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ORIGINAL RESEARCH

Constructing smarter and more sustainable urban ecosystems: a dynamic analysis of challenges and initiatives

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Abstract

Cities' weaknesses have been revealed by their struggle to respond to current challenges (*e.g.*, pandemic crises and population and urbanization exponential growth). Urban planners are thus increasingly concerned about implementing initiatives in their metropolises that favor a better present and future quality of life. In this context, cities need to become enablers of economic and social development and increased prosperity through the integration of technologies into projects promoting smarter and more sustainable urban ecosystems. These ecosystems are, however, highly complex due to their specificities and multifaceted nature, which makes analyzing them a difficult endeavor. Based on a constructivist and complementarity logic, this study sought to develop a multicriteria analysis model to support relevant decision-making processes in this study context. A panel of experts was recruited to create the analysis system using a combination of cognitive mapping and the decision-making trial and evaluation laboratory technique in an neutrosophic context. This approach overcomes various flaws identified in previous related research. The entire procedure focused on enhancing the experts' learning through participation not only to structure the problem under analysis but also to identify and prioritize the factors and/or determinants of smartness and urban sustainability. The model provides a holistic, solid, and clear vision of the decision problem that fosters appropriate choices when creating and evaluating smart, sustainable urban ecosystems.

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1 Introduction

Over half of the world's population currently lives in urban areas. Experts expect a further exponential increase in population and urbanization (United Nations (UN), 2020), which requires a stronger focus on living conditions in cities. Metropolises face numerous challenges that jeopardize both these urban areas' development and their current and future ability to provide citizens with an adequate quality of life. This situation means that urban planners urgently need to understand and organize their cities and provide creative solutions that make them more livable.

Municipalities should be treated as urban ecosystems capable of combining natural and built environments, integrating technologies that improve people's way of life, and continuously supporting long-term sustainability (Mouratidis, 2021). This approach creates smart, sustainable urban ecosystems, yet no clear consensus exists on which factors influence the development of smart, sustainable cities because of this topic's complexity and wide scope. To ensure a better quality of life, more livable environment, and more solid economic prospects for metropolises, researchers need to reflect more deeply on urban ecosystems' dynamics and understand their challenges and the initiatives that facilitate the development of these environments.

Urban ecosystems have been extensively analyzed and assessed, but the various evaluation methods available suffer from limitations. These include: (1) the unclear way in which evaluation criteria are identified and defined (Barão et al., 2021; Pinto et al., 2022); (2) a failure to identify these criteria's relevance to smart, sustainable urban ecosystems' construction; and (3) the absence of analyses of the dynamics of cause-effect relationships between the criteria (Ferreira et al., 2022). These past limitations can serve as catalysts for future research that expands the existing knowledge and provides opportunities for improvement. To address these general limitations, the present study sought to strengthen decision makers' ability to understand which determining factors have to be considered while creating and/or analyzing smart, sustainable urban ecosystems. Two research questions were addressed:

- How can decision makers identify the key initiatives that contribute to and/or shape conceptualizations of smart, sustainable urban ecosystems?
- Which determinants have a significant impact on—and thus should be prioritized during—the development and analysis of these ecosystems?

To this end, the present research applied the strategic options development analysis (SODA) method to simplify the application of cognitive mapping and decision-making trial and evaluation laboratory (DEMATEL) techniques in a neutrosophic environment. The goal was to help experts examine the dynamics of causal relationships between determining factors, deal with uncertainty, and express their ideas more accurately during the decision-making process (Abdel-Basset et al., 2018). The current study adopted a constructivist stance (*i.e.*, a process-oriented approach based on learning through participation), so the combined methodology could facilitate the formulation of a consensus around recommended solutions. The results thus offer a more complete, detailed, and self-evident view of the decision problem under analysis.

The methodologies were applied during two online group sessions due to restrictions related to the coronavirus disease-19 pandemic, with a panel of experts on relevant subjects.

These sessions promoted group interactions and open discussions about how to structure the factors affecting smart, sustainable urban ecosystems' development, thereby providing the necessary input for the creation of a group cognitive map. Subsequently, the DEMATEL technique helped the decision-maker panel examine the key factors' cause-and-effect relationships in the context of smart, sustainable cities and conduct the respective neutrosophic assessments. The present research, therefore, combined DEMATEL and neutrosophic logic for the first time to facilitate a study of smart, sustainable urban ecosystems. This novel methodological framework contributes to the literature on operational research/management science (OR/MS), on the assessment of this type of ecosystems, and encourages future investigations of the decision problem in question.

This paper is organized into five sections. The next section presents a literature review of the conceptualization of smart, sustainable urban ecosystems and some supporting approaches, after which the research gaps and theoretical framework are discussed. The third section explains the methodologies adopted. The fourth follows up with the methodological application and main results. The final section concludes the paper by explaining the insights gained and offering recommendations for future research.

2 Related literature and research gaps

The term ecosystem was initially used only to designate a system composed of living organisms and their environment (Tansley, 1935). This concept is now closely linked to urbanized areas as it is frequently associated with cities. Urban ecosystems' distinctive, multifaceted nature means that they are highly complex (European Commission, 2020). In addition, increasingly dense social, environmental, and economic contexts currently affect cities (Rzevski et al., 2020; Vieira et al., 2022), so researchers' interest in analyzing these ecosystems' metabolism and urban ecology has grown noticeably. Thus, treating cities as ecosystems appears to have become a fundamental part of urban planning.

Urban ecosystems are widely believed to be associated entirely with cities and their surroundings. However, the European Union (2020) more broadly defines this concept as a socio-ecological system in which most populations live, which has two dimensions. The first is green infrastructure (*i.e.*, strategically planned networks of natural areas), while the second is built infrastructure (*i.e.*, houses, buildings, roads, bridges, industrial and commercial areas, and construction sites). The importance of urban ecosystems continues to increase as populations and urbanization have expanded. The UN (2020) estimates that more than half of the world's population currently resides in urban areas. Population growth is also expected to occur exclusively in metropolitan areas (UN, 2020). These trends have generated an urgent need to create solutions that allow urban planners to understand their cities and organize them into more livable environments (Allam & Newman, 2018).

The smart city concept emerged in response to this challenge. Despite being a relatively recent concept, it has quickly gained importance due to governments' interest in creating smarter metropolises (Shamsuzzoha et al., 2021). According to the Institute for Management Development (2016), the term smart city describes residential areas that apply technologies to enhance urbanization's benefits and reduce its challenges. The literature, however, shows that no consensus exists on the conceptualization of smartness in urban contexts (Mora et al., 2017).

Cities are vital to achieving sustainable development goals as these areas are the main catalysts for economic development and increased prosperity (Castanho et al., 2021). Human capital development, in particular, is crucial for economic sustainability to be achieved. In this sense, well-planned and managed cities can offer improved social value and promote environmental sustainability. For metropolises to be sustainable, they must be planned, developed, and administered so that they provide economic, social, and environmental benefits, and thus improve their residents' quality of life. Smart, sustainable cities are urban entities capable of integrating social and digital technologies into processes and coordinating the existing knowledge to overcome economic, social, and environmental challenges that affect municipalities' long-term viability (Hara et al., 2016). According to Gil-Garcia et al. (2015), cities become smarter when they are able to combine natural and built environments, with a focus on achieving long-term sustainability. Smart cities also need a solid government that provides residents with adequate, secure support systems through effective administration and timely public services. Gil-Garcia et al. (2015), however, argue that these measures are useless if the residents are not involved. Municipality smartness depends on the community's willingness to *"accept and actively promote a self-sustainable economic policy, that can be harnessed through* [the] *constant participation of local associations, crowdfunding projects and other initiatives aimed at enhancing human capital"* (Cappellaro et al., 2019, p. 161).

