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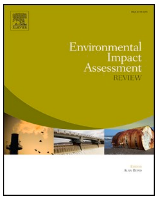

The integration of multi-agent system and multicriteria analysis for developing participatory planning alternatives in urban contexts

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ABSTRACT

Decision-making problems, particularly in transformation and planning processes, often involve multiple conflicting objectives/criteria that should be considered. However, it is possible to distinguish between two different types of problems. In the first type, a predefined and discrete set of alternatives has to be evaluated. In the second type, conversely, the set of suitable solutions is not explicated in advance but requires constraint functions for its definition. Alternative generation for choice problems is a vital activity in decision analysis that is sometimes overlooked and underdeveloped. Within this context, the present contribution proposes an integrated approach for supporting a participatory process of scenario planning. This approach combines three interrelated steps. Firstly, data pertaining to the context are collected using SWOT and Stakeholder Analysis. Secondly, the elicitation of preferences expressed by the main stakeholders involved in the planning process is conducted through a multicriteria method. Thirdly, a multi-agent system (MAS) supports the scenario building phase. MAS takes into account both the satisfaction of citizens' and stakeholders' preferences and the comprehensive sustainability of the site, according to a set of multi-dimensional indicators. The generation of alternative scenarios is contingent upon the consideration of preferences and sustainable performance, but also on the suitability of current and new land uses, which are based on a rich set of data elaborated through a Geographic Information System (GIS). The case study of Basse di Stura in Turin (Italy) represents a useful example to test the applicability of this integrated approach. This is due to the fact that the transformation in this area is at an impasse, due to the high pollution of the soil and the different perspectives of the stakeholders involved. The results reveal the ability of this integrated approach in facilitating the development of participatory solutions, that can take into account sustainable objectives, stakeholders' needs and the specificity of the context under analysis.

1. Introduction

The formulation of policies and strategies in urban contexts represents a decision-making activity that is informed by a synthesis of knowledge and assessment. In particular, policy making and scenario building for sustainable development are a distinct category of decision making activities, characterized by a multiple interrelationships and trade-offs (Boulanger and Bréchet, 2005; Halla et al., 2022; Opon and Henry, 2020). The presence of multiple objectives, a multitude of stakeholders, and the costs and benefits of sustainability issues collectively present a significant challenge to effective working practices (Caprioli and Bottero, 2021; Ferretti and Grosso, 2019). In particular, these latter aspects highlight the need to consider the existence of multi-spatial and multi-temporal elements, the presence of long-term and/or unforeseen externalities, uncertainties, and the interaction between human beings and natural or technological systems (Allais and Gobert, 2019; Boulanger and Bréchet, 2005). In light of the necessity to consider a multitude of conflicting aspects and stakeholders in this context, it is crucial to differentiate between two types of decision problems. The first type involves the evaluation of a predetermined, discrete set of alternatives. The second type is characterized by necessity to specify constraint functions to generate the alternatives that are not explicitly defined in advance (Colorni and Tsoukiàs, 2020). The construction of alternatives is, in itself, a decision-making process (Colorni and Tsoukiàs, 2020). This may be achieved by directly involving stakeholders and Decision-Makers (DMs) in the decision-aiding process, asking for their preferences in order to identify the most preferred and shared solutions. It is notable that the topic of alternative construction is

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largely absent from the existing literature, with only a limited number of contributions addressing this area, as recently reviewed by Colorni and Tsoukiàs (2020). Moreover, although the construction of alternatives has been explored through various research disciplines (including policy, economics, operational research and design), there is a lack of consideration of individual or group preferences, and their interpersonal utility comparison in policy design (Ferretti et al., 2019).

To fill this gap, the present work proposes an integrated approach for the co-construction of alternative scenarios among the stakeholders, with a particular focus on the sustainable performance of the alternatives in question. Qualitative analysis (SWOT Analysis and Stakeholder Analysis (SA)) are combined with quantitative approaches (multicriteria decision analysis (MCDA) and multi-agent system (MAS)). The applicability of the integrated approach is tested in a case study of a brownfield site to be regenerated in Northern Italy. The integrated approach, firstly, develops SWOT and SA to support the collection of the relevant information about the area under analysis and the different perspectives of the stakeholders interested in this decision-making process. Secondly, a panel of experts is involved in a brainstorming process to select potential alternative actions for implementation in the area. Thirdly, citizens and key stakeholders are asked to elicit their preferences regarding the aforementioned actions using a MCDA. Finally, MAS supports the scenario building phase. The actions weighted through MCDA are used in combination in MAS to create the alternative scenarios, taking into account both the satisfaction of citizen and stakeholder preferences and the overall sustainability of the site regeneration. The generation of alternative scenarios also depends on the suitability of current and new land use patterns, resulting from the development of combined actions in the area. These patterns are informed by a comprehensive array of spatial data, which is elaborated through a Geographic Information System (GIS).

In particular, the proposal can be of significant benefit in the context of an Environmental Impact Assessment (EIA). The complexity of current decision-making processes has led to an increased importance being placed on environmental assessments (including EIA), alongside purely economic assessments (Mondini, 2016). Nevertheless, an integrated approach is essential in EIA. Firstly, it can facilitate an evaluation prior to definition of the project, including the incorporation of participatory input, in contrast to the conventional application of EIA. Secondly, in order to guarantee that any negative impacts do not exceed an acceptable threshold, which is the primary objective of EIA, the proposal can suggest alternatives that provide a balance between benefits and costs. Thirdly, the integrated approach can address the limitations of most applications of EIA, which may frequently undervalue the economic and social impacts of a project (Tian et al., 2025).

As with EIA, the adoption of integrated methodologies has been further explored by authors to overcome the limitations inherent to single methods (see, for example, the literature review developed by Marttunen et al. (2017)). This is due to the fact that it is strategic to analyze each phase of the decision problem from its initial stages to the selection of the most appropriate alternative according to the context and the stakeholders involved (Bottero et al., 2022; Dell'Anna et al., 2024; Creswell and Plano Clark, 2011).

Developing an integrated approach allows DMs to guide the development of sustainable and circular strategies by considering different perspectives and satisfying the demands of society and the city (Cerreta and Panaro, 2022; Han et al., 2023; Shen et al., 2012). As in most planning and regeneration processes, DMs are mainly the public administration, policy makers, and public bodies, striving to transform the city and aiming to achieve a comprehensive sustainable vision, considering environmental protection, social cooperation, technological advancement, and cultural preservation. However, DMs are not always able to adequately consider the needs of citizens in real contexts, nor the different perspectives of other key stakeholders involved in planning and regeneration processes, such as environmental agencies, developers, citizens and owners, among others (Corrente et al., 2023). In this way, the proposed integrated approach can represent an innovative exploration of alternative design in decision analysis and operational research, with the objective of producing salient, credible, evident, and legitimate results (Bottero et al., 2021; Cash et al., 2003; Ferretti and Grosso, 2019; Tsoukias et al., 2013). In particular, the proposed mixed-method allows the stakeholders to collaborate in the generation of alternative solutions. In contrast, the majority of contributions pertaining to land use management entail stakeholders merely selecting from a range of predefined alternatives proposed by the analyst (e.g., Buron Brarda et al., 2023). Furthermore, when the contributions do propose collaborative work, the problem is usually related to site selection (e.g., Azarafza et al., 2018; Besharati Fard et al., 2022; Nemdili and Hamdadou, 2021; Omari et al., 2022, 2023) or the choice between a few land uses at the city-regional level (e.g., Abolhasani et al., 2023; Li and Liu, 2007; Saint-Bois et al., 2024; Zhang et al., 2016). In contrast, this work employs a district level rather than the city-regional level, and the collaboration results in a comprehensive project design for an area with very specific interventions (e.g., the establishment of a research center, a sports field or an urban garden).

The work therefore seeks to address to the following questions: How to support DMs in designing salient and legitimate alternatives? Is it possible to apply a generalizable approach in real case studies? Is the approach able to consider at the same time the co-construction among stakeholders and the evaluation of the sustainable performance of the alternative scenarios?

The remaining part of the paper is structured as follows. In Section 2, it is detailed the general integrated approach proposed for generating alternatives. Section 3 presents the application of the integrated approach to the selected case study. Section 4 illustrates the results, while Section 5 contains concluding remarks and insights into future research perspectives.

2. Methodological background

This paper proposes an integration of different tools and methods (Fig. 1) that provide an operational approach capable of supporting the design of the alternative scenarios according to a strategic and participatory approach. Specifically, the mixed-method combines problem framing tools (i.e., SWOT Analysis, SA, and a focus group), a weighting elicitation procedure based on a recent multicriteria method (i.e., the Best-Worst Multicriteria method (BWM) (Rezaei, 2015)) and a scenario building process using MAS. As it is possible to see in the right part of Fig. 1, the combination of approaches allows for mutual reinforcement and synergy (Ferretti, 2016) starting from the identification of the problem and objectives through preliminary analysis of the context and stakeholders, to the design of the best performing and participatory options.

2.1. Problem framing: SWOT analysis and stakeholders analysis

In public policy and decision-making, SWOT and SA tools are appropriate for developing preliminary analysis of context and providing a solid basis for the subsequent evaluation stages.

On the one hand, the acronym SWOT, which stands for Strengths (S), Weaknesses (W), Opportunities (O), and Threats (T), enables the decomposition of a given problem into its exogenous (i.e., potential opportunities and threats) and endogenous (i.e., strengths and weaknesses) components. Consequently, SWOT helps to understand the current situation and to identify the aspects that can maximize positive outcomes while reducing negative impacts. In general, the contents of the SWOT are organized into four sections, which collect the characteristics identified as strengths, weaknesses, opportunities and threats. In addition, SWOT can also be organized according to thematic areas or assets according to the project, plan or program under analysis. These assets may include, for example, tourism, services, society, governance, and so forth.

