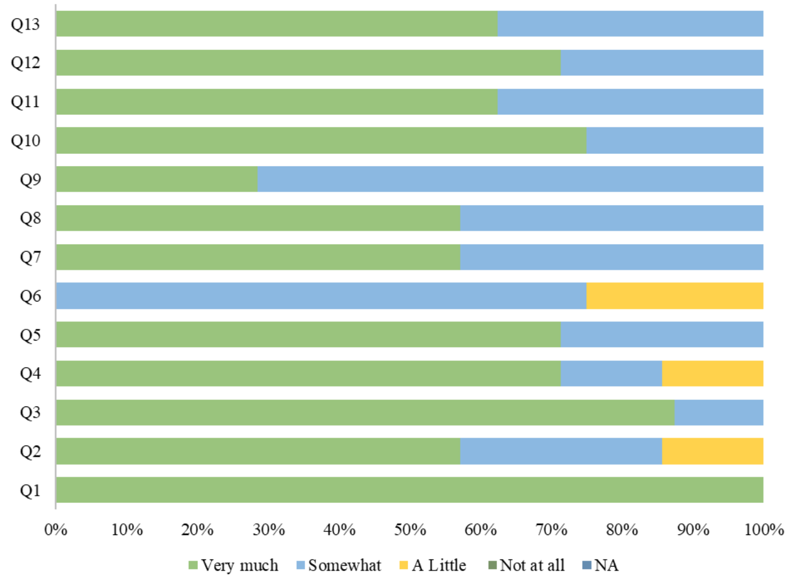

Figure 14: Perceived usability of the tools in step 3.

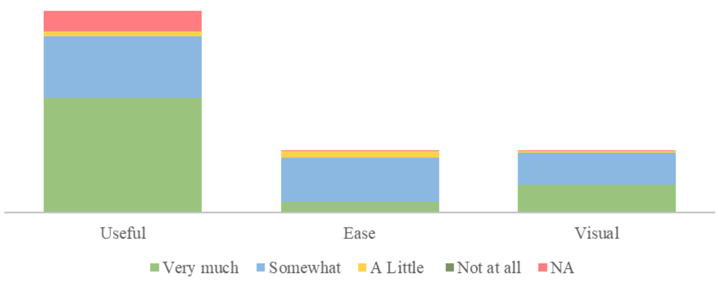

Figure 15: The total received answers based on usefulness, ease of understanding and visual effectiveness of the tool.

In conclusion, Figure 15 shows a summary of the total answers received regarding the usability of the developed MC-SDSS tool based on the three criteria of usefulness, ease of use, and visual effectiveness. Most participants found that the tool was very useful for making better decisions with respect to the sustainable development of their city. Most stakeholders determined that the tool was easy enough to use and it was effective for visualisation. However, improvements need to be addressed based on the stakeholders.

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

This section summarises the overall results and conclusions. Additionally, suggestions are made for further studies. The principal goal of this work was to develop a new MC-SDSS to support participative processes for defining effective scenarios to improve the energy performance of buildings on an urban scale. This study creates a link between energy and the economic, societal, technical, and environmental performances of retrofitting interventions. The research boundaries were delineated by focusing on the thermal energy consumption of existing residential building stock because they characterise most European cities. Available data on these buildings were first collected and geo-referenced from various sources. Finally, an interactive MC-SDSS was created to support the decision makers (DMs) in defining energy saving scenarios in real time. This work provides significant innovative progress in the research field in that an interactive plug-in for UEP in a GIS environment (MC-SDSS) was developed.

The main advantages of this MC-SDSS in the field of UEP can be summarised as follows:

- To facilitate participative processes;
- To facilitate visualisation opportunities for the decision process in specific areas;
- To consider multiple criteria (e.g., economic, environmental, technical, and, in particular, social aspects);
- To manage and store a considerable amount of geo-referenced data;
- To illustrate results requested by users in different spatial forms (e.g., maps, graphs);
- To illustrate the distribution of the geometrical characterisation and energy consumption patterns of buildings.

Given the goal and the boundaries of the research, a research question was formulated and addressed within the research path. In this concluding section, a synthetic answer is proposed by the author by summing up the key findings presented throughout this work.

Research question: “How useful are interactive MC-SDSS tools in supporting the stakeholders in UEP decisions for the built environment?” and “How can their usability be improved?”

A new MC-SDSS has been developed to support stakeholders with different backgrounds and preferences. The tool is an interactive plug-in for use in an ArcGIS environment. MC-SDSS can assist participants in a user-friendly way to define energy refurbishment scenarios. Furthermore, the tool provides an opportunity to generate suitability maps with which the stakeholders can analyse the suitability level of their decisions. Participants were able to rapidly experiment with different energy renovation scenarios and to change the assumption. This created an effective interaction between the stakeholders. They could visualise very complex problems related to energy saving scenarios using different dynamic colourful maps, charts, and indicators. Two workshops were organised to fulfil the objectives of the research.

- The first workshop involved real stakeholders who identified the related evaluation criteria and their importance (Section 2.1.3).
- The second workshop involved mostly the same stakeholders who tested the usability of the MC-SDSS tool based on their considerations during the first workshop, and primarily to improve the tool (Section 4).

Furthermore, the answers collected from the distributed questionnaires during the second workshop were analysed by considering three criteria: usefulness, ease of use, and visual effectiveness. Most participants expressed that the tool was very useful for making better decisions, easy enough to use, and effective at the visualising processes. Apart from comments on the tool usability, three main suggestions to improve the tool were as follows:

- Improvement of the data entry quality to increase the accuracy of scenario analyses;
- Installation of smart meters to access real-time data;
- Enlargement of retrofitting solutions (e.g., adding photovoltaics and DH network options).

Challenges: This study proposes the development of a new MC-SDSS that can define dynamic retrofitting scenarios together with stakeholders. This process has several barriers, including:

- The need for the tool to be open source.
- Limitation of the number of retrofitting solutions, building clusters, and stakeholders in the investigation.
- The time-consuming nature of a workshop that involves real stakeholders.
- The inclusion of conflicting points of view and the aggregation of the preferences of the stakeholders in participative decision-making.

Future developments: The current MC-SDSS provides a basic framework for developing scenarios in UEP. The refurbishment solution, as well as the building clusters, will need to be extended. Furthermore, more historical data will be added to the geospatial database including other new databases on natural gas consumption measure (for a larger part of the city) and building stock characterisation (for each building). Additionally, smart meters can be installed in the future to directly transfer real-time data to the MC-SDSS tool. Interestingly, the MC-SDSS developed as part of this study could be a basis for numerous spatial analyses of other areas such as transportation, territorial, environmental, real estate and landscaping. It is possible to adapt the tool to its functions; however, technical expertise and relative data are needed for modelling and adaption. Another noteworthy area of research would be to further investigate the details of understanding the topic of social evaluation criteria related to energy retrofitting projects. To fulfil this objective, more qualitative methods such as interviews, as well as online questionnaires are needed. The willingness of the citizen to requalify their buildings also needs to be investigated using real data.

This research uses the WLC model to analyse the suitability of defined scenarios. Further research can focus on the investigation of MCA methods, which gives rating outcomes to DMs. Several methods that might be particularly interesting for this purpose are ELECTRE [84], PROMETHEE [85], and MACBETH [86].

These methods could be integrated with the developed tool to provide a more comprehensive overview of the "*best*" decision-making process. This will be challenging because it requires a complicated programming language and further efforts on speed reduction of the process.

Finally, an interesting possibility that can be further developed is to create an Open Access MC-SDSS for UEP. During this investigation, a new web-based MC-SDSS was developed and the process is ongoing. This is called V-smart (Visualisation-sustainable multicriteria analysis retrofitting for territory); it allows dynamically interactive sessions among stakeholders, permitting the exchange of information to support UEP processes. V-smart was developed in collaboration with the technical support of the Information System Consortium of the Piedmont region (CSI-Italy). It is mainly based on the Quantum GIS (QGIS) software (GNU General Public License, freely available at www.qgis.org) and the virtual globe CESIUM (cesiumjs.org) system. The guidelines of V-smart are under preparation to aid urban actors and DMs in planning low-carbon cities.

Acknowledgment

This study is part of a national Smart City & Communities project, named "EEB-Zero Energy Buildings in Smart Urban Districts" (www.smartcommunitiestech.it). A new MC-SDSS, which is an interactive plug-in of GIS environment is developed within three-year Ph.D. research work of Sara Torabi Moghadam under the supervision of Professor Patrizia Lombardi and Professor Guglielmina Mutani [87].

Authors would like to also thank two anonymous reviewers for their constructive and precious comments which contributed to significantly improve this work.

Contributions statement

S.T.M. formal analysis, investigation, methodology, modeling and impact assessment, GIS visualization, workshop organizing; writing original draft; P.L. funding acquisition, supervision and revision the whole work and activities.

Authors declare no conflict of interest.

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Appendices

Table 7: Description of the considered pre-selected criteria.