Cities must increasingly be treated as urban ecosystems capable of offering countless benefits to all members of society. Measures should be implemented that make metropolises smarter and more sustainable, which appears to be crucial to creating cities that provide a better quality of life, a more livable environment, and stronger economic prospects. Given the current rapid rate of urbanization, varied projects have already been developed to make cities smarter and more sustainable in response to many urban problems. These adjustments of urban environments require planners to overcome numerous challenges by implementing appropriate initiatives. Thus, smart city initiatives are a long process that involves different components of urban areas (Khan et al., 2020), but these efforts are extremely important to making urban environments smarter and more sustainable.

Assessments and analyses of smart, sustainable urban ecosystems must consider a broad set of indicators and variables, which makes these evaluations a complex task. Researchers have increasingly sought to identify which variables should be taken into consideration during analyses and how urban ecosystem assessments can be facilitated. Some studies have been summarized in Table 1, including their corresponding contributions and limitations.

An overall review of the existing literature and an analysis of Table 1 revealed that extensive research has been carried out in recent decades on how to analyze and assess urban ecosystems. However, three transversal limitations were detected in prior studies. First, the methods used to identify and define evaluation criteria were not clearly explained (Barão et al., 2021; Pinto et al., 2022). Second, researchers failed to specify the criteria's significance for smart, sustainable urban ecosystem development. Last, previous investigations lack analyses of the dynamics of the criteria's cause-effect relationships (Ferreira et al., 2022; Lemos et al., 2022). Despite these limitations, the extant studies have served as catalysts for additional research, which has expanded the current knowledge about this topic and offered opportunities for improvement.

The present study sought to meet the need for a different analysis model that can overcome the aforementioned limitations and that will contribute to better practices and substantive developments in smart, sustainable urban ecosystem assessment. This research took a constructivist, process-oriented position based on cognitive mapping and DEMATEL techniques applied in a neutrosophic environment. The aim was to identify concrete initiatives that help create and evaluate smart, sustainable urban ecosystems by using a multicriteria analysis system that addresses some of the limitations of previous investigations.

Table 1 Urban ecosystems studies: contributions and limitations

Authors	Methods	Contributions	Limitations
Dakhia and Berezowska-Azzag (2010)	Urban institutional and ecological footprint	The proposed instrument helps decision makers visualize ecological deficits within urban metabolisms The model covers energy, water, waste, materials, transportation, and built-up areas	The sample includes sectors that do not cover all dimensions of sustainability The instrument uses sectors that are not broad enough to offer a comprehensive understanding of which indicators contribute information on how to build sustainable urban ecosystems
Dizdaroglu et al. (2012)	Indexing model for assessment of sustainable urban ecosystems	The proposed approach assesses and monitors interactions between human activities and urban ecosystems, offering qualitative information on significant environmental problems The model provides a snapshot of the current environmental situation of different locations	The lack of data for some indicators forced the authors to make assumptions The instrument only covers environmental indicators The assessment of land use was done using remote sensors, so some lands' utility was not clearly identified
Mörtberg et al. (2013)	Land-use evolution and impact assessment model	The instrument developed evaluates the sustainability of urban development projects The indicators integrate urban ecosystems and urban systems, which is useful to decision makers	The model was only applied in the Stockholm area, which means the results cannot be generalized Relatively little information was used to develop the model, which reduces the credibility of results
Palumbo et al. (2021)	Bibliometric analysis and literature review	The results clarify the concepts of smart, sustainable urban ecosystems, and urban sustainability The findings contribute to the creation and organization of smart, sustainable urban ecosystems	The methodology used may take into account articles that were cited in other papers for negative reasons The methodology identified poorly discriminated clusters, which do not include causal relationships between the components The identified clusters have no practical applications

3 Methodological background

Problem solving and decision making are intrinsically linked. These processes are complex and require methods and systems that enable decision makers to manage complex decision problems. The decision-support tools used in the present study were applied in three main phases: (1) problem definition and structuring; (2) evaluation of potential action plans; and (3) definition of recommendations and implementation (Belton & Stewart, 2002).

The first phase involved cognitive mapping, which helped decision makers to identify and select the evaluation criteria to be incorporated in the model. In the second phase, the DEMATEL method was applied together with neutrosophic logic to analyze the criteria's interrelationships. During this process, a facilitator was present to ensure successful analyses by intervening as an impartial observer during the group work sessions. This person was not a specialist in the subject matter analyzed but was familiar with the techniques applied.

3.1 SODA approach, cognitive mapping, and neutrosophic logic

According to Keeney (1992), the decision-making process begins when a problem is recognized as an opportunity to reach good decisions rather than simply as an obstacle. For this reason, Rosenhead (1996) further suggests that decision makers need to consider problem structuring as fundamental to successful assessment processes since *"a well-structured problem is a problem half solved"* (Belton & Stewart, 2002, p. 35). Defining and structuring challenges facilitates the identification, characterization, and prioritization of the elements that need to be evaluated through a creative process of clarifying an initially perplexing problem (Ferreira, 2011). Several methods have been developed previously to help decision makers appropriately structure complex issues, which produce graphical representations of problems and construct more innovative solutions (for examples and details, see Rosenhead (1996) and Ackermann and Eden (2010)).

The current research relied on the SODA method to sustain and apply cognitive mapping. With the assistance of a facilitator, SODA was used to focus the group work sessions on individual actors and involve them in the decision-making process by allowing them to express their ideas and opinions about the problem in question. This method also seeks to ensure that the issue is fully analyzed and understood, including producing a graphical representation of the decision problem and acknowledging the individual experts' different perspectives during the entire process (Ackermann & Eden, 2010). As an integral part of SODA methodology, cognitive maps structure and visualize complex challenges. These maps help decision makers gain a fuller understanding of the relevant problem as they reflect on—and negotiate with each other over—which key criteria and/or determinants most influence the issue. Cognitive mapping is able to: (1) include qualitative variables; (2) structure complex decision situations; (3) support group work; and (4) facilitate the development and implementation of strategic solutions (Faria et al., 2018).

To represent problems more clearly, cognitive maps are based on *"short pieces of text linked with unidirectional arrows"* (Eden, 2004, p. 674). That is, these maps are composed of nodes (*i.e.*, concepts or statements) and arrows that reveal the causal relationship between the different concepts (Andrade et al., 2022; Village et al., 2013). Cognitive mapping is a process that encourages stakeholders to learn about the problem analyzed, understand the organization of decision makers' thought process, and obtain information about the issue at hand. Despite the method's clear advantages, the resulting maps do not include the intensity of causal relationships between concepts or take into account the uncertainty underlying these ideas. According to Agboola et al. (2012), the world is full of indeterminate situations that decision makers cannot ignore. Thus, various approaches have been proposed as a way to deal with this uncertainty. The present study specifically incorporated neutrosophic logic to address indeterminacy.