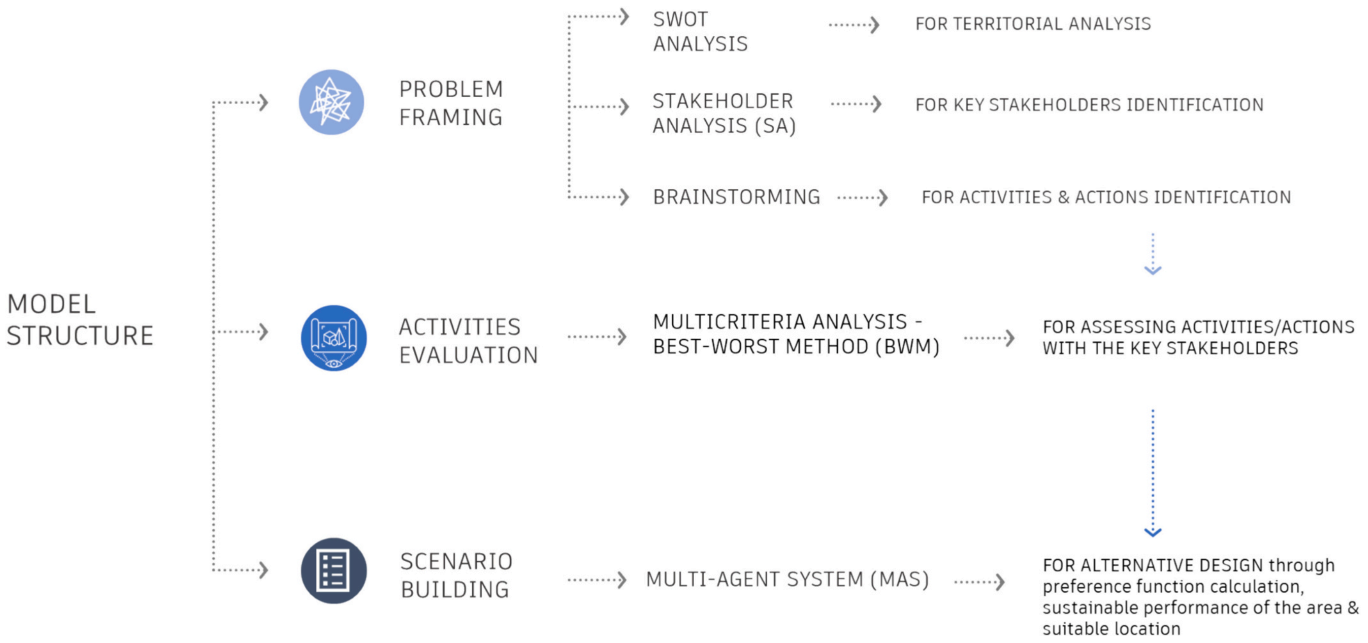

Fig. 1. Structure of the integrated approach.

On the other hand, SA facilitates the identification of the stakeholders involved and interested in the process or problem under analysis. The development of SA provides an overview of the interests and objectives of all individuals or groups, with the aim of clarifying the values and preferences of each of them. Moreover, SA makes it possible to anticipate potential relationships and conflicts (Dente, 2014). In practice, the SA starts with the identification of the list of actors and stakeholders involved, highlighting the stakeholder level of intervention (national, regional, local), the category of actors to which they belong (political, bureaucratic, special interest, general interest, experts), and the resources that they exercize (political, economic, legal, cognitive), as well as the stakeholder roles and expectations (Bottero et al., 2021; Dente, 2014). In this study, two well-known tools for performing SA are combined: the Social Network Analysis (SNA) (Marin and Mayntz, 1991; Rhodes, 1997) and the power-interest analysis (PWA) (Johnson and Scholes, 1999; Mendelow, 1981). On the one hand, PWA identifies the power and interest of each stakeholder in relation to the specific issue under investigation. On the other hand, SNA maps the relationships and exchange of resources between the stakeholders. The size and form of the network provide insight into the coalitions and pivotal actors within the decision-making context (Bottero et al., 2020). Furthermore, SNA can also be employed to calculate specific indexes that describe certain dynamics (Berta et al., 2018). These include the density and the complexity of the network, as well as the centrality of each stakeholder within the network.

In order to generate alternative options, SWOT and SA are essential for gathering all the relevant information about the problem and the different needs and expectations of the stakeholders involved in the decision-making process. Developing them at an early stage makes it possible an in-depth analysis of the reference context, which can then inform the definition of the policies, strategies and actions to be adopted. Furthermore, the identification of potential courses of action that align with the objectives of the stakeholders can foster consensus and the acceptance of the proposed project, plan, program or policy.

In this study, the SWOT is structured according to the primary characteristics that define the area under investigation, organizing them into two groups (i.e., natural and anthropic elements). The SA combines a PWA and a SNA to identify the key stakeholders and actors to be involved in the subsequent stages of the evaluation process. This is done with a view to understanding the respective level of power, interest and relationships of the aforementioned parties in this decision-making process.

2.2. *Activities evaluation: multicriteria analysis*

MCDA is a class of methods that are capable of conducting a comparative assessment of alternatives or heterogeneous measures (Figueira et al., 2005; Roy and Bouyssou, 1995). MCDA permits the consideration of the full range of aspects that define a complex decision-making process, encompassing both economic and extra-economic values (Caprioli and Bottero, 2021; Cinelli et al., 2014; Roy, 1985). In MCDA, the evaluation procedure is frequently characterized by the presence of strong interactions between the analyst, DMs and stakeholders at various stages. This facilitates the considerations of all the stakeholder perspectives involved in the decision-making process, thereby enhancing the overall assessment.

Many MCDA methods have been proposed (for a complete review, it is possible to refer to Figueira et al. (2005); Greco et al. (2016)). To choose among them, this work used the MCDA Methods Selection Software (MCDA-MSS), accessible at http://mcdamss.com (Cinelli et al., 2022). In accordance with the responses provided, one of the methods proposed is the best-worst method (BWM), developed by Rezaei in 2015. BWM is a comparison-based method that uses two vectors of pairwise comparisons to determine the criteria weights (Rezaei, 2016). The DM or stakeholder first chooses the best (i.e., most desirable, most important) and the worst (i.e., least desirable, least important) criteria, and then compares the best criterion to the other criteria, and the other criteria to the worst criterion (Rezaei, 2016). The weights are identified using a non-linear minmax model which minimizes the highest absolute difference between the weight ratios and their related comparisons.

Two calculation procedures may be employed with BWM, which may produce two different weight results. On the one hand, it may result in multiple optimal solutions, meaning that solving the problem results in several sets of weights for the criteria. On the other hand, BWM can produce a unique solution, employing a linear procedure. Methodological and formulation details about these two calculations can be found in Rezaei (2015, 2016).

The advantages of BWM include the reduction of effort and time required by the interviewee in the comparison of criteria, as well as the reduction of inconsistency that characterizes some other MCDA methods. Furthermore, the structure of BWM based on the comparison of best and worst aspects is particularly suitable for the comparison of alternative actions or strategies (instead of criteria/aspects) in complex urban transformations. Indeed, in cases where multiple stakeholders with different opinions are involved in a transformation process and no predefined alternatives are available, the exploration of priorities in the implementation of strategies can be more useful and efficient.

In this study, BWM was used to express the preferences of the key stakeholders to activities and actions (see Section 3.2.2). The actions (belonging to different activities) are those that can be implemented in combination in the study area to create the alternative scenarios. To determine the two vectors of pairwise comparisons, the linear BWM approach was applied using the existing tool called BWM Solvers (https://bestworstmethod.com/software/).

2.3. Scenario building: multi-agent system (MAS)

The third model that informs the integrated decision aiding process proposed in this paper is MAS. In some research, MAS is used as a synonym for agent-based model (e.g., Epstein and Axtell, 1996; Gilbert and Terna, 2000), whereas other authors distinguish the two models if the types of agents are one or multiple or according to the field of research. Nevertheless, both models are simulation models able to realize a detailed representation of a complex system, considering the behaviours and the interactions of multiple agents. MAS represents a suitable tool to study and manage the urban systems affected by countless aspects, including economic, social, and environmental aspects, which are notoriously challenging to simulate (Motieyan and Mesgari, 2018; Torrens, 2000). Agents in MAS are characterized by: (a) autonomy in their environment and their interactions; (b) self-sufficiency, uniqueness, individual identifiability, and modularity; (c) a state that varies over time; and (d) a social dynamic that influences agent behaviours through interactions with others. Therefore, agents can be established as stand-alone entities to fulfil specific functions (Ghadimi et al., 2018). However, it is only through MAS that these multiple interacting agents can work collectively through cooperation or competition to solve problems that would be beyond their individual capabilities (O'Hare and Jennings, 1996).

In this research, MAS supports the scenario building phase. This is done by implementing different actions (see Section 3.2.2) taking into account both the satisfaction of stakeholder preferences and the overall sustainability of the transformation, as indicated by a set of multi-dimensional indicators (see Section 3.2.3). The generation of alternative scenarios is also contingent upon the suitability of current and new land uses (i.e., actions), which are based on a rich set of GIS data.

3. Case study application

3.1. Study area and conceptualization

This work uses a de-industrialized and down-grounded area in the city of Turin (Italy), called Basse di Stura (Fig. 2), to test the applicability of the integrated approach. There are several reasons for the selection of this area as the case study: 1) the local administration has expressed interest in the development of this area, both in terms of the natural potential of the site and for its strategic location; 2) the transformation has reached an impasse, due to the high level of soil pollution; 3) the main use planned for the area is classified as public area, which requires the consideration of all relevant parties, from the citizens to the private owners; 4) the objectives of the various stakeholders involved are significantly divergent; 5) the area has undergone a significant change in its uses over the years, shifting from an agricultural vocation to an industrial one, which has resulted in fragmentation and underdevelopment.

To develop the proposed model, different datasets were used. These included a) open data regarding infrastructural networks, buildings, water systems and green areas. These data were used to develop a raster map measuring 10 × 10 meters. This map shows the land uses of the Business-As-Usual scenario (BAU) (i.e., the state of the art of the area before any hypothetical transformation). In addition to this, the following datasets were used: b) public and private ownership of the areas; c) territorial indexes of the lands; d) hydrogeological bands; e) soil pollution of the areas; f) demographic data at the neighbourhood scale of the surrounding districts, such as age, household size educational level and professional status.