	Criteria	Literature	Description	Unit
Environmental	CO_2 emissions	[29,33,35,38, 88,89]	measure the equivalent emission of CO_2, which is avoided by the examined action.	Tons/ year
	NO_X, PM_{10} emissions	[29]	direct impact on the health of the community and an indirect impact on the social state of the community.	Tons/ year
Economic	Payback period (PBP)	[30,40]	performance measure used to evaluate the efficiency of an investment or to compare the efficiency of a number of different investments.	Years
	Investment cost	[29,30,33,36, 56,89,90]	investment costs related to refurbishment of the building (efficiency investment) and/or new heating system (infrastructure investment).	Euro
	Socio-economic feasibility	[65]	the economic capability and willingness of the people.	Number
	Maintenance and Operational (M&O) costs	[89]	running fixed and variable costs due to the maintenance of the heating system (does not take into account fuel costs).	Euro
Technical	Reliability	[33,36,69,88]	efficiency of the technology and the requalification result.	Ordinal scale
	Technical life	[69]	durability of the whole strategy in relation to the service life of each retrofit measure.	Years
Social	Social acceptability	[33,40,89,90]	the perception of the people related to specific impacts due to the refurbishments.	Ordinal scale
	Local job creation	[30,33,35,88, 91]	potentiality of creating job and better regularity of the employee.	Man-day/ ordinal scale
	Architectural impact	[31,37]	the visual and architectural impact of refurbishments in the existing built environment.	ordinal scale

Table 8: Questions regarding considered (*i*) macro-section "Retrofitting Measure".

(i) Retrofitting Measures		
A-Retrofitting the heating energy system for building groups (i.e., boiler replacement)		
Q1. Are the heating system retrofitting simulations for buildings clusters useful?	U	□ *Very much*
Q2. Are they understandable and easy to use?	E	□ *Somewhat* □ *A Little*
Q3. Are the results of these simulations visualized effectively?	V	□ *Not at all*
Q4. Do you have any suggestions to improve these simulations and/or their visualization?		
B- Retrofitting the envelope system of buildings (i.e., window replacement, wall insulation)		
Q5. Are the envelope system retrofitting simulations for buildings clusters useful?	U	□ *Very much*
Q6. Are they understandable and easy to use?	E	□ *Somewhat* □ *A Little*
Q7. Are the results of these simulations visualized effectively?	V	□ *Not at all*
Q8. Do you have any suggestions to improve these simulations and/or their visualization? Q9. Do you have any suggestions to modify or add retrofitting measures?		

Explain your motivation.

Table 9: Questions regarding created (ii) macro-section "Indicators".

(ii) INDICATORS

Q10. How useful are the indicators in the instrument? • Investment Cost (M€) • Investment Cost (M€/GWh) • Global CO_2 Emissions (tonnes) • Global CO_2 Emissions-Reduction (%) • Local NO_X emission (tonnes) • Local PM_{10} emission (kg) • Architectural Impact (rank) • Job Potential (man-day) • Reliability (rank) • Energy Consumption (GWh) • Energy Saving (%) • Socio-Economic feasibility (%)	*U*	□ *Very much* □ *Somewhat* □ *A Little* □ *Not at all*
Q11. Are they understandable and easy to use?	*E*	□ *Very much* □ *Somewhat* □ *A Little* □ *Not at all*
Q12. Do the proposed indicators adequately provide the information you need to support the understanding of energy scenarios on a local scale?	*V*	
Q13. Do you have any suggestions to improve their visualization / other indicators that might be essential? Which?		

Explain your motivation.

Table 10: Questions regarding emerged (iii) macro-section "Map of Results".

(iii) MAP OF RESULTS		
Q14. Are the final results of the energy saving map in percent useful?	*U*	□*Very* □ *Enough* □ *Little* □ *Not at al*
Q15. Are they understandable and easy to use?	E	
Q16. Are the results of these maps visualized effectively?	V	
Q 17. Do you have any suggestions to improve these simulations and/or their visualization?		

Explain your motivation.

Table 11: General questions on the workshop Session.

General Questions on the Workshop Session	
Q1. The session produced useful results Q2. I am confident that the group solution is correct Q3. I am satisfied with this session Q4. Now I have more information about energy-related decision-making on the urban level Q5. Now I have a better vision regarding the views of the other participants Q6. I would use the presented tool and the results of this session in working practice Q7. We have reached a shared view of the problem Q8. We have achieved a shared vision of the goals Q9. We have achieved a shared vision of possible solutions Q10. I felt as part of a working group Q11. The presented instrument has highlighted a new approach to energy at the urban level Q12. The basic hypothesis presented for model development is clear Q13. The terms used during the session are understandable	□*Very* □*Enough* □ *Little* □ *Not at al*

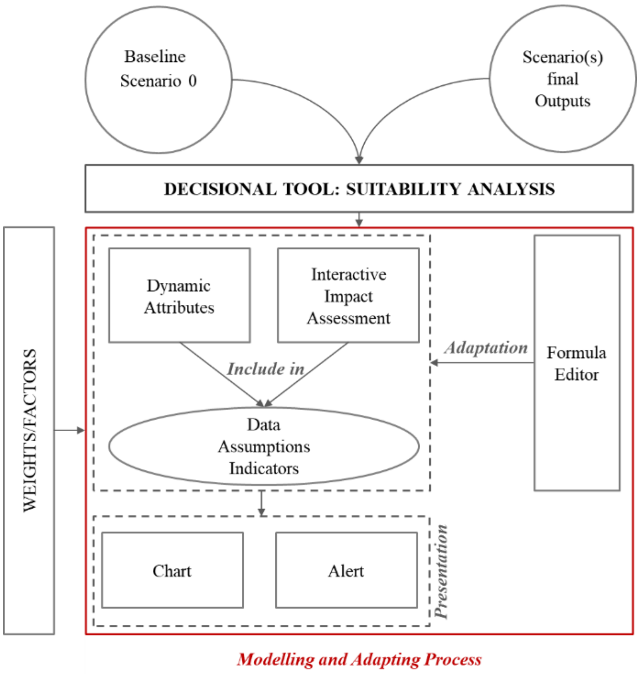


Figure 16: Schematic flowchart of MC-SDSS design; suitability modelling.

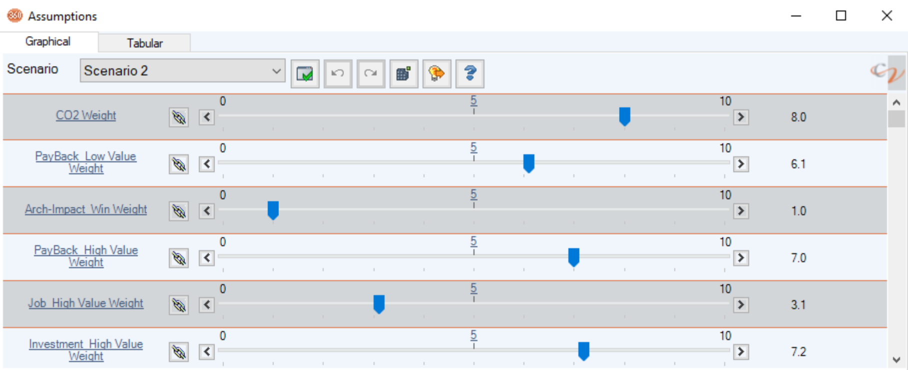


Figure 17: Representative CommunityViz weight sliders on a 10-point scale.

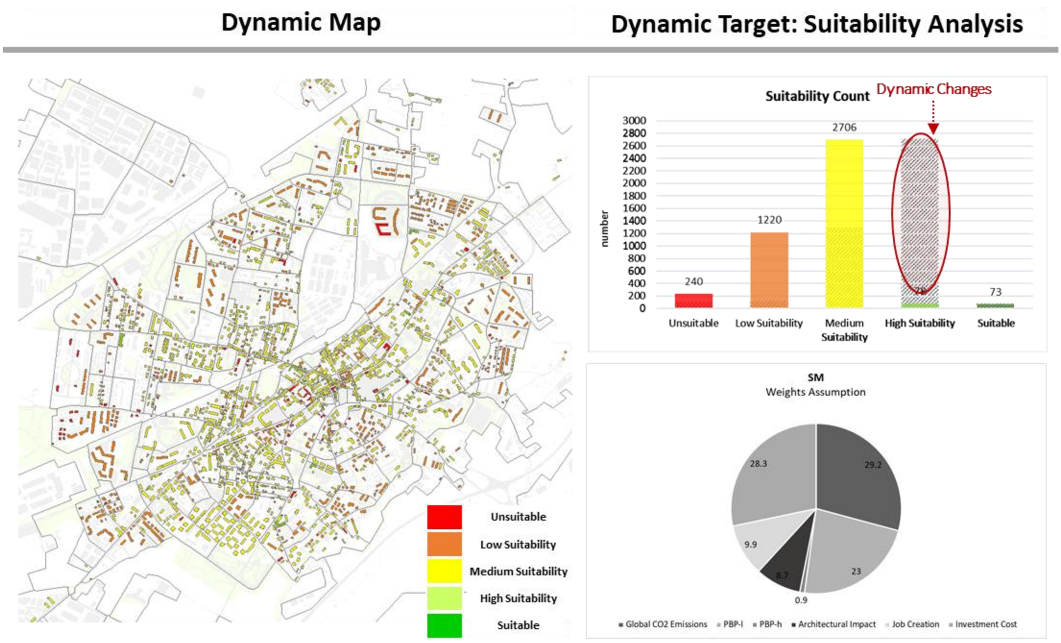


Figure 18: Suitability modelling, i.e., Scenario 1 “expert-oriented”, different weights.