Neutrosophic logic is used *"to model phenomena that are not perfectly determined or known"* (Schweizer, 2020, p. 101) as this approach seeks to explore the origins and dimensions of neutrality to represent reality in a broader way (Smarandache, 2007). Neutrosophic logic states that each variable x (*i.e.*, the statement or criterion under analysis) can be described as having three components: (1) a degree of truth (T); (2) a degree of indeterminacy (I); and (3) a degree of falsity (F) (Kandasamy & Smarandache, 2003). The neutrosophic components T, I, and F are represented as standard or non-standard real subsets of [–0, + 1], in which T = [–0, + 1]; I = [–0, + 1]; F = [–0, + 1]. Thus, experts analyzing a multicriteria decision problem can respond to specific statements by expressing the probability that each statement is true (*e.g.*, $T = 0.6$), its degree of uncertainty (*e.g.*, $I = 0.4$), and its chances of being false (*e.g.*, $F = 0.1$). The experts' understanding of variable x in this case (*i.e.*, 0.6, 0.4, and 0.1) stresses that the T, I, and F percentages do not necessarily have to add up to 100%. In a final step, a mechanism is used to transform the three neutrosophic components (*i.e.*, T, I, F) into a single value (*i.e.*, crispification). For the current research, crispification Eq. (1) was applied to obtain a crisp value for each causal relationship (Pramanik et al., 2016):

$$w_k^c = \frac{1 - \sqrt{((1 - \mathrm{T_k})^2 + (\mathrm{I_k})^2 + (\mathrm{F_k})^2))/3}}{\sum_{k=1}^{r}\left\{1 - \sqrt{((1 - \mathrm{T_k})^2 + (\mathrm{I_k})^2 + (\mathrm{F_k})^2))/3}\right\}} \tag{1}$$

in which $w_k^c \geq 0$.

Neutrosophic logic is a more empirically robust, realistic tool that supports decision making since this logic, in addition to dealing with the issue of uncertainty, gives decision makers greater freedom to follow their intuition regarding truth, falsity, and indeterminacy of causal links. This approach is relatively new, but, when applied to complex decision problems, neutrosophic logic appears to generate more realistic results (Ferreira & Meidutė-Kavaliauskienė, 2019).

3.2 DEMATEL

Gabus and Fontela (1972) created the DEMATEL technique to analyze and structure interconnected, complex decision problems, represent criteria's interrelationships, and *"help to prioritize factors based on type of relationship as well as identifying the severity of their effect on other factors"* (Atthirawong et al., 2018, p. 2). DEMATEL can be used to evaluate different factors in order to convert the interdependent relationships between them into groups of causes (*i.e.*, higher priority factors that have a greater effect on others) and effects (*i.e.*, less significant factors that receive more influence from others) (Si et al., 2018). This technique thus identifies credible and feasible solutions and places them in a hierarchy by importance. Sumrit and Anuntavoranich (2013) state that decision makers should follow a sequence of essential steps to apply DEMATEL.

3.2.1 Step one

The first step is to calculate initial direct-influence matrix Z after a group of specialists E produces matrix $n \times n$ using a five-point scale ranging from 0 to 4 (0 = "No influence"; 1 = "Little influence"; 2 = "Medium influence"; 3 = "Strong influence"; and 4 = "Very strong influence"). Matrix Z is understood as $Z = [a_{\mathrm{ij}}]\ n \times n$ and represented as shown in Eq. (2) (Ullah et al., 2021):

$$Z = \begin{matrix} C1 \\ C2 \\ \vdots \\ Cn \end{matrix} \begin{bmatrix} 0 & a12 & \dots & a1n \\ a21 & 0 & & a2n \\ \vdots & \vdots & \ddots & \vdots \\ an1 & an2 & \cdots & 0 \end{bmatrix} \tag{2}$$

3.2.2 Step two

The second step is to create normalized direct-influence matrix X by applying normalization to matrix Z. This procedure uses Eqs. (3) and (4):

$$X = \frac{Z}{\lambda} \tag{3}$$

$$\lambda = max\left(\max_{1 \le i \le n} \sum_{j=1}^{n} z_{ij}, \max_{1 \le j \le n} \sum_{i=1}^{n} z_{ij} \right) \tag{4}$$

in which λ is a normalizing constant equal to a criterion's largest effect or the total of matrix Z's lines i has on other factors, as well as that criterion's maximum influence or the total of matrix Z's columns j receives from the other factors.

3.2.3 Step three

The third step is to build total-influence matrix T using Eq. (5):

$$\mathrm{T} = \lim_{h \to \infty} (X^1 + X^2 + \cdots + X^h) = X(\mathrm{I} - X)^{-1} \tag{5}$$

in which I is an identity matrix and elements t_{ij} are the direct and indirect effects that factor i has on factor j. Matrix T represents the total influence present in each factor's relationships.

3.2.4 Step four

The fourth step is to calculate the totals of total-influence matrix T's rows and columns, whose respective values are represented by vectors R and C. These vectors are represented by Eqs. (6) and (7), respectively:

$$R = \left[\sum_{j=1}^{n} t_{ij} \right]_{n \times 1} = [r_i]_{n \times 1} \tag{6}$$

$$C = \left[\sum_{i=1}^{n} t_{ij} \right]_{1 \times n} = \left[c_j \right]_{1 \times n} \tag{7}$$

in which r_i is the total of the ith row in matrix T and r_i represents the total direct or indirect influence this factor has over all other evaluation criteria. In turn, c_j is the total of the ith column of matrix T, thereby representing the total direct or indirect effects that factor i receives from other variables.

Since $i = j$ and $i, j \in \{1, 2, \ldots n\}$, the $R + C$ value is understood as "prominence" (*i.e.*, a factor's degree of importance in the analysis system). Concurrently, the R–C value represents "relationship" (*i.e.*, a factor's degree of influence in the system). These values can be used to divide the factors into a group of causes (*i.e.*, donors) and a group of effects (*i.e.*, receptors). Two possible situations thus arise. First, when r_i–c_j is positive, factor i has direct influence on the other criteria, so it belongs to the group of causes. Second, if r_i–c_j is negative, the remaining factors influence factor i, so this variable is included in the effects group.

3.2.5 Step five

The fifth step is to determine the threshold (α) value to identify the most critical factors of the decision-support system. This value is calculated by averaging the scores in matrix T using Eq. (8):

$$\alpha = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \left[t_{ij}\right]}{N} \tag{8}$$

In this step, the goal is to eliminate the factors with the least effect and significance in the total-influence matrix, which facilitates interpretations of the interrelationship map (IRM) generated in the next step.

3.2.6 Step six

The last step is to develop a DEMATEL cause-effect map or IRM by mapping the coordinate sets of $(r_i + c_i, r_j - c_j)$. $R + C$ values refer to the horizontal axis and R–C values to the vertical axis. This graphic representation provides important information to decision makers about the most significant factors and their respective influence on the other evaluation criteria. As shown in Fig. 1, the cause-effect relationship diagram is divided into four quadrants that reflect the factors or criteria's relative positions. Quadrant I includes the core factors (*i.e.*, central factors). Quadrant II contains the driving factors (*i.e.*, determining factors). Quadrant III are the independent factors. Finally, quadrant IV comprises the impact factors.

Overall, DEMATEL is an extremely useful tool that converts factors' interdependence into cause-effect relationships and determines which criteria have a greater or lesser impact on the

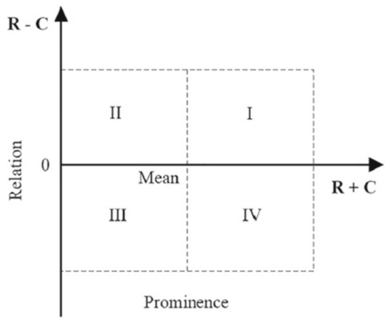

Fig. 1 Interrelationship map. Source: Yazdi et al. (2020)

decision-support model (Dalvi-Esfahani et al., 2019). This methodology can thus contribute to a better identification and understanding of practical solutions to complex problems through graphical representations of causal relationships. These IRMs are based on experts' opinions and help decision makers understand which determining factors should be prioritized (Kumar & Dixit, 2018).