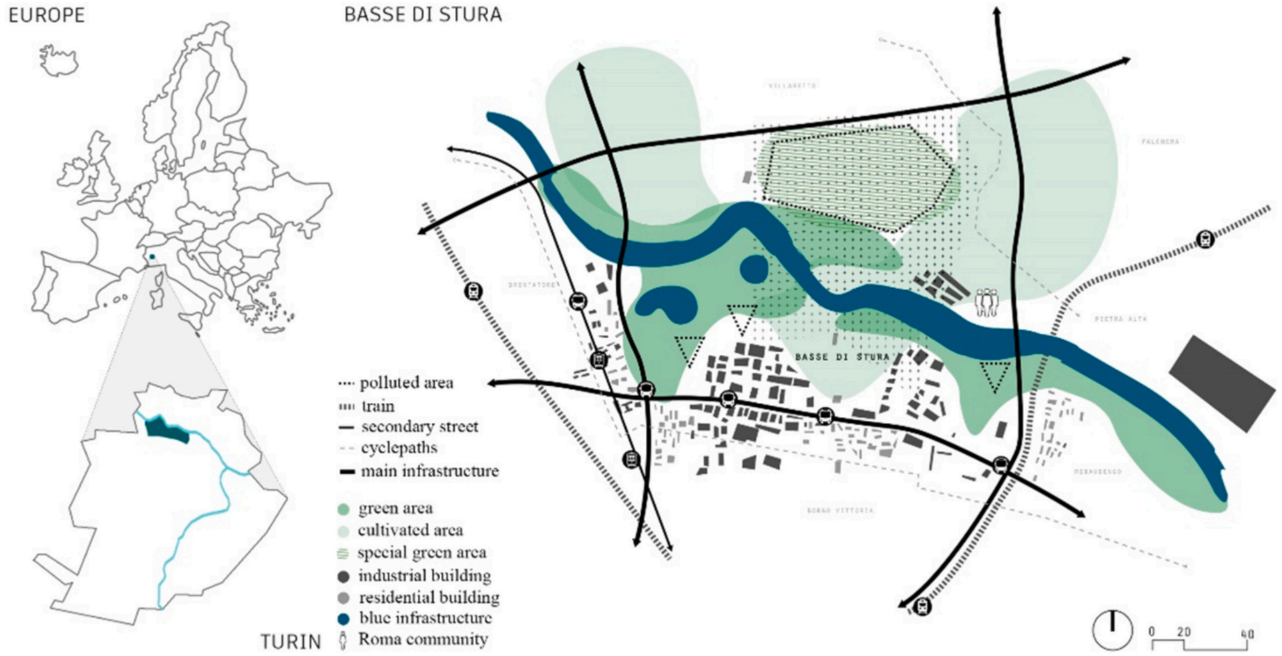

Fig. 2. Localization and the main characteristics of Basse di Stura area (Bottero et al., 2021).

3.2. Model development

This study employs a three-phase methodological approach, as follows:

- phase I is dedicated to defining the problem, by gathering data and information concerning the area, the decision-making process and the stakeholders involved, using SWOT and SA;
- phase II applies the BWM to identify the different preferences of the relevant stakeholders regarding the development of the area;
- phase III consists of developing MAS to construct coherent and participatory scenarios, taking into account the comprehensive enhancement of sustainability in the area and the preferences of the stakeholders.

3.2.1. First phase: problem framing

The problem framing phase employs the use of SWOT Analysis and SA. These two analyses are based on a collection of data and information about the area, obtained through document analysis, on-site inspection and interaction with the municipality.

In the initial stage of the problem framing process, a SWOT Analysis is conducted. Given the distinctive characteristics of the area under analysis, the SWOT Analysis investigates natural and an anthropic elements separately (Fig. 3).

Looking at Fig. 3, SWOT Analysis highlights the unexpressed potential of the area. The area is characterized by many natural elements, including a river, extensive green spaces and a mountainous view. However, the majority of the area functions have been abandoned, are contaminated, or are characterized by social marginality. Failure to intervene could result in irreversible impacts to the area. Conversely, the location benefits from strategic accessibility, including proximity to a highway, railway, airport, and the planned underground line. The extensive green spaces and the river could facilitate connectivity with the green and blue infrastructure of the Metropolitan City. The potential inclusion of the area within environmental projects could facilitate the restoration and enhancement of its habitats. Education has the potential to foster awareness about the area among both present and future generations, with topics such as social justice and waste recycling. The potential river flooding represents a significant risk to the area, with the possibility of further damage. The local economy is experiencing a decline as a result of the progressive abandonment of the farmhouses and industrial facilities. Some opportunities include the adaptive reuse of industrial buildings for green energy production and the creation of new jobs through the design of co-working spaces. The implementation of green technology may be facilitated by the introduction of tax incentives and subsidies, which could attract investors and support the development of energy policies. However, the long-term transformations and the requirement for significant economic resources may act as deterrents to investment. The ongoing revision of the Municipal Plan for the city provides an opportunity to regenerate the area.

In the second stage of the problem framing, SA is applied with the objective of identifying parties who can contribute to the decision-making process and whose outcomes could affect the results of this process (Dente, 2014). From the documents and on-site inspection, a comprehensive list of stakeholders was compiled. For each of these stakeholders, the following information was provided: their level of competence, the resources they carry out, and the types of actors they represent. Indeed, each stakeholder is motivated by a set of interests related to their goals, values, or preferences, which ultimately influence their stance on a given strategy. The aforementioned information was employed in the development of an integration of SA methodologies, namely the SNA and PWA. The results for the present case study are represented in Fig. 4. The nodes represent the stakeholders, while the arrows illustrate the connections between them. In accordance with PWA, the dimensions of the circles are indicative of the power of the stakeholders, whereas the proximity to the centre is representative of the stakeholders' interest with respect to the transformation of the area. In accordance with SA and following Berta et al. (2018) calculation, the centrality index is calculated as follows:

$$C = \frac{k_i}{\sum K_i}$$

where C is the centrality index that varies between 0 and 1, ki is the number of relations of each stakeholder and K_i is the total sum of relations of all stakeholders in the network. The centrality index is a measure of the capacity of each stakeholder to exert control over the relationships they hold with other participants in the network. The centrality values for each stakeholder are presented in grey within the circle in Fig. 4. The integration of PWA and SNA was instrumental in identifying the primary stakeholders to be engaged in the subsequent assessment stages. These included the citizens, the developers, the environmental expert, the municipality and the owners. Indeed, the analysis reveals that the municipality of Turin occupies a pivotal role, exhibiting the highest centrality index, due to its relations with 18 other stakeholders. This is an unsurprising outcome, given that the city of Turin is the main promoter of the process and the landowner of certain lands. Conversely, the remaining stakeholders have a low centrality

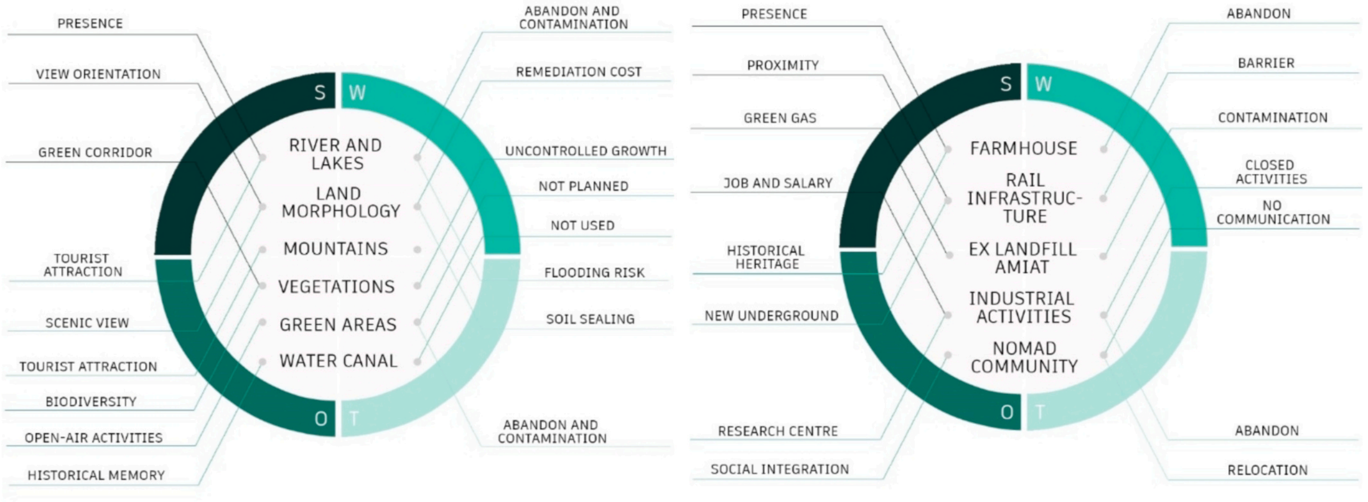

Fig. 3. SWOT Analysis for the natural (left side) and anthropic elements (right side) (Bottero et al., 2020).

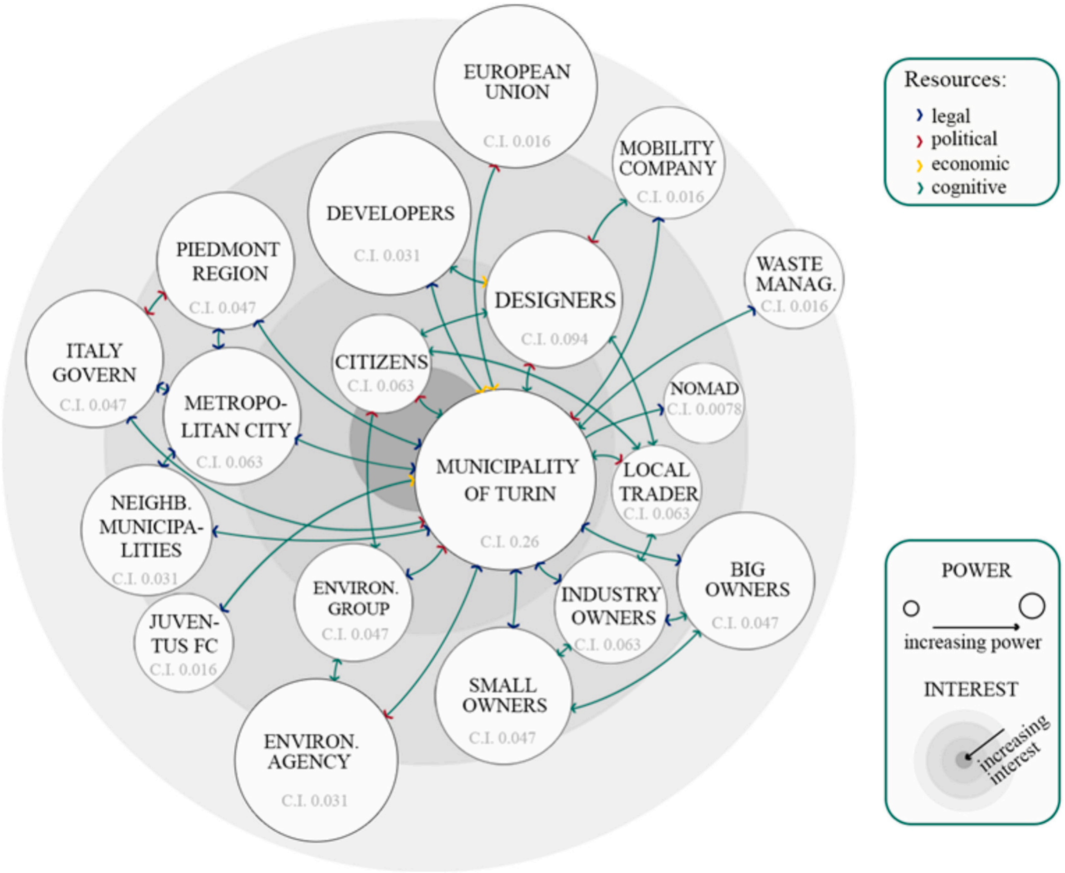

Fig. 4. Stakeholders map for the Basse di Stura case study (Bottero et al., 2020).

index. Therefore, they have a limited capacity to direct the process, with a maximum of five relationships (such as the designers) and a minimum of one (such as the nomad community or the waste management company). Nevertheless, the transformation is not feasible without the assistance of numerous additional stakeholders. For instance, the owners of the area (i.e., big, small and industrial owners) and developers are pivotal in facilitating the transformation, as evidenced by their position close to the centre and with relatively large dimension. Another important stakeholder is the citizens, whose power is limited but whose interest is considerable. Furthermore, environmental groups and the environmental agency collectively have a strong power and interest in the area. Consequently, these five stakeholders (i.e., the municipality, owners, developers, citizens and environmental groups) are regarded as the pivotal actors in the transformation process, and their needs have been incorporated into the subsequent stages of the model.