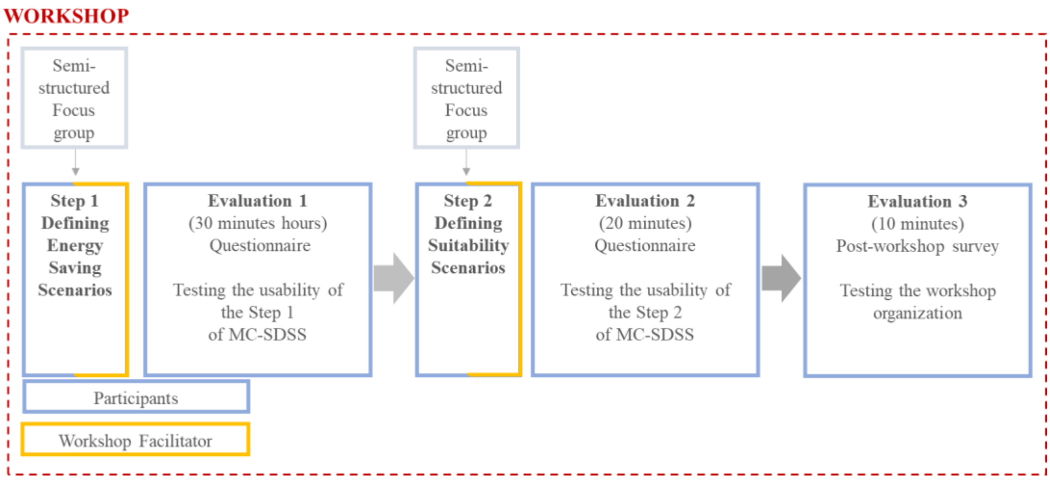


Figure 19: Workshop Structure.

Figure 20: Scenario 2 "stakeholder-oriented" in MC-SDSS; maps and charts.

Figure 21: Active Action Control for assumptions of Scenario 2 “stakeholder-oriented”.

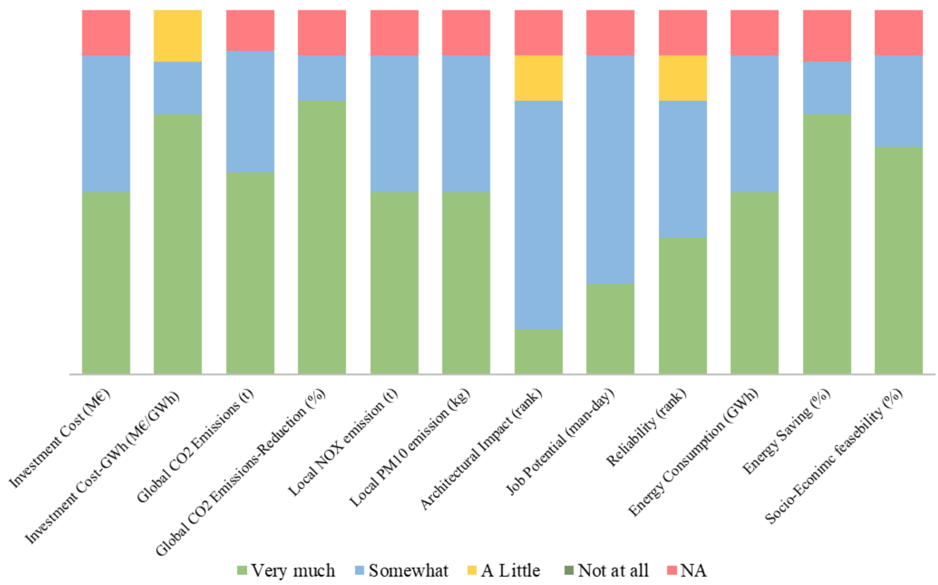


Figure 22: Answers received for Q10 regarding individual indicator.

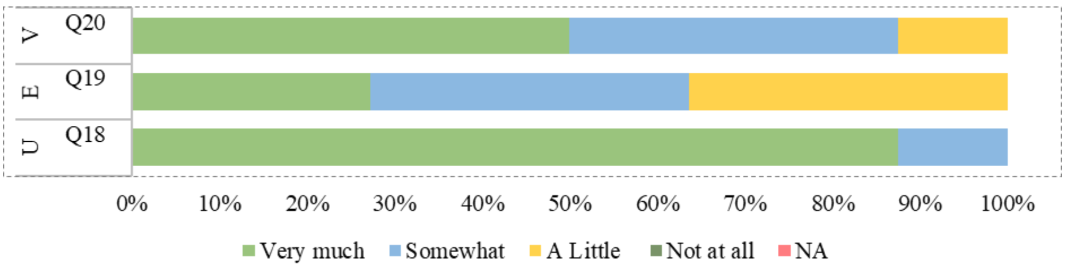
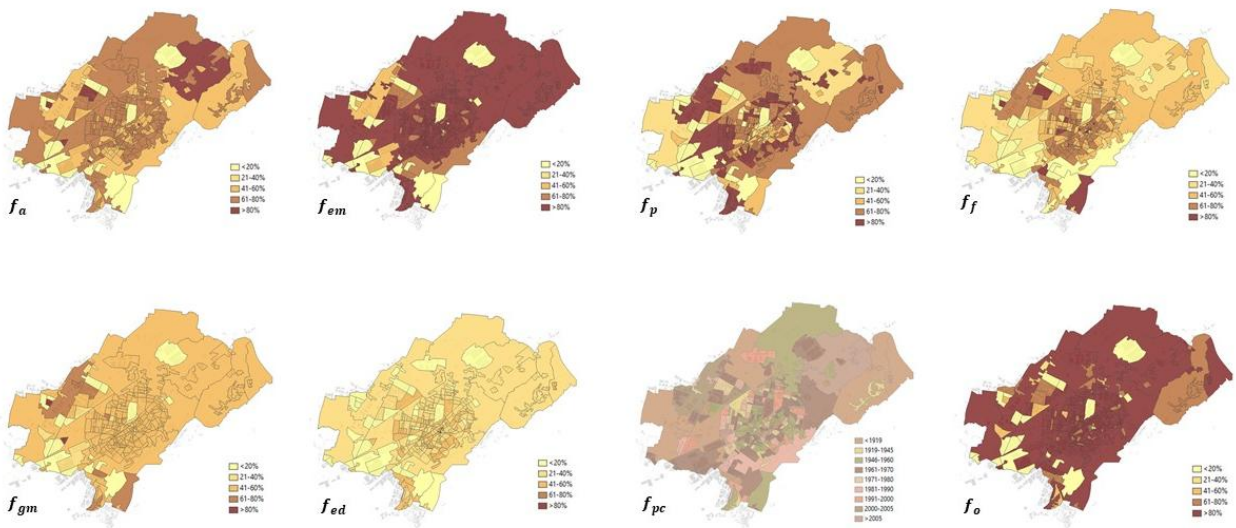


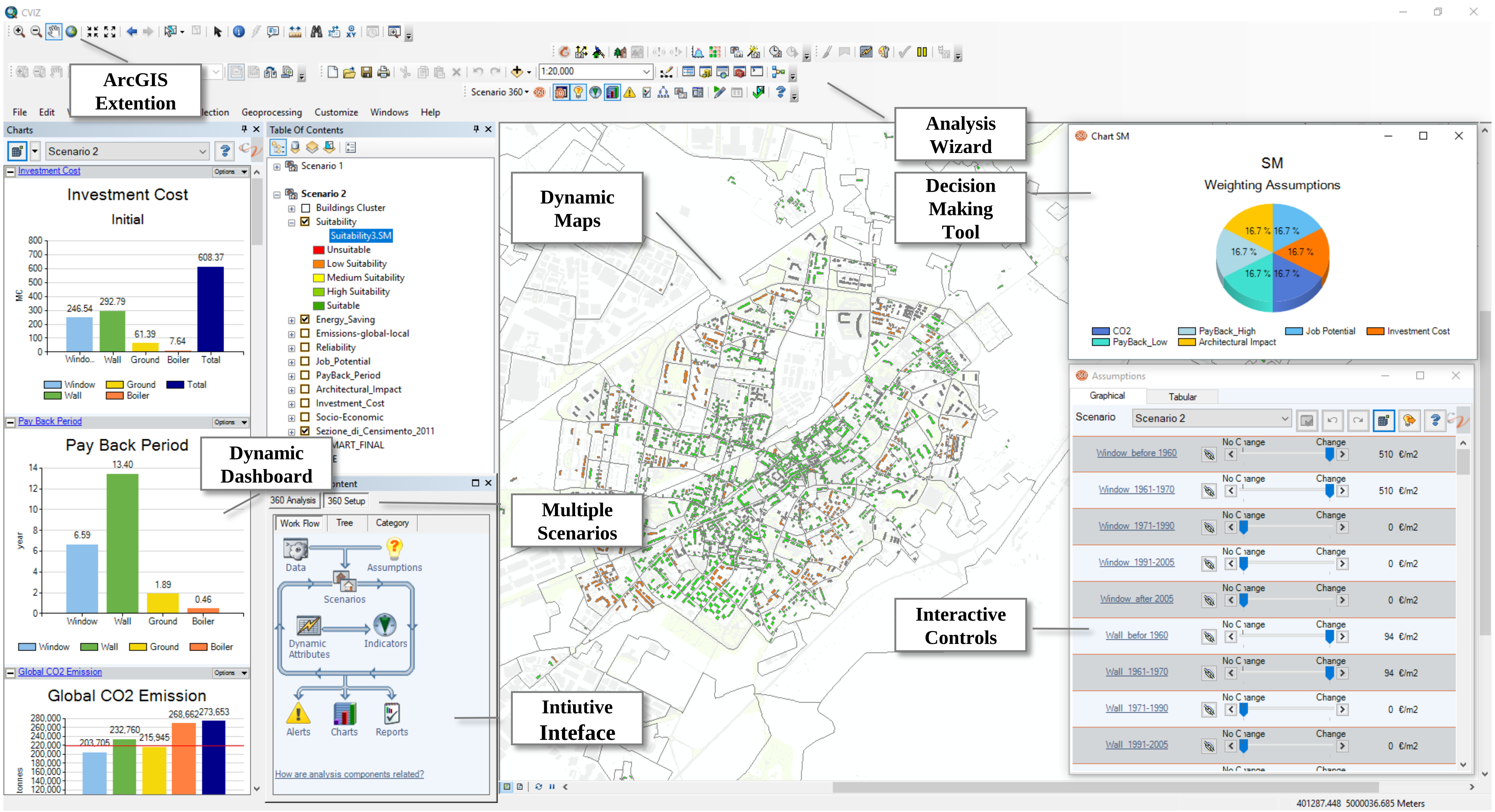
Figure 23: Perceived usability of the instruments in step 2.