4 Application and results

The main goal of this study is to develop a multicriteria analysis system to facilitate decision making by identifying and analyzing key initiatives and challenges inherent in smart, sustainable urban ecosystems. To this end, cognitive mapping was applied in the structuring phase, followed by DEMATEL combined with neutrosophic logic during the evaluation phase. These techniques required a panel of experts with knowledge and experience related to sustainability and urbanism, who met in two sessions to structure and evaluate the decision problem, thereby contributing to the creation of a more dependable model (Ferreira & Meidutė-Kavaliauskienė, 2019).

The literature reveals a lack of unanimity on how many panel members should be recruited, but the general guideline followed is 6 to 10 people (Eden & Ackermann, 2004) to ensure the results are consistent and realistic. An effort was also made in the current research to incorporate a variety of decision makers with different opinions and types of experience. The panel comprised a group of eight professionals who were available and committed to participating in this study. Notably, due to the process-oriented nature of the methodology, representativeness was not—and did not have to be—a significant concern (*cf.* Bell & Morse, 2013; Ormerod, 2020; Soares et al., 2022). The on-going pandemic meant that all group work sessions took place exclusively in online platforms. As mentioned previously, a facilitator was present at all times to accompany decision makers during the sessions, providing crucial assistance that made the discussions more productive.

4.1 Structuring phase: collective cognitive map

The first group session comprised the structuring phase and lasted approximately three hours. The main objective was to gather the information needed to generate a group cognitive map. This first group session was divided into three distinct parts. The Miro platform (see http://www.miro.com) was used to apply the methodologies, which facilitated remote, simultaneous interactions among all the decision makers.

The session began with each panel member briefly introducing themselves, followed by the facilitator's presentation of the research context. To kick off the first part of this session, the panel was asked a trigger question: *"Based on your professional knowledge and experience, what challenges, measures, and initiatives should be considered during the development of smart, sustainable urban ecosystems?"*. The aim was to stimulate interactions between all the experts.

To collect the necessary input for the map, the "post-its technique" (Ackermann & Eden, 2010) was applied, which required each panelist to write on post-it notes what he or she considered the most pertinent response to the trigger question. The experts were told that each note should contain only one evaluation criterion followed by a positive (+) or negative (–) sign to indicate the criterion's impact on the decision problem in question.

After 177 criteria were identified, the second part of the first session began, in which the post-it notes were grouped into clusters or areas of interest made up of groups of related criteria, thereby dividing the contents into subtopics. In the end, seven clusters were defined and labeled as follows: *technological factors* (C1); *organizational factors* (C2); *communication and engagement* (C3); *environmental sustainability* (C4); *well-being and quality of life* (C5); *information, training, and knowledge* (C6); and *funding sources* (C7). In the last part of the session, the experts discussed the internal structure of each cluster, ranking the criteria within each by order of importance in that cluster's overall context (*i.e.*, the most significant factors were placed at the top, the intermediate ones in the middle, and the least important ones at the bottom).

After the first group session, the *Decision Explorer* software (http://www.banxia.com) was used to construct a cognitive map based on the information collected, which generated a holistic view of the decision problem. In the second session, the experts discussed and validated the map. If they did not agree with its form and/or content, they could make the necessary adjustments. The map's final version is presented in Fig. 2.

The cognitive map proved to be extremely useful as a representation of the decision makers' knowledge, experience, and values. The results provide solid information about and a holistic view of the problem in question. After the map had been confirmed, the second session could focus on applying DEMATEL in a neutrosophic environment.

4.2 Evaluation phase: DEMATEL in a neutrosophic context

The structuring phase produced a collective representation of the group's knowledge about smart, sustainable urban ecosystems. The evaluation phase then proceeded with the incorporation of the quantitative methodology into the decision-making process during the second group work session. Lasting approximately three hours, the evaluation began with a brief presentation of the DEMATEL technique and neutrosophic logic.

The practical application of both approaches required the decision makers to fill in eight influence matrices. The first matrix covered the relationships between clusters, while the remaining seven matrices corresponded to the criteria's interactions within each cluster. The experts used the DEMATEL scale ranging from 0 to 4 (see Sect. 3.2.1) to determine the strength of the causal relationships between the variables. The panel members also integrated the neutrosophic components into their opinions, namely the probability as a percentage of each relationship being: true (T); uncertain (I); or false (F). Given the large number of criteria in each cluster, the decision makers used nominal group technique (NGT) and multi-voting to identify the most important criteria in each cluster and fill in the corresponding matrices.

After the second session ended, the next step consisted of applying crispification to the values assigned by the panel, which produced a crisp value for each cause-effect relationship that is closer to reality according to the experts' opinions. These values were then used to complete all the DEMATEL steps (see Sect. 3.2). The first round of analysis focused on the relationships between the clusters defined by the panel (see Table 2). The second group work session had previously generated the matrix shown in Table 3, which includes the causal links' neutrosophic values later subjected to crispification. The results of the latter step are listed in Table 4.

Table 4 provided the values needed to construct direct-influence matrix Z. The crispification equation numerator was multiplied by the degree of influence assigned by the decision makers so that the scale value (x) could be determined for each causal relationship. The final crisp weights were then used to fill in direct-influence matrix Z (see Table 5). After this step,