3.2.2. *Second phase: evaluation of the activities through MCDA*

The construction of the SWOT analysis and the consideration of the values and preferences emerging from the SA have provided a comprehensive understanding of the area. This has in turn enabled the formulation of the prospective vision of the area. The knowledge collected in the previous phase is employed in a brainstorming session, during which a group of experts is consulted for the purpose of identifying future strategies for the implementation of the area. The focus group was structured into three parts. Firstly, all the experts were informed about the area, the data, and the information acquired during the preliminary analysis. Secondly, they started the brainstorming phase, during which ideas and perspectives were discussed. This phase resulted in a preliminary list of possible strategies. Thirdly, the most appropriate actions were defined collectively and clustered into five different groups of activities, as detailed below and hierarchically illustrated in Fig. 5:

- social and educational activities: (SE1) Farm school, (SE2) Educational tour on the natural and industrial history of the area, (SE3) Social centre, (SE4) Allotments;
- activities in nature: (NA1) Nature trails along the river, (NA2) Birdwatching, (NA3) Butterfly farm, (NA4) Horse farm;
- technological activities: (BE1) Cultivated areas of no-food crop, (BE2) Bioenergy areas, (BE3) Research centre;
- sport activities: (SA1) Soccer/tennis/basket/volley fields, (SA2) Skatepark/Roller rink, (SA3) Outdoor equipment, (SA4) Cycle path;
- organized sites: (OS1) Children's play area & pic-nic area, (OS2) Dog park, (OS3) Study spaces, (OS4) Organized beaches along the river.

The analysis of the context and the consultation of experts have provided insights that have informed the creation of knowledge related to the area under investigation, as well as the development of alternative strategies. Nevertheless, the pivotal point of this case study, and indeed of the majority transformation and regeneration processes, is the achievement and satisfaction of the needs, expectations, and objectives of the stakeholders. The analysis has thus considered the direct inclusion of stakeholders' preferences regarding the transformation of the area. The analysis considers five key stakeholders: the municipality of Turin, an owner of the area, a potential developer, an environmental expert, and the citizens. As illustrated in SA (Section 3.2.1), these five stakeholders represent the most interested and influential parties in this decision-making process. To elicit the stakeholders' preferences, a MCDA method, specifically the linear model of BWM (see Section 2.2) is employed.

The weights assigned to activities and actions was obtained through the administration of an individual online survey provided to each

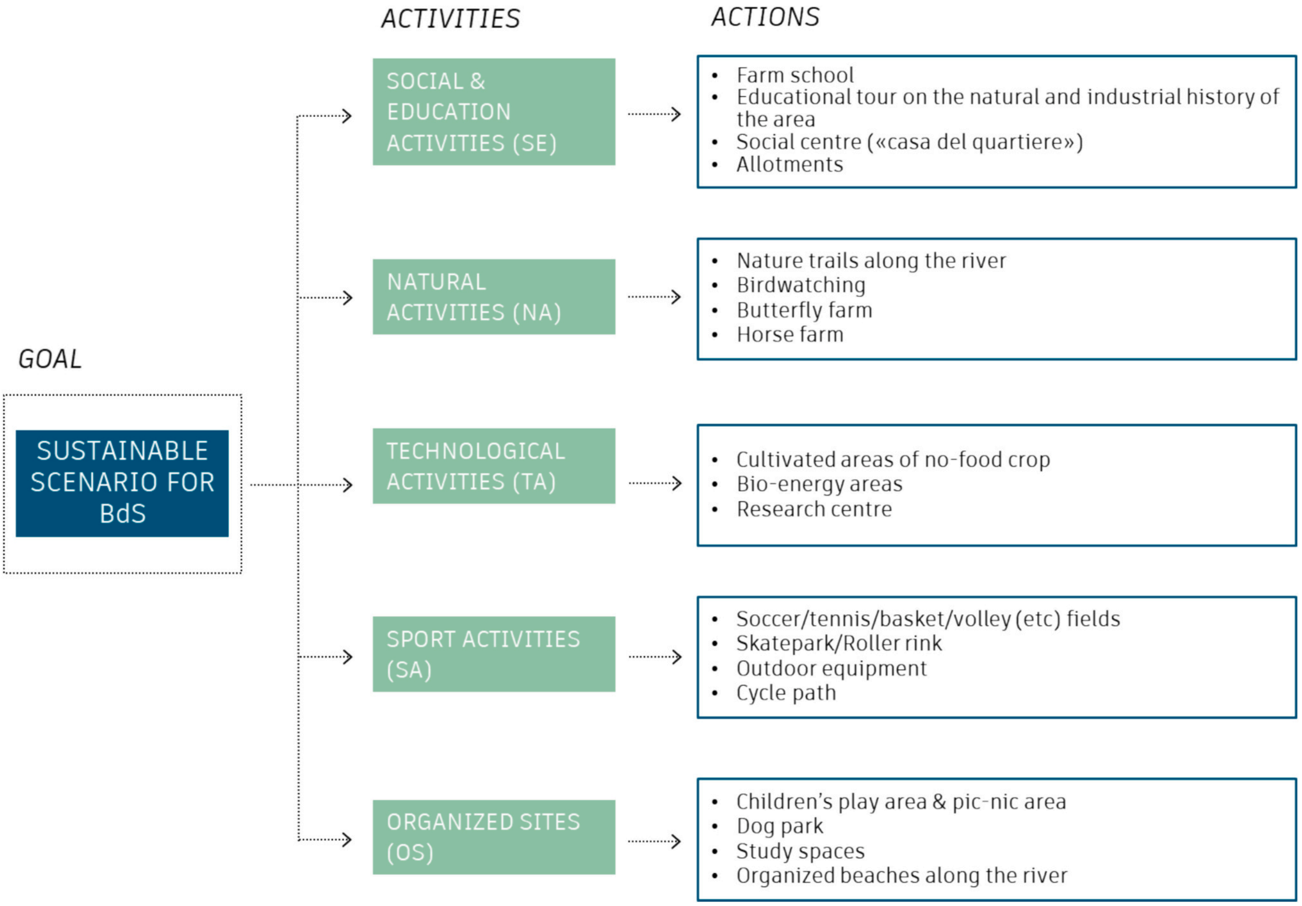

Fig. 5. The hierarchic structure of activities and related actions.

stakeholder. In the face-to-face meeting, each stakeholder responded to the survey with the assistance of the analyst. The survey is comprised of seven distinct sections. The first section serves as an introductory section, providing an overview of the case study, a description of the contents and objectives of the survey, a concise explanation of BWM, and an illustration of the activities and actions to be evaluated. In this section, the respondents were also asked to indicate the stakeholder they represented, selecting from the following options: the developer, the environmental expert, the municipality, the owner, or the citizen. In the second section, each stakeholder indicates the most important (BEST) and least important (WORST) ACTIVITY for the sustainable transformation of the area. Furthermore, the respondent indicates the ratio of preference for the BEST ACTIVITY over the other ACTIVITIES and for all the activities over the WORST ACTIVITY. Table 1 exemplary illustrates the preferences expressed by the municipal stakeholder (using the 9-point scale proposed by Saaty (1980)) and the weights obtained through the linear BWM. *Ksi* represents the consistency ratio, which is defined as a value between 0 and 1. A value close to 0 indicates greater consistency, while a value close to 1 indicates less consistency (Rezaei, 2016). A linear BWM procedure is employed for all the calculations, using the tool called BWM Solvers (https://bestworstmethod.com/software/).

In Sections 3, 4, 5, 6, and 7, the stakeholder is asked to indicate the most important (BEST) and least important (WORST) ACTIONS for the

Table 1
Preferences expressed by the municipality to the activities.

	Socio-educ activities	Natural activities	Technological activities	Sport activities	Organized sites
Select the best	Organized sites				
Select the worst	Socio-educ activities				
Best to Others	Socio-educ activities	Natural activities	Technological activities	Sport activities	Organized sites
Organized sites	5	3	3	2	1
Others to the Worst	Socio-educ activities				
Socio-educ activities	1				
Natural activities	4				
Technological activities	4				
Sport activities	4				
Organized sites	5				
	Socio-educ activities	Natural activities	Technological activities	Sport activities	Organized sites
Weights	**0.061**	**0.158**	**0.158**	**0.236**	**0.388**
Ksi	0.085				

implementation of each activity. These activities are classified as follows: socio-educational activities, activities in nature, technological activities, sporty activities, and organized sites. This implies that, for each section, a set of actions related to a single activity is compared through BWM. The weights provided by the five stakeholders, derived through the linear BWM, are reported in Tables 2 and 3, respectively for the level of activities and the level of actions. Furthermore, it is important to note that the results presented in Tables 2 and 3 regarding the citizen stakeholder require further clarification. Tables 2 and 3 show the geometric average of the BWM weights obtained from the individual responses of the 369 citizens of Turin, homogeneously distributed across all districts. This aggregation method was chosen to reduce the computational efforts and execution time associated with modeling all 369 citizens in the subsequent phase of the analysis (i.e., in MAS). Furthermore, from the outset of this research, an aggregation approach has been chosen, as this more accurately reflects the prevailing citizen sentiment (reducing the impact of outliers) and the manner in which they are consulted by public authorities, i.e. through representatives rather than individually. However, in other contexts, the model could directly use the preferences expressed individually.