Figure

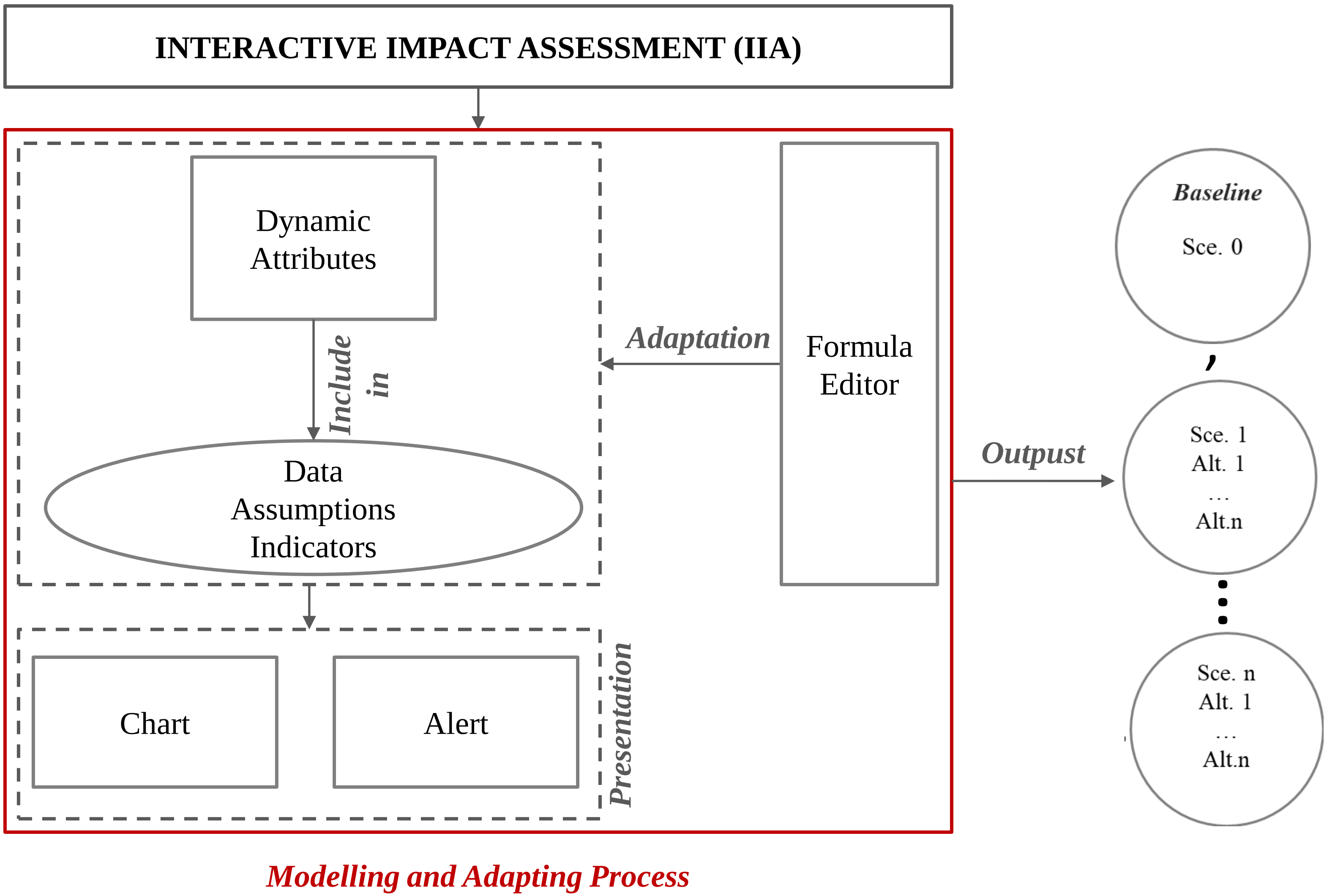


f_a
<20%
21-40%
41-60%
61-80%
>80%
f_{em}
<20%
21-40%
41-60%
61-80%
>80%
f_p
<20%
21-40%
41-60%
61-80%
>80%
f_f
<20%
21-40%
41-60%
61-80%
>80%
f_{gm}
<20%
21-40%
41-60%
61-80%
>80%
f_{ed}
<20%
21-40%
41-60%
61-80%
>80%
f_{pc}
<1919
1919-1945
1946-1960
1961-1970
1971-1980
1981-1990
1991-2000
2000-2005
>2005
f_o
<20%
21-40%
41-60%
61-80%
>80%

Figure

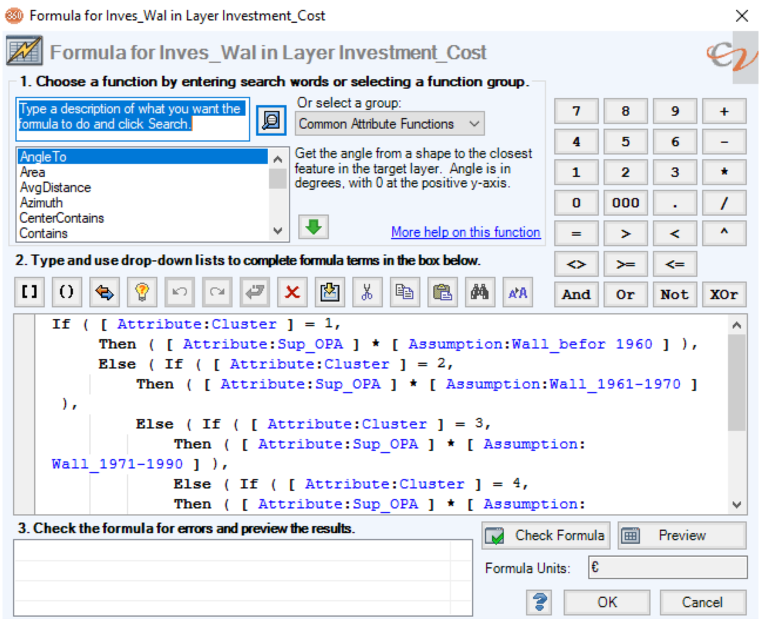

ArcGIS Extention
Analysis Wizard
Dynamic Maps
Decision Making Tool
Dynamic Dashboard
Multiple Scenarios
Interactive Controls
Intuitive Inteface

Figure



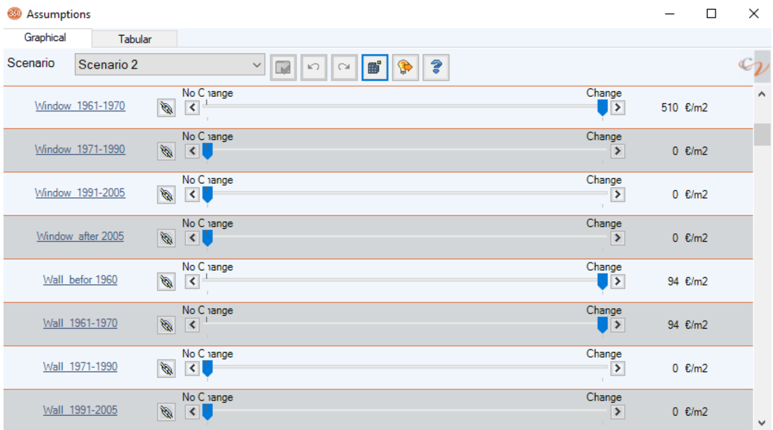
INTERACTIVE IMPACT ASSESSMENT (IIA)
Dynamic Attributes
Include in
Data Assumptions Indicators
Adaptation
Formula Editor
Chart
Alert
Presentation
Outpust
Baseline
Sce. 0
Sce. 1
Alt. 1
...
Alt.n
Sce. n
Alt. 1
...
Alt.n
Modelling and Adapting Process