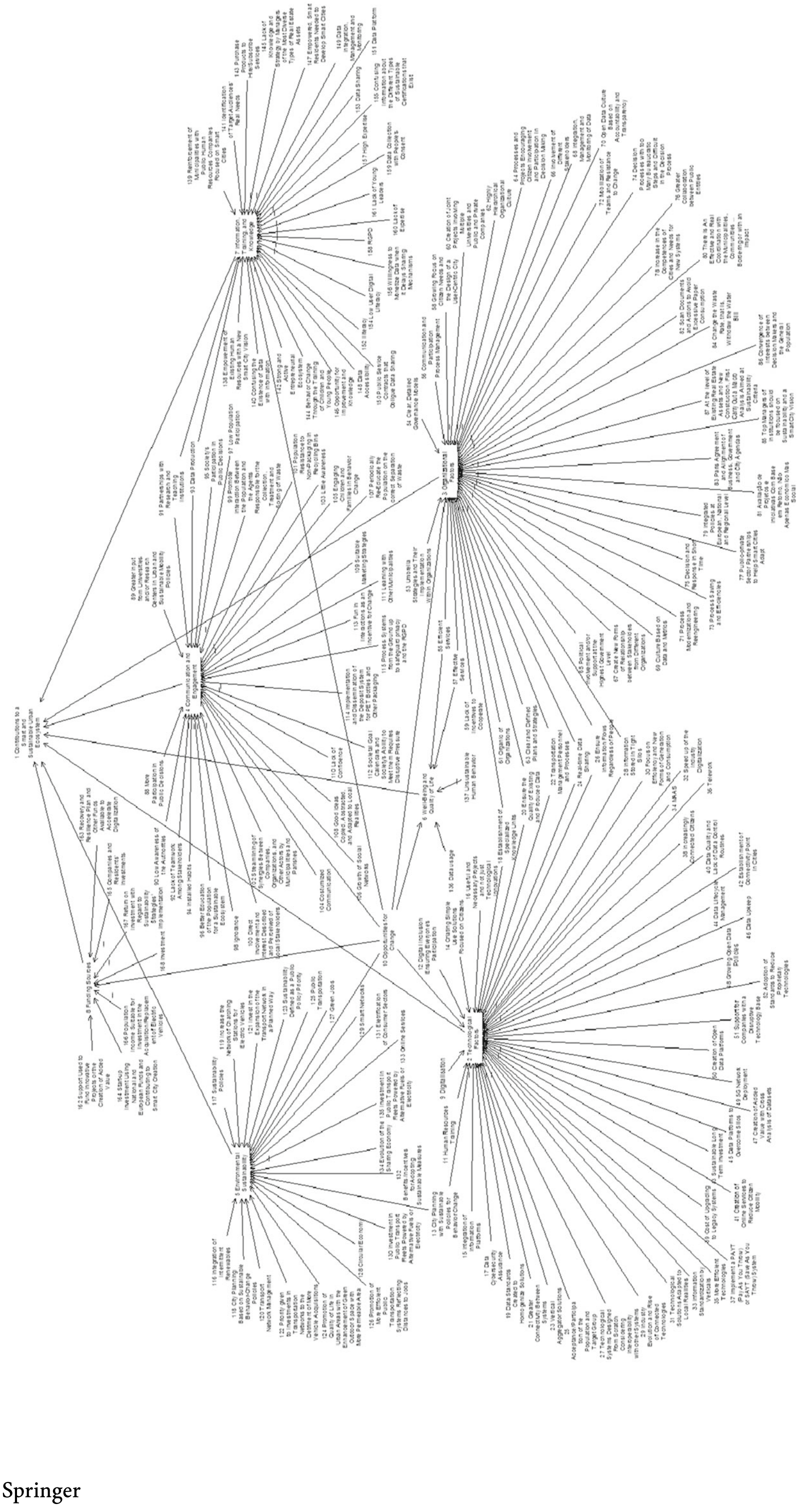

Fig. 2 Cognitive map

Table 2 Clusters identified

Clusters	
C1	Technological factors
C2	Organizational factors
C3	Communication and engagement
C4	Environmental sustainability
C5	Well-being and quality of life
C6	Information, training, and knowledge
C7	Funding sources

the panel could continue on to the remaining DEMATEL steps.

In the second step, normalized direct-influence matrix X was constructed using the relevant equations (see Sect. 3.2.2). Table 6 exhibits the results of this step.

The third step was to develop total-influence matrix T using Eq. (5) (see Sect. 3.2.3) after the three required matrices were completed (*i.e.*, matrix I, $I - X$, and $I - X^{-1}$). The results are shown in Table 7.

In matrix T, column R reflects the total influence that a given cluster has on the others, and row C comprises the remaining clusters' total influence on a given cluster. This matrix reveals that C6 has a strong total effect of 5.3111 on the other clusters. In contrast, C1 has the weakest impact on the six other clusters given its R value of 3.8873. The results in row C indicate that C6 is influenced strongly by the remaining clusters in the analysis system (*i.e.*, a C value of 5.1426).

To retain only the most critical factors for further analysis, the α value was defined by averaging the values of matrix T. In this case, α was 0.6388, which was then used to select the most influential relationships and highest values (*i.e.*, the italic cells in matrix T). This step was fundamental to the subsequent development of DEMATEL diagrams (*i.e.*, IRMs) as the results could be interpreted more fully. In addition, the R and C values were added and subtracted to provide a fuller understanding of each factor's degree of importance and influence. Table 8 presents the resulting values.

The last step consisted of generating a DEMATEL diagram that represents the final results of the cluster analysis. Figure 3 shows the distribution of the seven clusters along two axes, as well as the cause-and-effect relationships among them. Given that $R + C$ values indicate each cluster's degree of prominence in the analysis model, the $R + C$ axis provides the clusters' order of importance since a higher value on this axis represents a greater impact within the decision-support system. According to the specialist panel, C6 is the most significant, with the highest $R + C$ value (10.4537). In contrast, C3 has the lowest $R + C$ value (8.0926). Thus, this cluster is the least important, with a lesser impact on the system.

The R–C values represent each cluster's degree of influence and thus its membership in either the causes group, when R–$C > 0$, or effects group, when R–$C < 0$. Four of the clusters (*i.e.*, C3, C4, C6, and C7) are causes with direct influence on the remaining clusters. C1, C2, and C5 are effects since they are more heavily influenced by the remaining clusters and have weak relationships with the other clusters. Figure 3 not only highlights the relative importance of the seven clusters (*i.e.*, C6 > C7 > C5 > C1 > C4 > C2 > C3) but also reveals that C6 and C7 consist of core factors, C3 and C4 contain driving factors, C1 and C2 comprise independent factors, and C5 has impact factors.

Table 3 Matrix with neutrosophic values for clusters

	C1	C2	C3	C4	C5	C6	C7
C1	–	3.0 (0.8,0.1,0.1)	3.5 (0.5,0.5,0.5)	2 (0.8, 0.1, 0.1)	2.5 (0.6, 0.3, 0.2)	4.0 (1, 0.1,0.1)	2.5 (0.6, 0.4, 0.4)
C2	2.5 (0.9, 0.3,0.1)	–	3.5 (0.8, 0.5, 0.1)	2.5 (0.7,0.3,0.1)	3.5 (0.8, 0.3,0.2)	3.5 (0.8, 0.2, 0.1)	3.0 (0.7, 0.4, 0.3)
C3	2.5 (0.7, 0.5, 0.3)	3.0 (0.8, 0.2, 0.2)	–	4.0 (0.8, 0.2, 0.2)	3.0 (0.7, 0.3, 0.2)	3.5 (0.8, 0.2, 0.1)	3.0 (0.7, 0.2, 0.2)
C4	3.0 (0.7, 0.5, 0.2)	3.0 (0.6, 0.5, 0.2)	2.5 (0.7, 0.5, 0.1)	–	4.0 (0.9, 0.2, 0.1)	3.0 (0.8, 0.2, 0.1)	4.0 (1, 0.1, 0.1)
C5	4.0 (0.9, 0.1, 0.1)	4.0 (0.6, 0.3, 0.1)	2.5 (0.7, 0.5, 0.2)	2.5 (0.6, 0.5, 0.3)	–	3.0 (0.8, 0.2, 0.2)	3.5 (0.9,0.1,0.1)
C6	4.0 (0.9, 0.1,0.1)	4.0 (0.9, 0.1,0.1)	3.5 (0.8, 0.1,0.1)	3.0 (0.7, 0.2,0.2)	3.5 (0.9, 0.1,0.1)	–	3.5 (0.9,0.1,0.1)
C7	4.0 (0.9, 0.1,0.1)	1.5 (0.8, 0.6,0.4)	3.0 (0.8, 0.3,0.2)	4.0 (0.7, 0.3,0.2)	4.0 (0.9, 0.1,0.1)	4.0 (0.9, 0.1,0.1)	–