As expected, the results presented in Tables 2 and 3 reflect different perspectives among the stakeholders. The citizens would like to increase in the provision of leisure facilities and infrastructure. However, they are also aware of the opportunity of developing innovative solutions in

Table 2
Stakeholders' preferences for the activities.

	Socio-educational activities	Natural activities	Technological activities	Sport activities	Organized sites	Ksi
Citizen	0.214	0.214	0.393	0.071	0.107	–
Developer	0.229	0.066	0.229	0.361	0.115	0.098
Envir. expert	0.15	0.505	0.2	0.059	0.086	0.094
Municipality	0.06	0.158	0.158	0.236	0.388	0.085
Owner	0.428	0.156	0.234	0.117	0.065	0.043

Table 3
Stakeholders' preferences for the actions.

	SOCIO-EDUCATIONAL ACTIVITIES				
	Farm school	Educational tour	Social centre	Allotments	Ksi
Citizen	0.207	0.545	0.155	0.094	–
Developer	0.319	0.08	0.55	0.051	0.089
Envir. expert	0.489	0.261	0.057	0.193	0.091
Municipality	0.145	0.079	0.487	0.289	0.092
Owner	0.196	0.196	0.09	0.518	0.071

	NATURAL ACTIVITIES				
	Nature trails	**Birdwatching**	**Butterfly farm**	**Horse farm**	**Ksi**
Citizen	0.214	0.076	0.160	0.550	–
Developer	0.286	0.048	0.19	0.476	0.095
Environmental expert	0.518	0.196	0.196	0.09	0.071
Municipality	0.182	0.091	0.273	0.454	0.091
Owner	0.466	0.259	0.172	0.103	0.051

	TECHNOLOGICAL ACTIVITIES				
	Cultivated areas of no-food crop	**Bio-energy areas**	**Research centre**		**Ksi**
Citizen	0.472	0.083	0.444		
Developer	0.542	0.292	0.166		0.042
Environmental expert	0.244	0.111	0.645		0.089
Municipality	0.166	0.292	0.542		0.042
Owner	0.575	0.325	0.1		0.075

	SPORT ACTIVITIES				
	Soccer/tennis etc. fields	**Skatepark/Roller rink**	**Outdoor equipment**	**Cycle path**	**Ksi**
Citizen	0.281	0.063	0.469	0.188	
Developer	0.041	0.443	0.258	0.258	0.072
Environmental expert	0.518	0.196	0.196	0.09	0.071
Municipality	0.076	0.245	0.245	0.434	0.057
Owner	0.278	0.463	0.074	0.185	0.093

	ORGANIZED SITES				
	Children & picnic area	**Dog park**	**Study spaces**	**Organized beaches**	**Ksi**
Citizen	0.433	0.433	0.078	0.057	
Developer	0.258	0.041	0.258	0.443	0.072
Environmental expert	0.197	0.089	0.196	0.518	0.071
Municipality	0.153	0.231	0.231	0.384	0.077
Owner	0.059	0.5	0.147	0.3	0.088

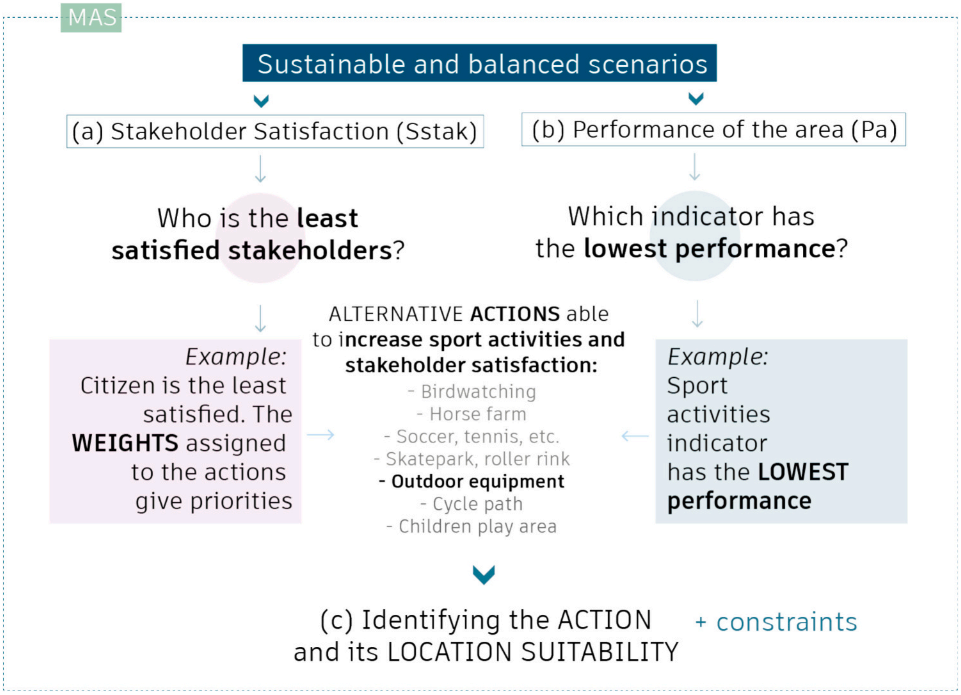

Fig. 6. Steps for the implementation of the model.

the area, in order to maintain it in good condition over the long-term. The developer prefers activities that have the potential to generate income, such as sporting facilities, in comparison to activities that are more closely associated with the natural environment. In contrast, the environmental expert is interested in the promotion of natural activities in opposition to impermeable areas. Similarly, the municipality prioritizes the provision of spaces for all residents, whereas the owner perceives the need of incorporating individuals engaged in socio-educational activities to stimulate interest in the area.

3.2.3. *Third phase: scenario building*

Once the preferences of activities and actions have been defined by the relevant stakeholders through BWM, it is possible to proceed to the next stage, the MAS. The present work uses the open-source software Netlogo 6.1.1 to implement the MAS. Due to the complexity and the multiple perspectives involved in the transformation of the area, the objective of this MAS is to build the transformation alternatives taking into account the sustainability of the area and the preferences of the stakeholders. To do this, the model has been designed in such a way as to enhance both the overall sustainable performance of the area, and the satisfaction of the different stakeholders. The combination of these two parts makes it possible to identify the effective actions in terms of sustainability, as well as in terms of the stakeholders' needs. Moreover, the model incorporates detailed data to select the location that is the most suitable, considering the past uses of the area.

Three phases are repeated in the model in each time iteration[1] (Fig. 6). Each of these phases is described in detail below and synthetized here as follows:

a) To increase the satisfaction of the stakeholders, the model finds the stakeholder that is least satisfied by the actions implemented in the area;
b) To increasing the overall sustainability of the area, the model selects the indicators (presented for the first time below) with the lowest performance;
c) Once the first two phases ((a) and (b)) have been completed, the model identifies the action that achieves (a) and (b), and then starts to search for the most suitable location for this action.

In particular, Fig. 6 shows the three phases executed in each iteration and presents an example of the action activated (i.e., outdoor equipment) according to the stakeholder least satisfied (e.g., citizen) and the indicators with the lowest sustainability performance (sport activities).

a) **Increasing the satisfaction of the stakeholders (stakeholders satisfaction function)**

To identify the stakeholders who are the least satisfied, the model employs the use of an individual satisfaction function for each stakeholder involved. The satisfaction function expresses the level of satisfaction experienced by the stakeholder with regard to the transformation of the area. This is calculated as the weighted sum of all activities and related actions (see activities and actions in 3.2.2) when activated in the area. The satisfaction function is formally expressed as follows:

$$S_j = \sum_{z}^{Z} w_{jz} a_z$$

$$w_{jz} = v_{ij} w^{*}_{jz}$$

Where v_{ij} is the weight of an activity (Table 2), w^{*}_{jz} is the local weight of an action (Table 3) within an activity, w_{jz} is the global weight of an action, a_z is a binary variable indicating whether an action is activated ($a_z = 1$) or not activated ($az = 0$), and *i, j,* and *z* are indices for activities, stakeholders, and actions, respectively.

---

[1] The MAS employs a procedure that involves the completion of the three phases (a; b; c) within a single iteration (hereafter also called tick). Upon the conclusion of these three phases, the model initiates a subsequent iteration, maintaining the same underlying logic, but incorporating the data accumulated during the previous iterations. The model may then terminate in accordance with the conditions outlined in Section 4.

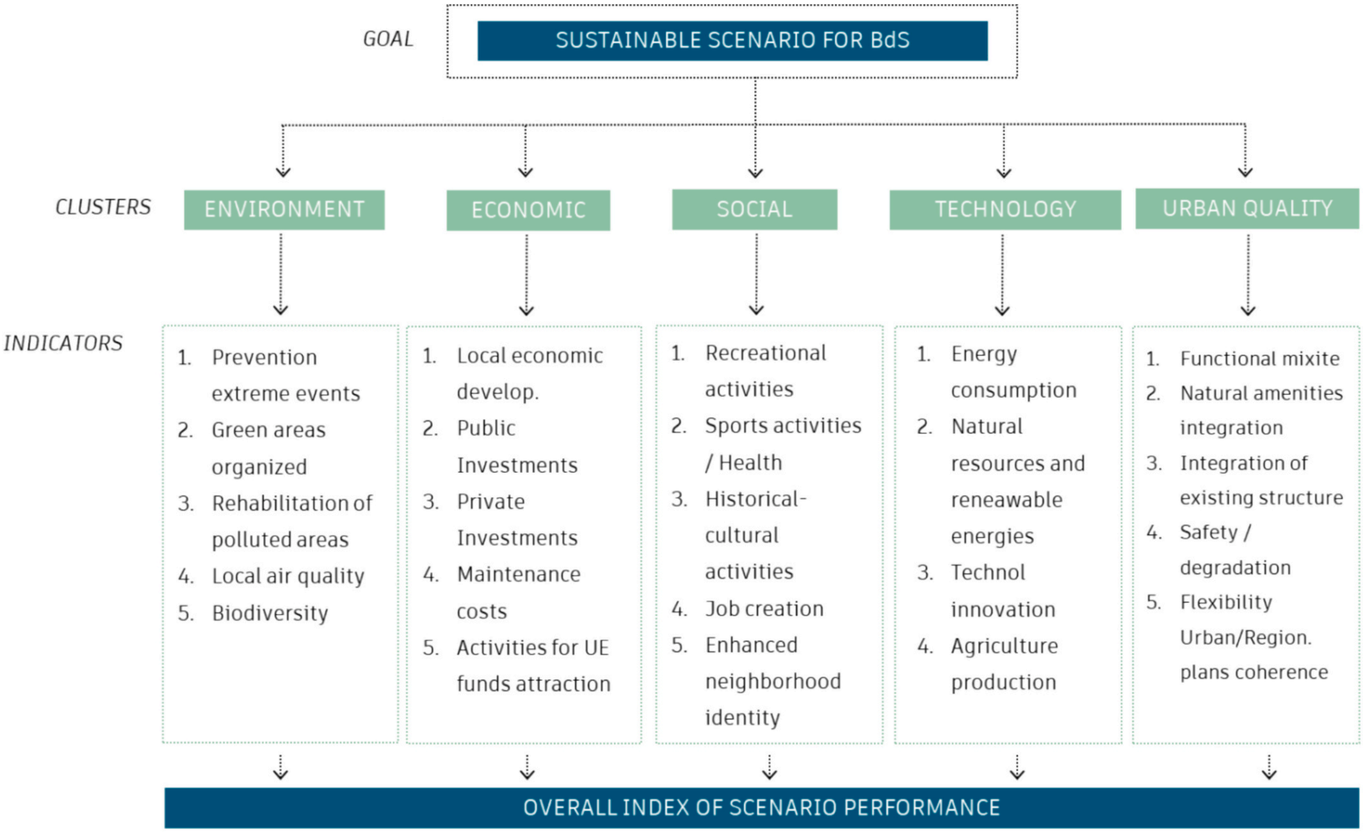

Fig. 7. The hierarchic structure of clusters and indicators.