Figure

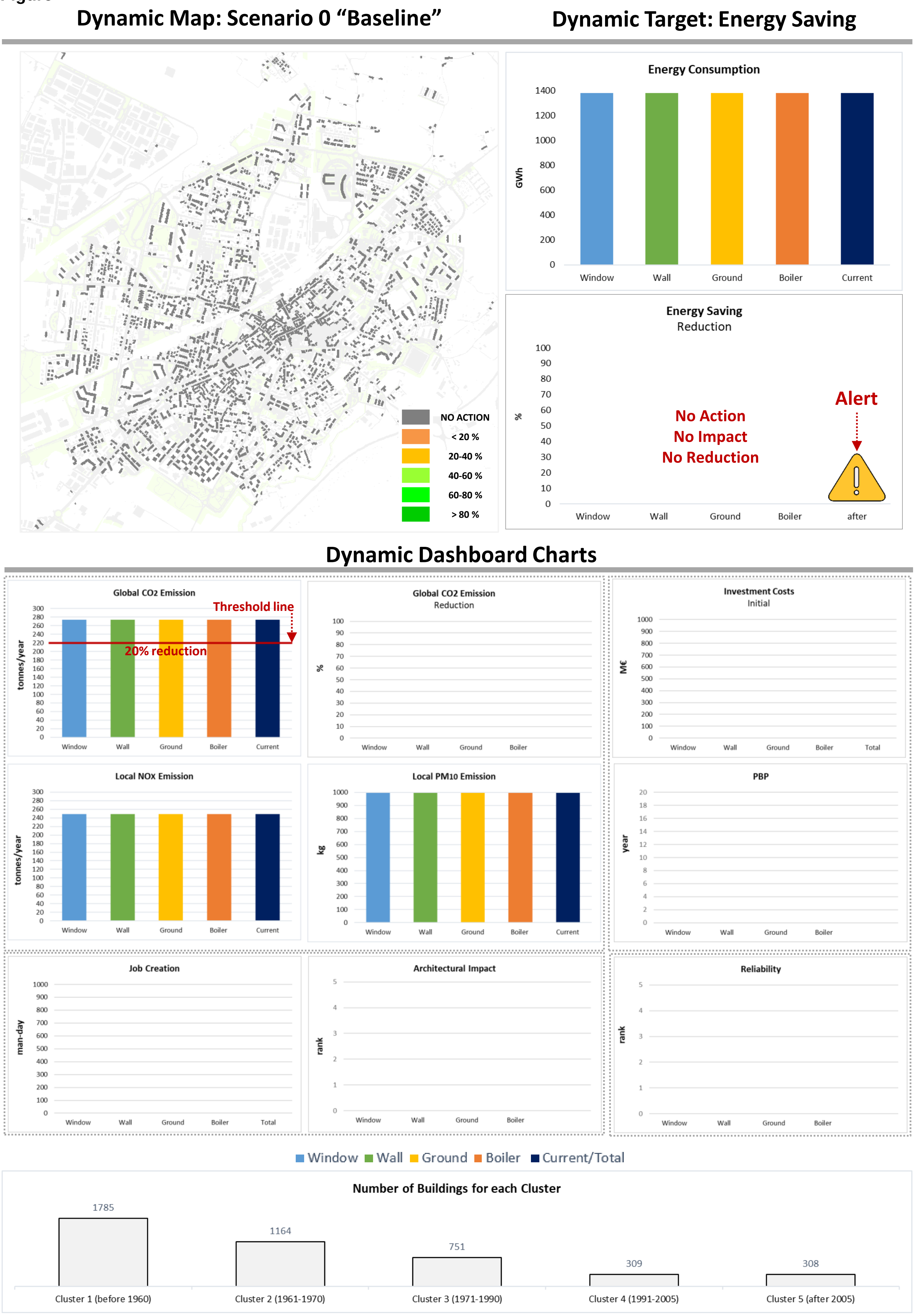


Formula for Inves_Wal in Layer Investment_Cost
Formula for Inves_Wal in Layer Investment_Cost
1. Choose a function by entering search words or selecting a function group.
Type a description of what you want the formula to do and click Search.
Or select a group:
Common Attribute Functions
AngleTo
Area
AvgDistance
Azimuth
CenterContains
Contains
Get the angle from a shape to the closest feature in the target layer. Angle is in degrees, with 0 at the positive y-axis.
More help on this function
2. Type and use drop-down lists to complete formula terms in the box below.
If ([Attribute:Cluster] = 1,
Then ([Attribute:Sup_OPA] * [Assumption:Wall_befor 1960]),
Else (If ([Attribute:Cluster] = 2,
Then ([Attribute:Sup_OPA] * [Assumption:Wall_1961-1970]
),
Else (If ([Attribute:Cluster] = 3,
Then ([Attribute:Sup_OPA] * [Assumption:
Wall_1971-1990]),
Else (If ([Attribute:Cluster] = 4,
Then ([Attribute:Sup_OPA] * [Assumption:
3. Check the formula for errors and preview the results.
Check Formula
Preview
Formula Units:
€
OK
Cancel
7 8 9 +
4 5 6 −
1 2 3 *
0 000 . /
= > < ^
<> >= <=
And Or Not XOr

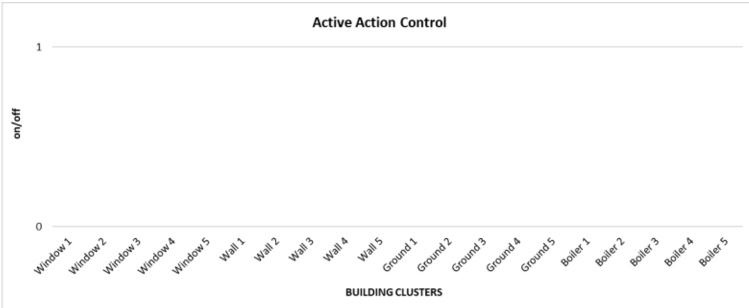
Figure


Assumptions
Graphical
Tabular
Scenario
Scenario 2
Window_1961-1970
510 €/m2
Window_1971-1990
0 €/m2
Window_1991-2005
0 €/m2
Window_after 2005
0 €/m2
Wall_befor 1960
94 €/m2
Wall_1961-1970
94 €/m2
Wall_1971-1990
0 €/m2
Wall_1991-2005
0 €/m2
No Change
Change