Table 4 Crisp neutrosophic values for clusters

Relationships Analyzed		DEMATEL Scale (X)	Neutrosophic Values			Neutrosophic Crispification		
			T	I	F	Crispification Equation Numerator	Crisp Weight W	Final Value in Matrix Z
Clusters Matrix	C1–C2	3.0	0.80	0.10	0.10	0.85858	0.02642	2.57574
	C1–C3	3.5	0.50	0.50	0.50	0.50000	0.01539	1.75000
	C1–C4	2.0	0.80	0.10	0.10	0.85858	0.02642	1.71716
	C1–C5	2.5	0.60	0.30	0.20	0.68909	0.02120	1.72272
	C1–C6	4.0	1.00	0.10	0.10	0.91835	0.02826	3.67540
	C1–C7	2.5	0.60	0.40	0.40	0.60000	0.01846	1.50000
	C2–C1	2.5	0.90	0.30	0.10	0.80851	0.02488	2.02129
	C2–C3	3.5	0.80	0.50	0.10	0.68377	0.02104	2.39320
	C2–C4	2.5	0.70	0.30	0.10	0.74834	0.02303	1.87085
	C2–C5	3.5	0.80	0.30	0.20	0.76195	0.02345	2.66683
	C2–C6	3.5	0.80	0.20	0.10	0.82679	0.02544	2.89378
	C2–C7	3.0	0.70	0.40	0.30	0.66335	0.02041	1.99005
	C3–C1	2.5	0.70	0.50	0.30	0.62141	0.01912	1.55352
	C3–C2	3.0	0.80	0.20	0.20	0.80000	0.02462	2.40000
	C3–C4	4.0	0.80	0.20	0.20	0.80000	0.02462	3.20000
	C3–C5	3.0	0.70	0.30	0.20	0.72920	0.02244	2.18760
	C3–C6	3.5	0.80	0.20	0.10	0.82679	0.02544	2.89378

Table 4 (continued)

Relationships Analyzed	DEMATEL Scale (X)	Neutrosophic Values			Neutrosophic Crispification		
		T	I	F	Crispification Equation Numerator	Crisp Weight W	Final Value in Matrix Z
C3–C7	3.0	0.70	0.20	0.20	0.76195	0.02345	2.28586
C4–C1	3.0	0.70	0.50	0.20	0.64410	0.01982	1.93230
C4–C2	3.0	0.60	0.50	0.20	0.61270	0.01885	1.83810
C4–C3	2.5	0.70	0.50	0.10	0.65843	0.02026	1.64609
C4–C5	4.0	0.90	0.20	0.10	0.85858	0.02642	3.43431
C4–C6	3.0	0.80	0.20	0.10	0.82679	0.02544	2.48038
C4–C7	4.0	1.00	0.10	0.10	0.91835	0.02826	3.67340
C5–C1	4.0	0.90	0.10	0.10	0.90000	0.02770	3.60000
C5–C2	4.0	0.60	0.30	0.10	0.70561	0.02171	2.82243
C5–C3	2.5	0.70	0.50	0.20	0.64410	0.01982	1.61024
C5–C4	2.5	0.60	0.50	0.30	0.59175	0.01821	1.47938
C5–C6	3.0	0.80	0.20	0.20	0.80000	0.02462	2.40000
C5–C7	3.5	0.90	0.10	0.10	0.90000	0.02770	3.15000
C6–C1	4.0	0.90	0.10	0.10	0.90000	0.02770	3.60000
C6–C2	4.0	0.90	0.10	0.10	0.90000	0.02770	3.60000
C6–C3	3.5	0.80	0.10	0.10	0.85858	0.02642	3.00503
C6–C4	3.0	0.70	0.20	0.20	0.76195	0.02345	2.28586
C6–C5	3.5	0.90	0.10	0.10	0.90000	0.02770	3.15000
C6–C7	3.5	0.90	0.10	0.10	0.90000	0.02770	3.15000
C7–C1	4.0	0.90	0.10	0.10	0.90000	0.02770	3.60000
C7–C2	1.5	0.80	0.60	0.40	0.56795	0.01748	0.85193

Table 4 (continued)

Relationships Analyzed	DEMATEL Scale (X)	Neutrosophic Values			Neutrosophic Crispification		
		T	I	F	Crispification Equation Numerator	Crisp Weight W	Final Value in Matrix Z
C7–C3	3.0	0.80	0.30	0.20	0.76195	0.02345	2.28586
C7–C4	4.0	0.70	0.30	0.20	0.72920	0.02244	2.91680
C7–C5	4.0	0.90	0.10	0.10	0.90000	0.02770	3.60000
C7–C6	4.0	0.90	0.10	0.10	0.90000	0.02770	3.60000
$\sum_{k=1}^{r} w_k^c = 1$, complies with Eq. (1) conditions (see Sect. 3.1)				Crispification equation denominator	32.49672	1	

T = truth; I = indeterminacy; F = falsity

Table 5 Direct-influence matrix Z for clusters

	C1	C2	C3	C4	C5	C6	C7	Total
C1	0.00	2.58	1.75	1.72	1.72	3.68	1.50	12.9
C2	2.02	0.00	2.39	1.87	2.67	2.89	1.99	13.8
C3	1.55	2.40	0.00	3.20	2.19	2.89	2.29	14.5
C4	1.93	1.84	1.65	0.00	3.43	2.48	3.67	15.0
C5	3.60	2.82	1.61	1.48	0.00	2.40	3.15	15.1
C6	3.60	3.60	3.01	2.29	3.15	0.00	3.15	18.8
C7	3.60	0.85	2.29	2.92	3.60	3.60	0.00	16.9
Total	16.3	14.1	12.7	13.5	16.8	17.9	15.7	

Table 6 Normalized direct-influence matrix X for clusters

Max				17.9			18.8
1/max				0.055729			0.053218
1/s				0.053217532			
	C1	C2	C3	C4	C5	C6	C7
C1	0.0000	0.1371	0.0931	0.0914	0.0917	0.1956	0.0798
C2	0.1076	0.0000	0.1274	0.0996	0.1419	0.1540	0.1059
C3	0.0827	0.1277	0.0000	0.1703	0.1164	0.1540	0.1216
C4	0.1028	0.0978	0.0876	0.0000	0.1828	0.1320	0.1955
C5	0.1916	0.1502	0.0857	0.0787	0.0000	0.1277	0.1676
C6	0.1916	0.1916	0.1599	0.1216	0.1676	0.0000	0.1676
C7	0.1916	0.0453	0.1216	0.1552	0.1916	0.1916	0.0000

Next, each cluster was analyzed by applying the same neutrosophic logic (*i.e.*, $x\ (T, I, F)$) and DEMATEL steps. The numerous criteria in the clusters could not all be analyzed at once, so the decision makers had to select the most significant criteria within each cluster using NGT and multi-voting. The remaining initial DEMATEL matrices (*i.e.*, group direct-influence matrix Z) include crisp weights estimated using the same equations as the above inter-cluster analysis. The intra-cluster analyses thus followed the same sequence of procedures based on more realistic values to construct a matrix T and final IRM for each cluster.

Beginning with C1, the experts chose the most significant criteria (see Table 9), which are hereafter referred to as subcriteria (SC) to distinguish them from the cluster-head criteria presented in the cognitive map. This reduced list facilitated the crispification of the values in the neutrosophic matrix (see Table 10). Direct-influence matrix Z for C1 were then filled in with crisp values (see Table 11), and the final results were generated.