b) **Increasing the overall sustainability of the area (performance of the area)**

To achieve the highest sustainability performance of the area, a set of indicators has to be considered to evaluate the ongoing implementation of the scenarios in MAS. These indicators result from a literature review,[2] and are then screened according to the knowledge acquired from the SWOT and the SA. The final list consists of 24 indicators, clustered into 5 clusters. The hierarchical structure of the evaluation is presented in Fig. 7, which illustrates the evaluation goal, the clusters, and the indicators.

Once the indicators have been identified, it is necessary to calculate their performance in each iteration and, subsequently, to determine the overall sustainable index. However, it is important to make a distinction between the sustainable index calculated in the initial iteration (referred to as P_0) and those assessed in the subsequent iterations (designated as P_1). It should be noted that no actions have been yet implemented in the first iteration, and thus the sustainable index P_0 is calculated for the BAU scenario. In contrast, the indexes P_1 are measured according to new land uses, which are based on the actions implemented in each iteration and the surface area covered by these actions. Accordingly, the calculation of P_1 does not take into account the historical land uses patterns associated with the BAU.

In order to calculate the indices P_0 and P_1, the performance of all the indicators in question must be evaluated. The performance of the indicators is also calculated in different ways according to the moment of the iteration of the simulation (P_0 or P_1). As detailed in the Supplementary materials, Table S.1 presents the unit of measurement and the calculation method of the performance of each indicator respectively in iteration 1 (T_0 performance) and in the subsequent iterations (T_1 performance). Moreover, it provides the standardization of the indicator performances. This is useful to enhance the comparison of the performances of all indicators, originally expressed in different units of measurement.

The calculation of the performance of the indicators is contingent upon the actions that are built in each iteration. Therefore, it has required the identification of the actions capable of increasing each indicator and to quantify this increase. For this purpose, a matrix (Table S.2 in the Supplementary materials) was built in collaboration with the expert panel.

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[2] The literature review searched for the main indicators used in MCDA for the evaluation of urban transformation. The analysis consisted in the consultation of the database Scopus in November 2024, using the following keywords: TITLE-ABS-KEY ("multicriteria" AND "sustainability" AND ("urban development" OR "urban transformation" OR "urban regeneration")). 92 documents result from this research, but only those written after 2015 are investigated more in-depth (i.e., 73 documents). This temporal limit has the aim of considering only manuscripts that can be influenced by the SDG framework set up in 2015. Another selection is then made according to the topic. It was specifically excluded those articles that dealt with the spatial location of facilities, or whose topic was completely different (hazard, coastal flow, etc.), or when they considered other scales of analysis (e.g., buildings or entire cities). 15 documents are finally used for the identification of the indicators (Abastante et al., 2022; Ali-Toudert et al., 2020; Anastasiadou and Gavanas, 2023; Berta et al., 2018; Bisello, 2020; Bottero et al., 2018, 2019; Caldatto et al., 2021; Della Spina, 2020; Della Spina et al., 2016; Della Spina and Rugolo, 2021; Feleki et al., 2020; Nikoloudis et al., 2020; Nogués and Arroyo, 2016; Ustaoglu and Aydınoglu, 2020).Moreover, the final list indicators are screened according to the knowledge acquired from the SWOT and the SA. The indicators specifically related to the architectural implementation and managing of the actions were deliberatively excluded, despite their potential significance in achieving sustainability goals, such as the management of waste collection, water reuse, or the installation of eco-products. These indicators are too specific for our level of analysis. Moreover, all indicators linked to the proximity of services and transportation were excluded from the evaluation, as they are independent from the transformation of the area.

This stage is of particular importance, as the selection of the action is not only a function of the stakeholder preferences, but also contingent upon the low level of performance of some indicator. Indeed, the model identifies, for each iteration, the indicators exhibiting the lowest performance level across the full range of indicators and it proposes them to the stakeholder in each iteration. This latter aspect allows the stakeholders to select the most preferential action from the set of potential actions that could improve the indicators with the lowest performance level.

c) Identifying the actions and their location

At this stage, the model is able to identifying the stakeholder with the lowest preference function and the indicator with the lowest performance. The stakeholder thus selects the action that is most preferred, among the set of actions that increases the sustainable index of the area. The action most preferred by the stakeholder is that which exhibits the highest values, considering both the weights assigned to the activities and the actions. For example, the most preferred action for the environmental expert is the construction of the nature trails, as this activity was assigned the highest weights among the natural activities, which are the preferred activity.

Once, the action is identified, the next step is to identify a suitable location. The selection of a suitable location is based on five considerations.

- The first constraint pertains to the feasibility of developing new land uses. This aspect implies that areas already implemented with actions are no longer available options.
- The second aspect concerns the locational suitability of the proposed actions. As shown in Table 4 and with the assistance of a panel of experts, a suitability gradient was assigned between the original land uses of the BAU scenario (in the columns) and the potential new action proposed (in the rows). In Table 4, the colours indicate respectively the highest suitability (green), the medium suitability (yellow), and the lowest suitability (red).
- The third aspect considers the proximity of the new action to other suitable actions. In order to place the action to be implemented in close proximity to the most suitable actions, the model selects the area with the highest number of suitable actions in the vicinity. Similarly to the second constraint, a table containing the level of suitability of the actions in proximity to one another was developed in collaboration with the expert panel, as illustrated in Table 5. In Table 5, the symbol "+" indicates a positive compatibility, 0 represents a neutral relationship, and "–"denotes a negative match.
- The fourth aspect considers the surface to be covered by each action. The minimum and maximum surface values for each action are based on a preliminary analysis of existing case studies or prototypes (see Table S.3 contained in the Supplementary Materials). In the simulation, the surface is randomly assigned a value that falls within the specified minimum and maximum range.
- The fifth constraint may eventually occur in two distinct circumstances. The first circumstance arises when it is necessary to implement a buildable action. In this case, two factors require consideration: the territorial index and the hydrogeological bands. With regard to the first factor, the model selects the available areas with the highest territorial index, without however excluding the others. With regard to the second factor, all areas falling within the specified hydrogeological bands are automatically excluded from the selection process. The second circumstance occurs when the designation of private or public ownership is a prerequisite. In such case, the model priorities the parcels displaying the desired ownership,

Table 4
Land uses suitability compared to the BAU scenario.

	Agriculture	Green area	Unculture pasture	Wood	Riverbank	Lake/River	Landfill	Road/Built	Residential	Commercial/ Industrial
SE1 - Farm school	🟩	🟩	🟩	🟨	🟥	🟥	🟥	🟥	🟥	🟥
SE2 -Educational tours	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
SE3 -Social hub	🟨	🟨	🟨	🟨	🟥	🟥	🟨	🟩	🟩	🟩
SE4 -Allotments	🟩	🟩	🟩	🟨	🟨	🟥	🟥	🟥	🟥	🟥
NA1 -Nature trails	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥
NA2- Birdwatching	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥
NA3 -Butterflies	🟩	🟩	🟩	🟩	🟩	🟥	🟨	🟥	🟥	🟥
N4 - Horse farm	🟩	🟩	🟩	🟩	🟩	🟥	🟨	🟨	🟥	🟥
BE1 - No food crops	🟩	🟩	🟩	🟨	🟨	🟥	🟨	🟥	🟥	🟥
BE2 - Bio-energies	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
BE3 - Research center	🟨	🟨	🟨	🟨	🟥	🟥	🟩	🟩	🟩	🟩
SA1 -Soccer/tennis fields	🟩	🟩	🟩	🟨	🟨	🟥	🟩	🟩	🟩	🟩
SA2 -Skatepark/roller rink	🟩	🟩	🟩	🟨	🟨	🟥	🟩	🟩	🟩	🟩
SA3 -Outdoor equipment	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟩	🟥	🟥
SA4 - Cycle paths	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩
OS1 -Child area	🟩	🟩	🟩	🟩	🟩	🟥	🟨	🟨	🟥	🟥
OS2 - Dog area	🟩	🟩	🟩	🟩	🟩	🟥	🟨	🟥	🟥	🟥
OS3 - Study area	🟩	🟩	🟩	🟩	🟩	🟥	🟨	🟥	🟥	🟥
OS4 - Organized beach	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥

Table 5
Land uses suitability among the actions.