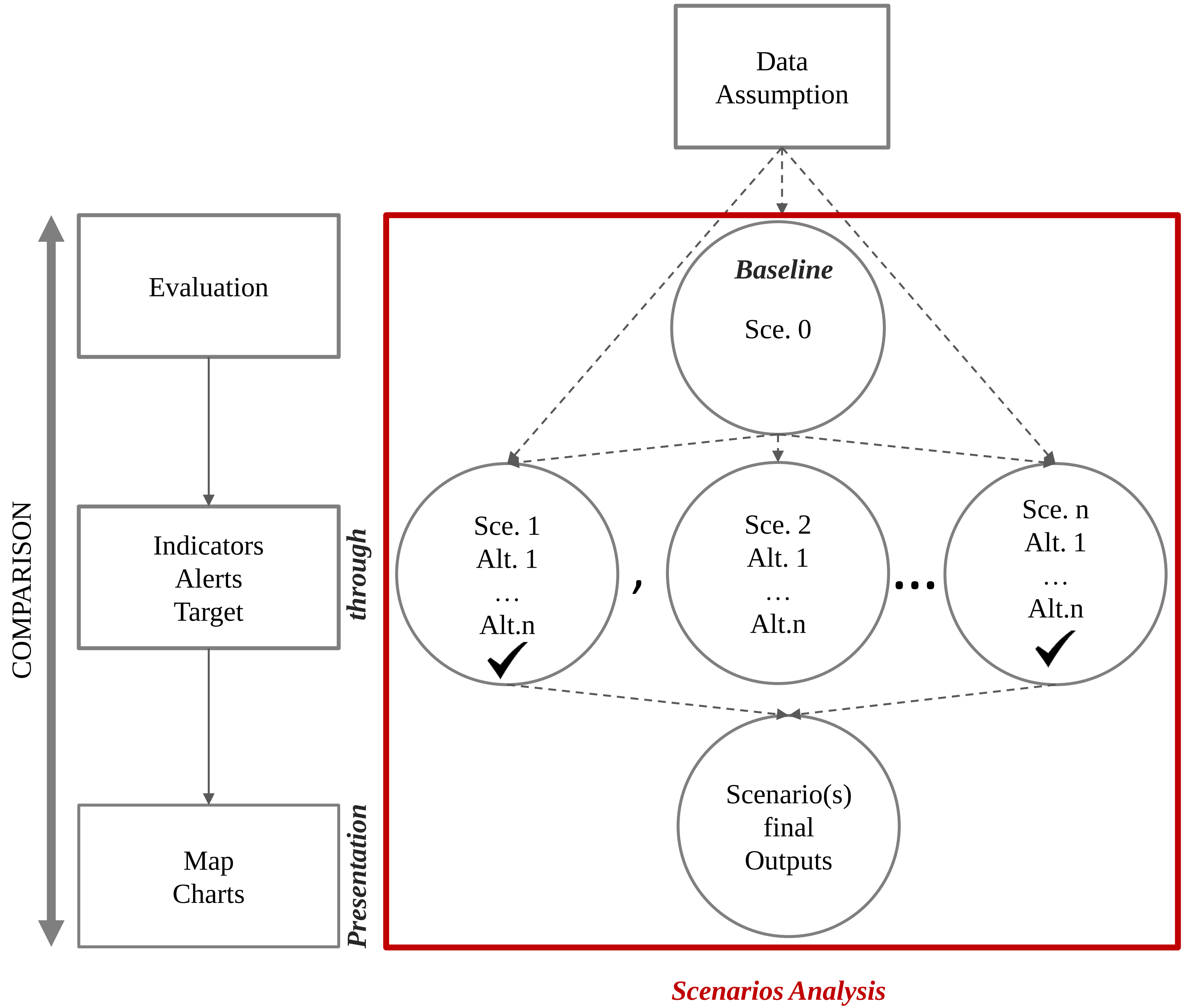
Figure


Dynamic Map: Scenario 0 "Baseline"
Dynamic Target: Energy Saving
NO ACTION
< 20 %
20-40 %
40-60 %
60-80 %
> 80 %
Energy Consumption
GWh
Window
Wall
Ground
Boiler
Current
Energy Saving
Reduction
%
No Action
No Impact
No Reduction
Alert
after
Dynamic Dashboard Charts
Global CO2 Emission
tonnes/year
Threshold line
20% reduction
Global CO2 Emission
Reduction
Investment Costs
Initial
M€
Total
Local NOX Emission
Local PM10 Emission
kg
PBP
year
Job Creation
man-day
Architectural Impact
rank
Reliability
Window
Wall
Ground
Boiler
Current/Total
Number of Buildings for each Cluster
1785
1164
751
309
308
Cluster 1 (before 1960)
Cluster 2 (1961-1970)
Cluster 3 (1971-1990)
Cluster 4 (1991-2005)
Cluster 5 (after 2005)

Figure


Active Action Control
1
0
on/off
Window 1
Window 2
Window 3
Window 4
Window 5
Wall 1
Wall 2
Wall 3
Wall 4
Wall 5
Ground 1
Ground 2
Ground 3
Ground 4
Ground 5
Boiler 1
Boiler 2
Boiler 3
Boiler 4
Boiler 5
BUILDING CLUSTERS

Figure

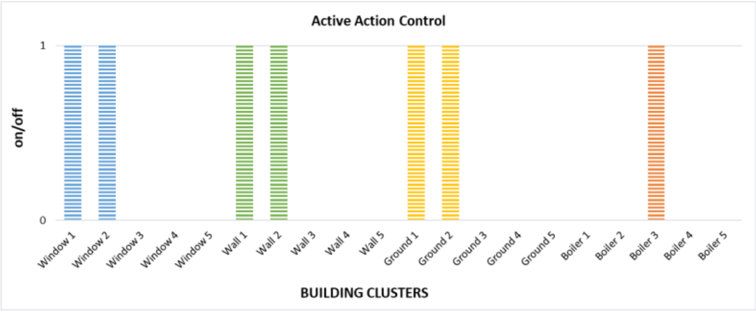


Data
Assumption
Evaluation
Indicators
Alerts
Target
Map
Charts
COMPARISON
through
Presentation
Baseline
Sce. 0
Sce. 1
Alt. 1
…
Alt.n
,
Sce. 2
Alt. 1
…
Alt.n
…
Sce. n
Alt. 1
…
Alt.n
Scenario(s)
final
Outputs
Scenarios Analysis

Figure

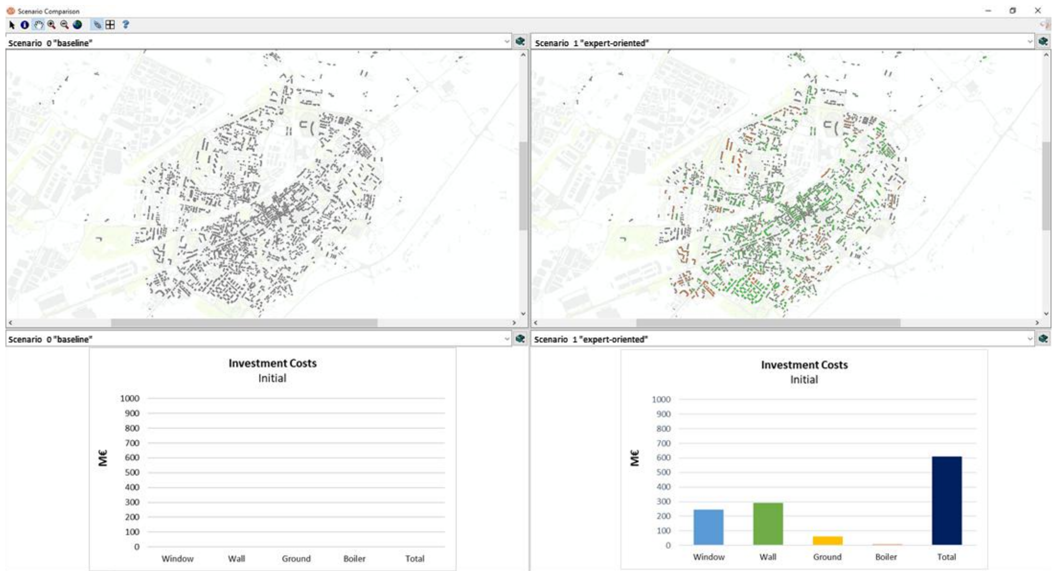
Dynamic Map: Scenario “expert-oriented”
Dynamic Target: Energy Saving
Scneario “baseline“
NO ACTION
< 20 %
20-40 %
40-60 %
60-80 %
> 80 %
Energy Consumption
GWh
Window
Wall
Ground
Boiler
Current
Energy Saving
Reduction
%
25.68
14.78
21.1
1.82
63.82
after
Dynamic Dashboard Charts
surpass the Threshold
Global CO2 Emission
tonnes/year
Global CO2 Emission
Reduction
25.56
14.94
21.09
1.82
Investment Costs
Initial
M€
Total
Local NOX Emission
dynamic changes
Local PM10 Emission
kg
PBP
year
Job Creation
man-day
Architectural Impact
rank
Reliability
Window
Wall
Ground
Boiler
Current/Total
Number of Buildings for each Cluster
1785
1164
751
309
308
Cluster 1 (before 1960)
Cluster 2 (1961-1970)
Cluster 3 (1971-1990)
Cluster 4 (1991-2005)
Cluster 5 (after 2005)

Figure



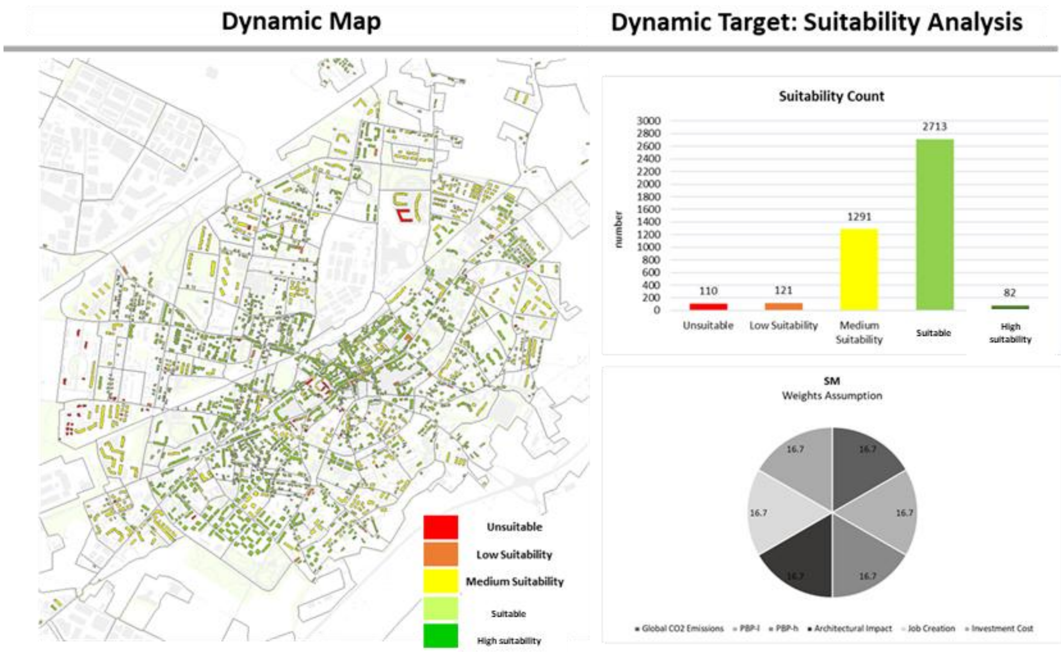
Active Action Control
1
0
on/off
Window 1
Window 2
Window 3
Window 4
Window 5
Wall 1
Wall 2
Wall 3
Wall 4
Wall 5
Ground 1
Ground 2
Ground 3
Ground 4
Ground 5
Boiler 1
Boiler 2
Boiler 3
Boiler 4
Boiler 5
BUILDING CLUSTERS