According to Table 12, the most influential factor is SC15, with an R value of 6.8715. Concurrently, SC15 is the most affected by the other selected SCs, with a C value of 7.2580. According to the $R + C$ values, C1 SCs' prioritization by importance should be: SC19 >

Table 7 Total-influence matrix T for clusters

	C1	C2	C3	C4	C5	C6	C7
I							
C1	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C2	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C3	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
C4	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
C5	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
C6	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
C7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
I–X							
C1	1.0000	– 0.1371	– 0.0931	– 0.0914	– 0.0917	– 0.1956	– 0.0798
C2	– 0.1076	1.0000	– 0.1274	– 0.0996	– 0.1419	– 0.1540	– 0.1059
C3	– 0.0827	– 0.1277	1.0000	– 0.1703	– 0.1164	– 0.1540	– 0.1216
C4	– 0.1028	– 0.0978	– 0.0876	1.0000	– 0.1828	– 0.1320	– 0.1955
C5	– 0.1916	– 0.1502	– 0.0857	– 0.0787	1.0000	– 0.1277	– 0.1676
C6	– 0.1916	– 0.1916	– 0.1599	– 0.1216	– 0.1676	1.0000	– 0.1676
C7	– 0.1916	– 0.0453	– 0.1216	– 0.1552	– 0.1916	– 0.1916	1.0000
$(I–X)^{-1}$							
C1	1.5042	0.5641	0.4848	0.4934	0.5878	0.7016	0.5514
C2	0.6292	1.4646	0.5316	0.5233	0.6548	0.6980	0.5991
C3	0.6332	0.5966	1.4380	0.6016	0.6638	0.7238	0.6389
C4	0.6744	0.5859	0.5319	1.4674	0.7336	0.7280	0.7125
C5	0.7329	0.6236	0.5260	0.5344	1.5649	0.7204	0.6761
C6	0.8492	0.7610	0.6790	0.6680	0.8292	1.7336	0.7912
C7	0.8015	0.6033	0.6053	0.6496	0.7956	0.8372	1.6022

	C1	C2	C3	C4	C5	C6	C7	*R*
Matrix*T*								
C1	0.5042	0.5641	0.4848	0.4934	0.5878	*0.7016*	0.5514	3.8873
C2	0.6292	0.4646	0.5316	0.5233	*0.6548*	*0.6980*	0.5991	4.1006
C3	0.6332	0.5966	0.4380	0.6016	*0.6638*	*0.7238*	*0.6389*	4.2959
C4	*0.6744*	0.5859	0.5319	0.4674	*0.7336*	*0.7280*	*0.7125*	4.4337
C5	*0.7329*	0.6236	0.5260	0.5344	0.5649	*0.7204*	*0.6761*	4.3782
C6	*0.8492*	*0.7610*	*0.6790*	*0.6680*	*0.8292*	*0.7336*	*0.7912*	5.3111
C7	*0.8015*	0.6033	0.6053	*0.6496*	*0.7956*	*0.8372*	0.6022	4.8947
C	4.8246	4.1991	3.7967	3.9376	4.8297	5.1426	4.5713	

Table 8 Given and received influence between clusters

	R	C	$R+C$	$R–C$
C1	3.8873	4.8246	8.7118	– 0.9373
C2	4.1006	4.1991	8.2996	– 0.0985
C3	4.2959	3.7967	8.0926	0.4992
C4	4.4337	3.9376	8.3714	0.4961
C5	4.3782	4.8297	9.2080	– 0.4515
C6	5.3111	5.1426	10.4537	0.1686
C7	4.8947	4.5713	9.4660	0.3234

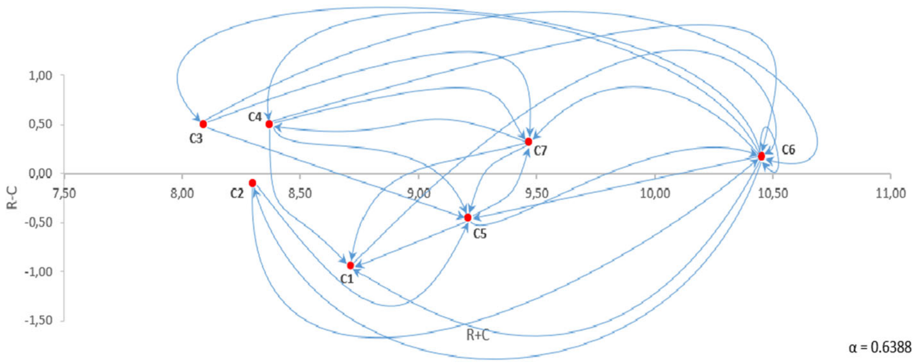

Fig. 3 Interrelationship map for clusters

Table 9 Most significant subcriteria: technological factors

Selected SCs	
SC11	Human resources training
SC12	Digital inclusion ensuring everyone's participation
SC15	Integration of information platforms
SC19	Data standards created to homogenize solutions
SC21	Greater connectivity between systems
SC24	Real-time data sharing
SC31	Technological solutions adapted to local realities

SC11 > SC21 > SC12 > SC31 > SC24. SC19 is overall this cluster's most prominent factor in the present analysis system as its $R+C$ value is the highest (*i.e.*, 11.2726).

As shown in Fig. 4, SC21 and SC15 fall below the $R–C$ axis (*i.e.*, SCs with a negative value). Thus, they form the effects group. The remaining SCs appear above the axis (*i.e.*, with a positive $R–C$ value), identifying them as causes that have more direct influence on the other two SCs. The IRM also reveals that SC11, SC12, and SC19 are core factors; SC24 and SC31 are driving factors; and SC15 and SC21 are impact factors.

Table 10 Matrix with neutrosophic values: technological factors

	SC11	SC12	SC15	SC19	SC21	SC24	SC31
SC11	–	3.0 (0.7,0.3,0.2)	4.0 (0.7,0.3,0.2)	3.5 (0.8,0.2,0.2)	3.5 (0.6,0.3,0.1)	3.0 (0.8,0.2,0.2)	4.0 (0.9,0.1,0.1)
SC12	3.5 (0.7,0.3,0.2)	–	4.0 (0.7, 0.3,0.2)	3.5 (0.7, 0.3, 0.2)	3.5 (0.7, 0.3, 0.2)	3.0 (0.8, 0.4, 0.2)	4.0 (0.7,0.3,0.2)
SC15	3.5 (0.8,0.2,0.2)	4.0 (0.9,0.1,0.1)	–	3.0 (0.8, 0.5, 0.2)	3.5 (0.7, 0.3,0.1)	4.0 (0.7, 0.3, 0.2)	4.0 (0.9, 0.1,0,1)
SC19	4.0 (0.7,0.2,0.2)	2.5 (0.6,0.4,0.2)	4.0 (0.9, 0.1,0.1)	–	4.0 (0.9, 0.1,0.1)	4.0 (0.8,0.3,0.2)	3.0 (0.7, 0.2,0.2)
SC21	3.0 (0.7,0.4,0.3)	4.0 (0.8, 0.2,0.2)	4.0 (0.8, 0.2,0.2)	2.0 (0.7, 0.3,0.3)	–	3.0 (0.7, 0.4, 0.3)	3.5 (0.8, 0.3, 0.2)
SC24	2.0 (0.7,0.3,0.3)	2.0 (0.7,0.3,0.3)	3.5 (0.9,0.1,0.1)	4.0 (0.9, 0.1,0.1)	4.0 (0.8, 0.3,0.3)	–	3.0 (0.7,0.2,0.2)
SC31	4.0 (0.7,0.3,0.2)	3.5 (0.7,0.3,0.2)	4.0 (0.7,0.3,0.2)	3.5 (0.7,0.3,0.2)	3.5 (0.8, 0.2,0.1)	4.0 (0.8,0.2,0.1)	–

Table 11 Direct-influence matrix Z: technological factors

	SC11	SC12	SC15	SC19	SC21	SC24	SC31	TOTAL
SC11	0.00	2.19	2.92	2.80	2.40	2.47	3.60	16.4
SC12	2.55	0.00	2.92	2.55	2.15	2.55	2.92	15.6
SC15	2.80	3.60	0.00	2.01	2.92	2.62	3.60	17.5
SC19	3.05	1.63	3.60	0.00	3.05	3.60	2.29	17.2
SC21	1.40	1.40	3.15	3.60	0.00	2.92	2.29	14.8
SC24	1.99	3.20	3.20	1.40	1.99	0.00	2.67	14.4
SC31	2.92	2.55	2.92	2.55	3.31	2.89	0.00	17.1
TOTAL	14.7	14.6	18.7	14.9	15.8	17.1	17.4	