	SE1	SE2	SE3	SE4	NA1	NA2	NA3	NA4	BE1	BE2	BE3	SA1	SA2	SA3	SA4	OS1	OS2	OS3	OS4
SE1 - Farm school		+	+	+	+	+	+	+	+	-	-	0	0	0	+	+	-	+	0
SE2 - Educational tours	+		+	+	+	+	+	+	+	-	+	0	0	0	+	+	0	+	0
SE3 -Social hub	+	+		+	+	+	+	+	+	-	0	+	+	+	+	+	+	+	+
SE4 - Allotments	+	+	+		+	+	+	0	+	0	0	0	0	0	0	0	0	0	0
NA1 - Nature trails	+	+	+	+		+	+	+	+	-	-	-	-	0	+	+	-	0	0
NA2-Birdwatching	+	+	0	+	+		+	+	+	-	-	-	-	0	+	+	-	0	0
NA3 - Butterflies	+	+	0	+	+	+		+	+	-	-	+	+	+	+	+	+	0	+
N4 - Horse farm	+	+	0	+	+	+	+		0	-	-	+	+	+	+	+	-	0	0
BE1 - No food crops	+	+	0	+	+	0	0	0		+	+	0	0	0	0	0	0	0	0
BE2 - Bio-energies	0	0	0	0	0	0	0	0	0		+	0	0	0	0	0	0	0	0
BE3 - Research center	+	+	0	+	+	0	+	0	+	+		+	+	+	+	0	0	+	+
SA1 - Soccer/tennis fields	+	+	+	0	+	+	+	+	0	+	+		+	+	+	+	+	+	+
SA2 - Skatepark/roller rink	0	0	0	0	0	0	0	0	0	0	+	+		+	+	+	+	+	+
SA3 - Outdoor equipment	+	0	+	0	+	0	0	+	0	-	0	+	+		+	+	+	+	+
SA4 - Cycle paths	+	+	+	+	+	+	+	+	+	-	+	+	+	+		+	+	+	+
OS1 - Child area	+	+	+	+	+	+	+	+	+	-	0	+	+	+	+		+	+	+
OS2 - Dog area	0	0	0	0	0	0	0	-	0	0	0	0	0	0	0	+		0	0
OS3 - Study area	+	+	+	0	+	+	+	+	+	+	+	+	+	+	+	0	0		+
OS4 - Organized beach	+	+	+	0	+	+	+	+	+	-	+	+	+	+	+	+	+	+	

without however excluding the others. One illustrative example of this last circumstance is that of the cycle paths, which are implementable if situated within public property areas.

4. Results and discussion

The model was executed many times within the same experiment, with the stop conditions varying on each occasion. The stop conditions are contingent upon the complete transformation of the area under analysis. This can occur in the model in a number of ways, including:

(i) when all the actions (i.e., 19) have been completed;
(ii) if one or more stakeholders are completely satisfied with the transformation ($S_j = 1$);
(iii) when the entire surface has been completely transformed;
(iv) a combination of (i), (ii) and (iii).

The software generated the same graphical representation and output data for all the stop conditions. With regard to the graphical representation, at the end of each simulation, the model is prompted to display the location of the actions and their extensions within the Netlogo interface, through the use of a designated color. The interface generates the abstract representation shown in Fig. 8. The use of different color to highlight specific areas was employed with the intention of facilitating the comprehesion of the action implemented, its locations and extent. The yellow lines represent the links that connect actions and indicators, as well as stakeholders and actions.

As anticipated in Section 3.2.3, the model functions on a step-by-step basis, whereby each iteration represents a discrete unit of work. Once all the procedures have been completed (i.e., (a), (b) and (c)) within a given iteration and the data have been recorded, the model starts a subsequent iteration, applying the same logic.

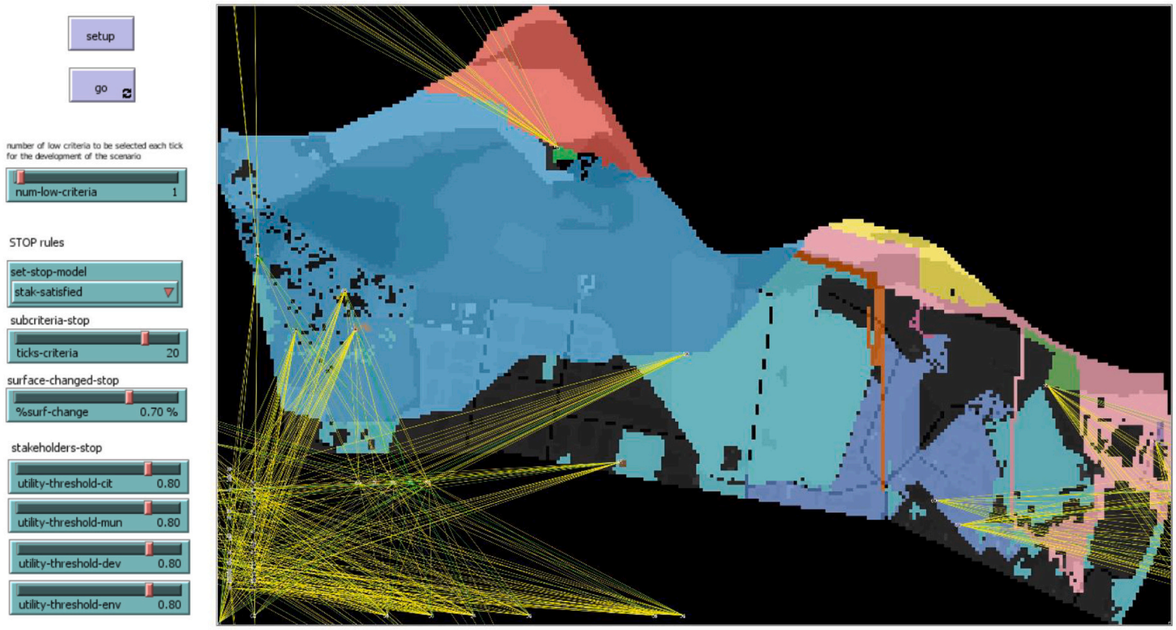
Concerning the output data, the information collected and recorded for each iteration is as follows:

- the BAU sustainable performance index at time 0 (P_0);
- the scenario sustainable performance index at time higher than 0 (P_1);
- the satisfaction functions of the stakeholders (S_j);
- the stakeholder who decides on the action in the step;
- the action activated in the step;
- the surface covered by the activated action.

These data are useful to monitor the ongoing simulation process, which is characterized by interactions among stakeholders, sustainable performance, and environmental context data. Furthermore, they provide a comprehensive overview of the effectiveness of the scenarios generated in the various runs. It should be noted that the model does not present a single optimal solution; rather, it offers a range of sustainable and balanced scenarios. These scenarios require further examination in order to ascertain their final performances in terms of stakeholder satisfaction and the sustainable achievement of the transformation. The following sections present a selection of results obtained from the data analysis.

Firstly, the common result of all the simulation is related to the BAU sustainable performance index (P_0), which is equal to 0.14. The objective of each iteration, which comprises all the simulations, is to increase this value by proposing transformation scenarios for achieving the overall sustainability of the area. Fig. 9 shows an example of a simulation, where it is possible to see the evolution of P_1 (orange) compared to P_0 (grey). For P_1, the top of the columns represents the performance value obtained in the iteration, composed of the value obtained in the previous iteration (dark orange) and the incremental value (light orange) after the implementation of a new action. This simulation run is neither the best nor the worst in terms of P_1, but simply shows an exemplary result of the model developed.

As illustrated in Fig. 9, P_1 overcomes P_0 only after tick 7. As mentioned in Section 3.2.3, this occurs because P_1 exclusively considers the contribution of the actions without incorporating the influence of the BAU land use. Furthermore, Fig. 9 clearly shows the extent to which each step contributes to the enhancement of the overall sustainability of the area. Consequently, the creation of a comprehensive scenario, comprising the combination of actions, is the only means of genuinely



number of low criteria to be selected each tick for the development of the scenario
num-low-criteria 1

STOP rules

set-stop-model: stak-satisfied

subcriteria-stop
ticks-criteria 20

surface-changed-stop
%surf-change 0.70 %

stakeholders-stop
utility-threshold-cit 0.80
utility-threshold-mun 0.80
utility-threshold-dev 0.80
utility-threshold-env 0.80

Legend

Farm school	6	Horse farm	76	Outdoor equipment	136
Educational tours	16	No food crops	86	Cycle paths	24
Social hub	26	Bio-energies	96	Child area	34
Allotments	36	Research center	106	Dog area	44
Nature trails	46	Soccer/tennis fields	116	Study area	64
Birdwatching	56	Skatepark/roller rink	126	Organized beach	94
Butterflies	66				

Fig. 8. Graphical representation of an exemplary scenario developed in Netlogo.

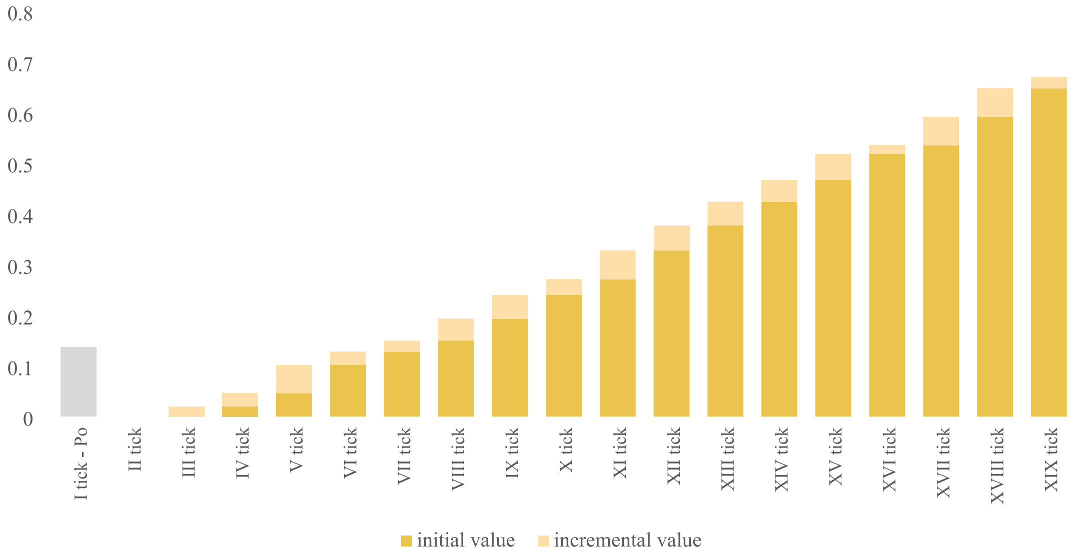


Fig. 9. Performances obtained for an exemplary scenario in each iteration.