Figure



Scenario Comparison
Scenario 0 "baseline"
Scenario 1 "expert-oriented"
Scenario 0 "baseline"
Investment Costs
Initial
M€
1000
900
800
700
600
500
400
300
200
100
0
Window
Wall
Ground
Boiler
Total
Scenario 1 "expert-oriented"
Investment Costs
Initial
M€
1000
900
800
700
600
500
400
300
200
100
0
Window
Wall
Ground
Boiler
Total

Figure

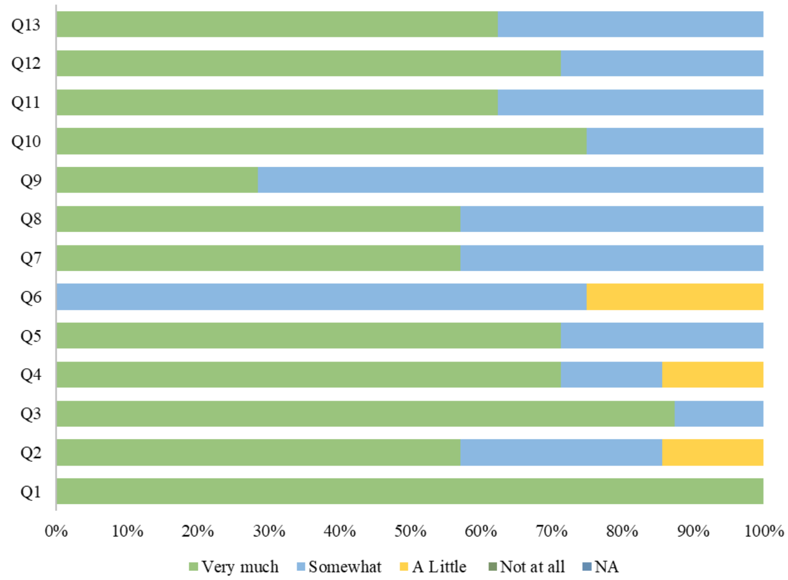


Dynamic Map
Dynamic Target: Suitability Analysis
Unsuitable
Low Suitability
Medium Suitability
Suitable
High suitability
Suitability Count
number
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
110
121
1291
2713
82
Unsuitable
Low Suitability
Medium Suitability
Suitable
High suitability
SM
Weights Assumption
16.7
16.7
16.7
16.7
16.7
16.7
Global CO2 Emissions
PBP-l
PBP-h
Architectural Impact
Job Creation
Investment Cost

Figure

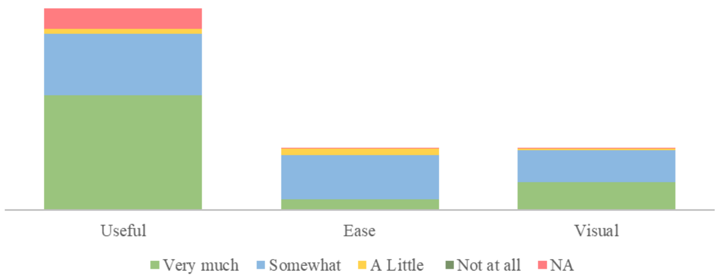
U: Usefulness E: Ease of use V:Visualization effectiveness
(i):retrofitting measurements (ii):Indicators (iii):Map of results
(iii)
(ii)
(i)
V Q16
E Q15
U Q14
V Q12
E Q11
U Q10
V Q7
E Q6
U Q5
V Q3
E Q2
U Q1
0%
20%
40%
60%
80%
100%
Very much
Somewhat
A Little
Not at all
NA

Figure

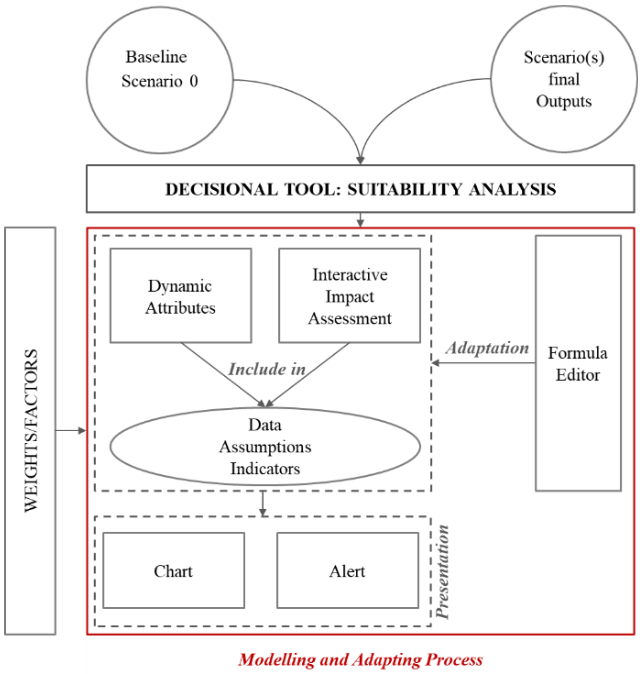


Q13
Q12
Q11
Q10
Q9
Q8
Q7
Q6
Q5
Q4
Q3
Q2
Q1
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Very much
Somewhat
A Little
Not at all
NA

Figure

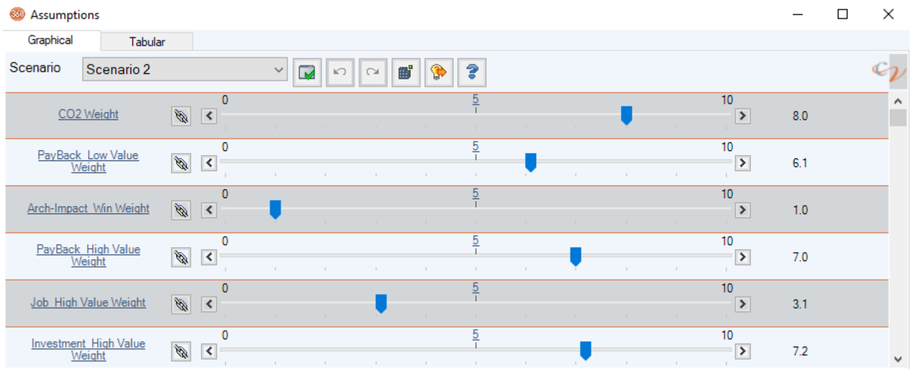


Figure

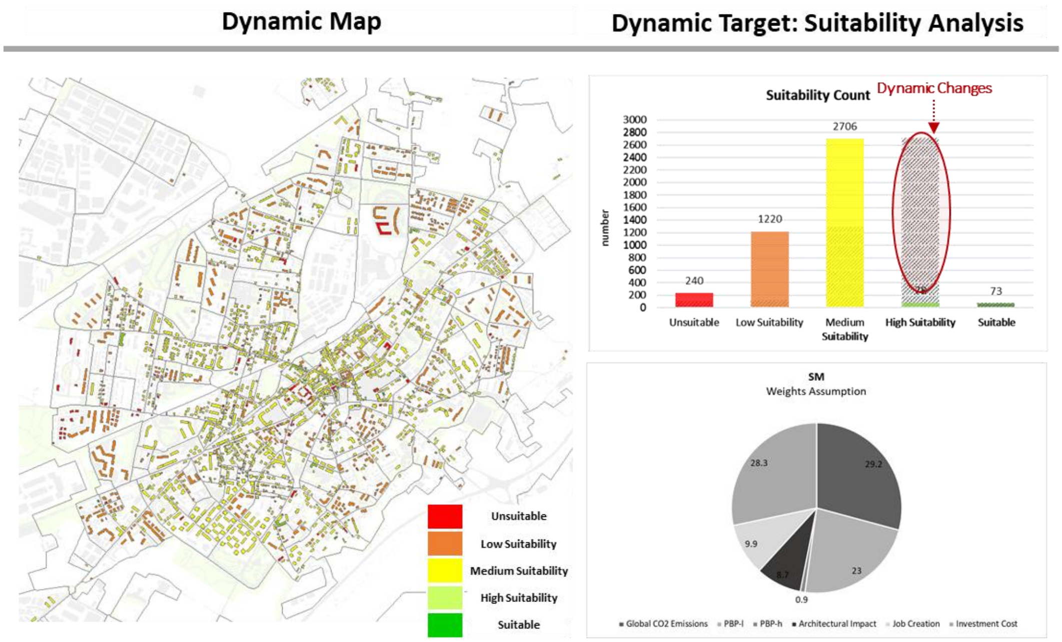


Baseline
Scenario 0
Scenario(s)
final
Outputs
DECISIONAL TOOL: SUITABILITY ANALYSIS
WEIGHTS/FACTORS
Dynamic
Attributes
Interactive
Impact
Assessment
Include in
Data
Assumptions
Indicators
Adaptation
Formula
Editor
Chart
Alert
Presentation
Modelling and Adapting Process

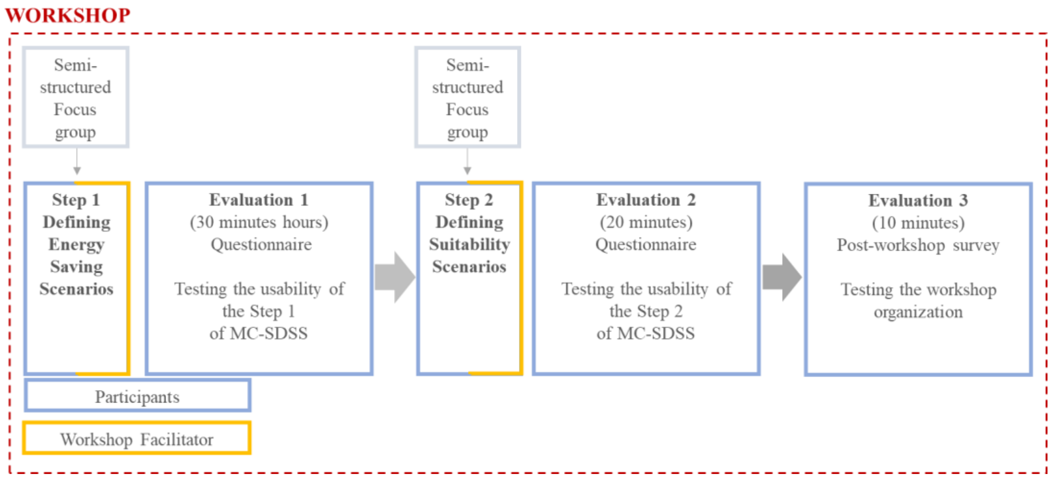
Figure


Assumptions
Graphical
Tabular
Scenario
Scenario 2
CO2 Weight
8.0
PayBack_Low Value Weight
6.1
Arch-Impact_Win Weight
1.0
PayBack_High Value Weight
7.0
Job_High Value Weight
3.1
Investment_High Value Weight
7.2
0
5
10

Figure


Dynamic Map
Dynamic Target: Suitability Analysis
Unsuitable
Low Suitability
Medium Suitability
High Suitability
Suitable
Suitability Count
Dynamic Changes
number
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
240
1220
2706
73
Unsuitable
Low Suitability
Medium Suitability
High Suitability
Suitable
SM
Weights Assumption
28.3
29.2
9.9
8.7
0.9
23
Global CO2 Emissions
PBP-l
PBP-h
Architectural Impact
Job Creation
Investment Cost

Figure

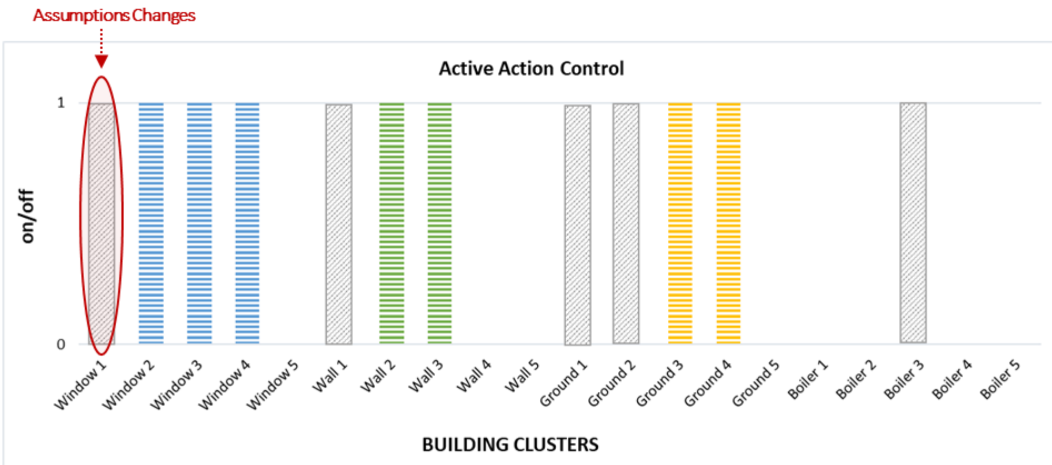


WORKSHOP
Semi-structured Focus group
Semi-structured Focus group
Step 1 Defining Energy Saving Scenarios
Evaluation 1
(30 minutes hours)
Questionnaire
Testing the usability of the Step 1 of MC-SDSS
Step 2 Defining Suitability Scenarios
Evaluation 2
(20 minutes)
Questionnaire
Testing the usability of the Step 2 of MC-SDSS
Evaluation 3
(10 minutes)
Post-workshop survey
Testing the workshop organization
Participants
Workshop Facilitator

Figure

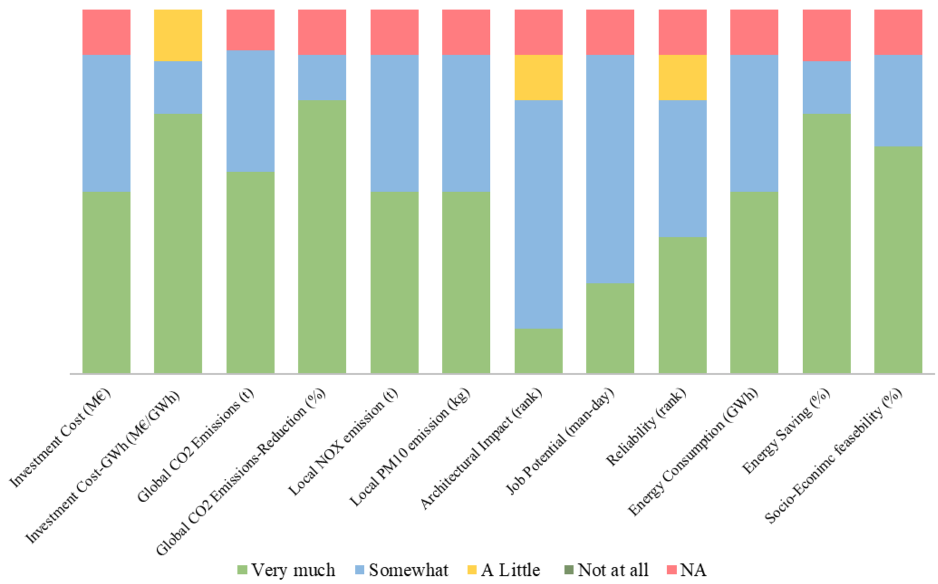

Dynamic Map: Scenario “stakeholder-oriented”
Dynamic Target: Energy Saving
Scneario “expert-oriented”
NO ACTION
< 20 %
20-40 %
40-60 %
60-80 %
> 80 %
Energy Consumption
GWh
Window
Wall
Ground
Boiler
Current
Energy Saving
Reduction
%
21.32
10.49
7.57
0
39.37
Window
Wall
Ground
Boiler
after
Dynamic Dashboard Charts
Global CO2 Emission
tonnes/year
Global CO2 Emission
Reduction
21.74
10.6
7.53
0
Investment Costs
Initial
M€
Window
Wall
Ground
Boiler
Total
Local NOX Emission
Local PM10 Emission
kg
PBP
year
Job Creation
man-day
Architectural Impact
rank
Reliability
rank
Window
Wall
Ground
Boiler
Current/Total
Number of Buildings for each Cluster
1785
1164
751
309
308
Cluster 1 (before 1960)
Cluster 2 (1961-1970)
Cluster 3 (1971-1990)
Cluster 4 (1991-2005)
Cluster 5 (after 2005)

Figure



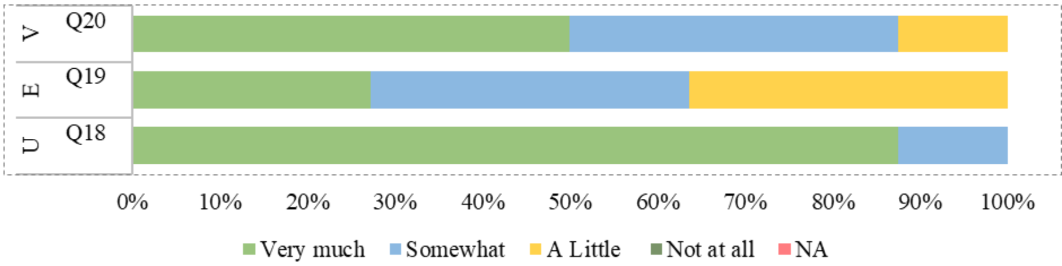
Assumptions Changes
Active Action Control
1
0
on/off
Window 1
Window 2
Window 3
Window 4
Window 5
Wall 1
Wall 2
Wall 3
Wall 4
Wall 5
Ground 1
Ground 2
Ground 3
Ground 4
Ground 5
Boiler 1
Boiler 2
Boiler 3
Boiler 4
Boiler 5
BUILDING CLUSTERS

Figure



Investment Cost (M€)
Investment Cost-GWh (M€/GWh)
Global CO2 Emissions (t)
Global CO2 Emissions-Reduction (%)
Local NOX emission (t)
Local PM10 emission (kg)
Architectural Impact (rank)
Job Potential (man-day)
Reliability (rank)
Energy Consumption (GWh)
Energy Saving (%)
Socio-Econimc feasebility (%)
Very much
Somewhat
A Little
Not at all
NA

Figure


V
E
U
Q20
Q19
Q18
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Very much
Somewhat
A Little
Not at all
NA