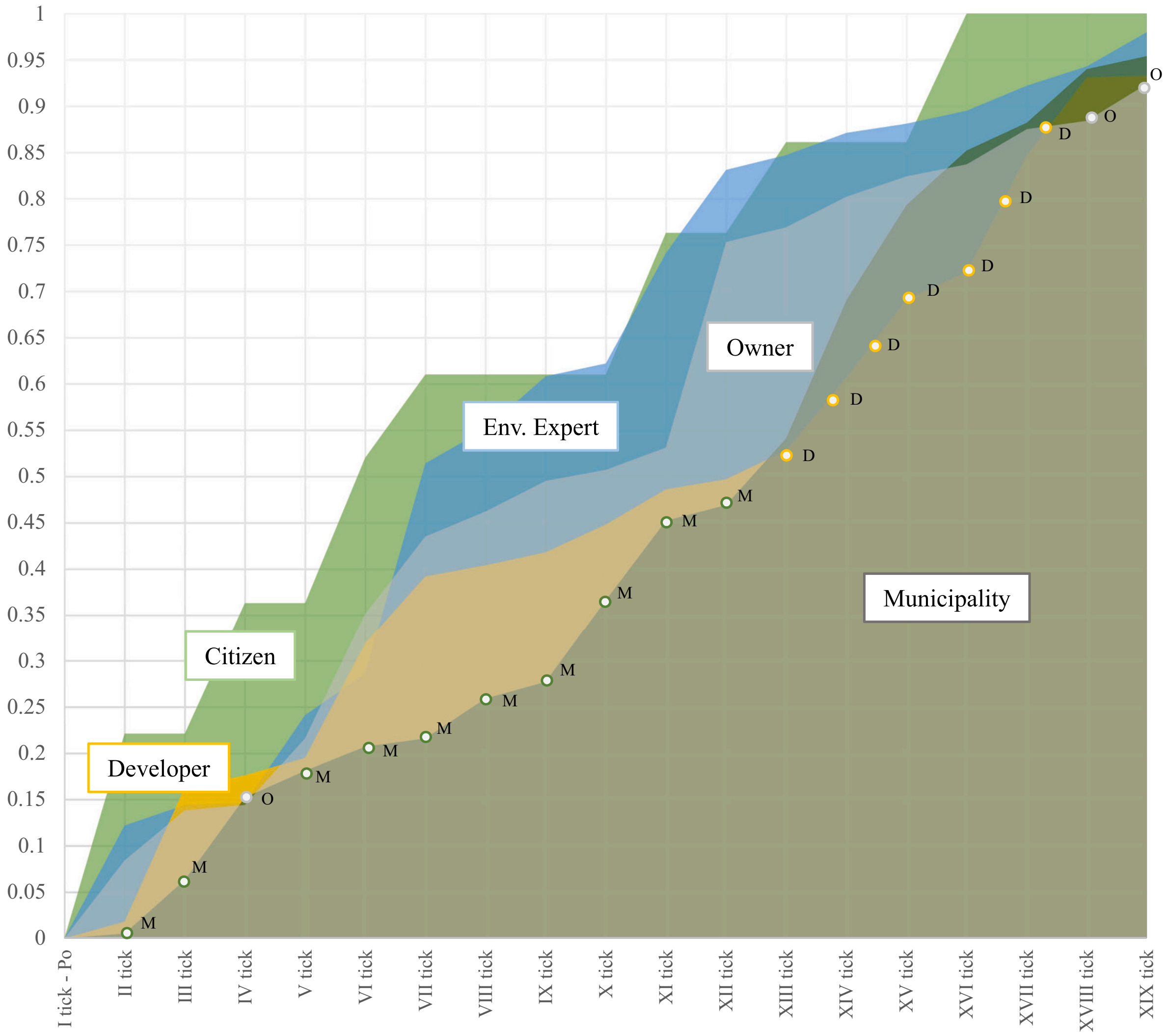


Fig. 10. Stakeholder preference functions obtained for an exemplary scenario in each iteration.

enhancing the quality of the area.

The results of the stakeholder preference functions for the same simulation are presented in Fig. 10. The areas illustrate the increase in stakeholder satisfaction. The circles and letters indicate the stakeholder with the lowest level of satisfaction, who selects an action in the specific iteration.

This exemplary case study demonstrates that stakeholders' satisfaction (Fig. 10) and the sustainable index achieve high levels (Fig. 9). These two aspects are inextricably linked, as the first one is connected to the second. Indeed, the least satisfied stakeholder chooses an action that meets their preferences and, at the same time, improves a low performance indicator, which serves to achieve the sustainability of the scenarios.

A comparison of the results obtained from the application of the various stop rules reveals that they yield comparable outcomes. In the case of the first stop rule, the number of activated actions is, in general, no less than 17. This occurs when actions 58 and 59 are activated as the final options and are unable to identify sufficient surfaces to accommodate the entire requested extension. Similarly, this phenomenon occurs with the third stop rule, where the rationale for halting the simulation is associated with the completion of a significant portion of the total area (specifically, 70 %). For the second stop rule, related to the satisfaction of the stakeholders, the levels of the satisfaction functions are not so high to stop the simulation in one of the first iteration. Indeed, the way in which the MAS was constructed ensures a balance between the satisfaction of the stakeholders, preventing the prioritisation of any one over the others. Consequently, the simulation continues for at least 14/15 iteration. The fourth rule, which is the combination of the second and the fourth stop rules, produces outcomes that are highly similar to those of the previous rules.

Table 6 presents the results of an high performing scenario, both in terms of the sustainability index achieved and level of stakeholder satisfaction. It is worth mentioning that this scenario is the best performing of the simulation runs, although it is unclear whether it represents the most efficient solution. This raises an issue that is inherent in many evaluation methods, including MCDA, where alternatives generated are considered as satisfactory and justified rather than optimal (Ferretti, 2012; Simon, 1960). The consideration of satisfactory and justified solutions means that the generation of alternative scenarios stops when the DM is satisfied, and certain thresholds defined at the beginning are reached. In this study, the model stops when satisfaction reaches 0.90 or above for all the stakeholders and a sustainability index equal or above 0.7. In a real decision process, it could be useful to ask the DM to define the model stop conditions, in order to generate alternative scenarios that directly follow DM's preferences. It was out of the scope of this study to find a large number of scenarios that offer greater efficiency. There are two reasons for this: firstly, there is not a client asking for specific outcomes from the evaluation; secondly, the aim of this work is to test the potential of the integrated approach. Of course, this implies that the more simulations run, the less likely it is that scenarios with higher efficiencies will be excluded.

Considering the scenario of Table 6, the actions implemented in the area and their extension are summarized in Table 7. This table also indicates the activation of the actions in the simulation. Furthermore, this insight may beneficial to identify in the different simulations the most relevant actions to be implemented.

Table 6
Results from the most performing scenario simulated.

Tick	Performance	Stakeholder	Satisfaction function
1	0.14	Citizen	0
		Env. expert	0
		Developer	0
		Municipality	0
		Owner	0
19	0.70	**Citizen**	1.00
		Env. expert	0.943
		Developer	0.99
		Municipality	0.98
		Owner	0.97

Table 7
Actions implemented in the most performing scenario simulated.

Tick	Action	Surface (sqm)	Tick	Action	Surface (sqm)
1	Outdoor equipment	65,600	11	Farm school	46,000
2	Bio-energies	215,700	12	Study area	500
3	Horse farm	900	13	Birdwatching	18,400
4	Butterflies	3100	14	Educational tours	155,200
5	Organized beach	26,600	15	Cycle paths	52,900
6	No food crops	1,067,400	16	Child area	300
7	Nature trails	8200	17	Skatepark/roller rink	1700
8	Dog area	300	18	Social hub	1600
9	Research centre	84,500	19	Soccer/tennis fields	250,000
10	Allotments	4600			

5. Conclusions

This paper proposed a mixed method that combined a spatially explicit MAS, informed by preliminary analysis (SWOT and SA) and a multicriteria method (i.e., BWM).

The applicability of the mixed-method was tested in an area of the city of Turin (Northern Italy), where a complex array of social, environmental, and economic factors are affecting its transformation. Besides the specificity of the case study under analysis, the work presented a generalizable integrated approach that can be replicated for other planning and management purposes. In particular, the mixed-method explored the generation of scenarios built according to stakeholder preferences and from a sustainable perspective. The bottom-up perspective, based on stakeholder preferences, facilitated the salience, credibility, evidentiary basis, and legitimacy of the decision. Concurrently, the set of indicators and the evaluation of their performance made it possible the realization of sustainable scenarios.

In the first stage of the process, the application of SWOT and SA supported the collection of the relevant data concerning the area under analysis and the different perspectives of the stakeholders involved in this decision-making process. In the second step, MCDA was employed to elicit stakeholders' preferences regarding a set of potential actions to be implemented in the area under analysis. In particular, BWM was perceived by the stakeholders as an intuitive method for selecting preferred options for planning and transformation. This outcome can be seen as relevant in the specific context of EIA, where there are often several variables to be considered. The reduction in the number of comparisons required to develop the BWM compared to other MCDA is particularly useful in this context. In addition, the choice between the best and worst aspect provides a more intuitive decision-making process for the different stakeholders involved. In the final step, the combination of the citizens and stakeholders satisfaction (using BWM weights) with the achievement of overall sustainable solutions is provided by MAS. In particular, the sustainable solutions are grounded on a set of multi-dimensional indicators to be increased and the suitable location of the new actions on the area.

However, some improvements can be made. As for MAS, the selection of a suitable area for the implementation of actions can be made using probability functions, as proposed by Tian et al. (2011). Some opportunities for expanding the results of the present study can be found in the estimation of action frequencies within the generated scenarios, as well as the identification of parameter costs associated with each action. A further improvement would be to restrict the number of actions that are implemented. This approach will facilitate the presentation of more reliable scenarios to DMs and stakeholders. Concurrently, this can assist in elucidating the priority actions to be implemented and those most frequently selected across the various scenarios. Additionally, the DM could be involved at the beginning of the process to define the stop conditions and the threshold to be reached in terms of stakeholder satisfaction and the sustainable index of the area. Furthermore, a potential future development would entail the selection of the initial stakeholder. At present, the model randomly selects one of the stakeholders at the outset of the simulation. The examination of the same stakeholder in numerous simulations can yield insights into the similarities and differences between the scenarios created according to the initial stakeholder involved. Also, the model could be modified to consider the individual opinions of the citizens without aggregating the BWM responses. The use of individual preferences rather than the average could be the basis for further sensitivity analysis, which represents a fundamental step in MCDA. Nevertheless, the adoption of multiple optimal solution weights obtained through BWM could be explored to analyze differences and similarities in the final scenarios.

Besides these limits, the proposed approach represents one of the initial attempts to focus on the design of alternatives rather than their evaluation from a predefined set of options. This approach can be readily applied to other case studies by adapting the actions, indicators, spatial data, and stakeholders weights to align with the specific case study, as is typical in all MCDA.

A promising avenue for further inquiry is the evaluation of targeted improvement actions at the district and urban levels. These could include the expansion of infrastructural connections, the introduction of enhancement of primary or supplementary services designed to improve citizens' quality of life, the reposition of certain facilities (such as hospitals) and the modeling of spatial distribution of existing and projected ecosystem services. These proposals could also exploit the dynamic capabilities of MAS and agent-based model.

CRediT authorship contribution statement

Caterina Caprioli: Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2025.107855.

Data availability

Data will be made available on request.

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