Table 12 Total-influence matrix T: technological factors

	SC11	SC12	SC15	SC19	SC21	SC24	SC31	R
SC11	0.7570	0.8657	*1.0643*	0.8878	*0.9232*	*0.9749*	*1.0385*	6.5114
SC12	0.8456	0.7303	*1.0257*	0.8454	0.8780	*0.9421*	*0.9751*	6.2421
SC15	*0.9273*	*0.9660*	*0.9796*	0.8981	*0.9868*	*1.0266*	*1.0871*	6.8715
SC19	*0.9228*	0.8731	*1.1272*	0.7842	*0.9776*	*1.0525*	*1.0185*	6.7560
SC21	0.7606	0.7651	0.9926	0.8513	0.7369	*0.9186*	0.9042	5.9293
SC24	0.7707	0.8293	*0.9737*	0.7458	0.8158	0.7626	0.9074	5.8053
SC31	0.9138	0.9046	*1.0948*	0.9034	*0.9846*	*1.0196*	0.9039	6.7247
C	5.8978	5.9340	7.2580	5.9159	6.3029	6.6967	6.8348	

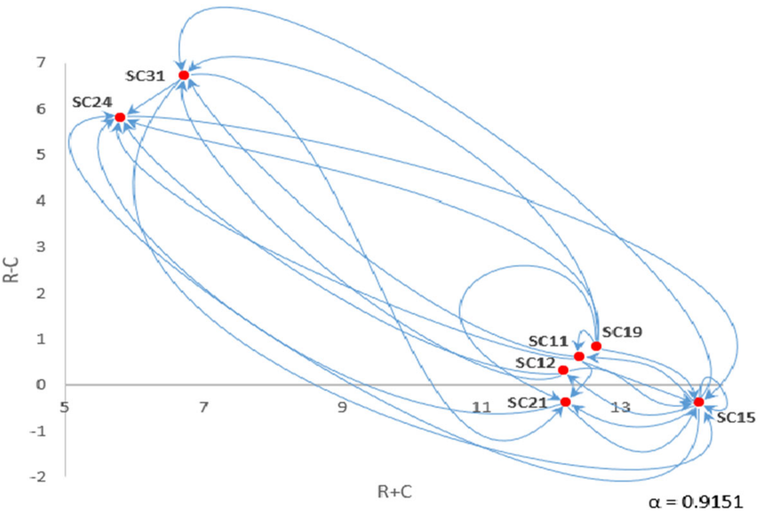

Fig. 4 Interrelationship map for technological factors

Table 13 Most significant subcriteria: organizational factors

Selected SCs	
SC22	Transportation management personnel and processes
SC53	Umbrella strategies and their implementation within organizations
SC54	Clear, detailed governance models
SC60	Creation of joint projects involving multiple universities and public and private companies
SC64	Processes and projects encouraging citizen involvement and participation in decision making
SC65	Political involvement and/or support at the highest government level
SC77	Public–private sector partnerships to help smart cities adapt

The SCs chosen for C2 are listed in Table 13. The neutrosophic matrix presented in Table 14 was next filled in by the decision makers. This matrix followed the same logic applied in previous analyses and served as a basis for this cluster's direct-influence matrix, which contains the crisp weights needed to complete the analysis (see Table 15).

As Table 16 shows, SC64 was identified as the factor that most influences the other SCs, with an R value of 7.3449. SC65, in contrast, is not only the most affected by the remaining SCs, with the highest C value of 7.3769, but also this cluster's factor of greatest importance to the analysis system, with an $R + C$ value of 14.2719. The following hierarchy was revealed: SC65 > SC53 > SC54 > SC77 > SC22 > SC54 > SC60.

The R–C values indicate that SC22, SC64, and SC77 belong to the causes group, with a positive R–C value, and thus have a direct impact on the remaining SCs. The remaining factors are effects with a negative R–C value. Based on the SCs' positions in the diagram (see Fig. 5), SC64 and SC77 are core factors, SC22 is a driving factor, SC54 and SC60 are independent factors, and SC53 and SC65 are impact factors.

C3 was then analyzed by following the same DEMATEL steps. After the most significant SCs were selected (see Table 17), the neutrosophic value matrix was created by the panel (see Table 18). Table 19 presents the results after crispification.

The IRM in Fig. 6 reflects the values listed in Table 20. SC88 has the most effect on the other determinants, with the highest total R value of 6.7281. This SC also is this cluster's most significant factor in the decision-support system, with an $R + C$ value of 12.3205. SC108 is the most affected by all the other SCs, with a C value of 6.7392. The $R + C$ values reveal that SC95 is the least important, producing the following overall ranking: SC88 > SC102 > SC108 > SC89 > SC95.

The division of the SCs into causes and effects groups confirmed that SC88, SC89, and SC102 are causes (*i.e.*, positive R–C values), while SC89 and SC102 are effects (*i.e.*, negative R–C values). The quartiles further reveal that SC88 and SC102 are core factors, SC89 is a driving factor, SC95 is an independent factor, and SC108 is an impact factor.

The same analysis was conducted with C4, whose selected SCs are presented in Table 21. The neutrosophic value matrix was created by the panel (see Table 22), which was later used to construct the direct-influence matrix shown in Table 23.

Table 24 shows that SC123 has the most influence on the other factors, with an R value of 9.8110. SC118, in turn, receives the most effects from the remaining SCs, with the highest C value (9.6939), as well as being this cluster's most important SC in the analysis system, with an $R + C$ value of 19.1565. The $R + C$ values thus confirm the following ranking by importance: SC118 > SC123 > SC126 > SC122 > SC128.

Table 14 Matrix with neutrosophic values: organizational factors

	SC22	SC53	SC54	SC60	SC64	SC65	SC77
SC22	–	3.5 (0.8,0.3,0.2)	4.0 (0.8, 0.3, 0.2)	4.0 (0.9, 0.2, 0.1)	4.0 (0.9, 0.2,0.1)	3.5 (0.9, 0.1,0.1)	4.0 (0.9, 0.2, 0.1)
SC53	2.5 (0.8,0.3,0.1)	–	4.0 (0.9,0.1,0.1)	3.5 (0.8, 0.2,0.1)	3.5 (0.8, 0.2, 0.1)	4.0 (0.9, 0.1,0.1)	3.0 (0.8, 0.2,0.1)
SC54	2.5 (0.8, 0.1,0.2)	4.0 (0.9, 0.1,0.1)	–	3.0 (0.7, 0.3, 0.3)	2.5 (0.7, 0.3,0.2)	3.5 (0.8, 0.1, 0.2)	3.0 (0.7, 0.1,0.3)
SC60	2.5 (0.7, 0.4,0.2)	3.0 (0.8, 0.2, 0.2)	2.5 (0.6,0.3,0.3)	–	3.0 (0.6,0.2,0.2)	4.0 (0.8, 0.3,0.1)	3.5 (0.7, 0.4,0.2)
SC64	3.5 (0.8,0.1,0.1)	3.5 (0.8, 0.3,0..1)	4.0 (0.9,0.1,0.1)	3.5 (0.9,0.3,0.1)	–	4.0 (0.9,0.1,0.1)	4.0 (0.9,0.1,0.1)
SC65	3.0 (0.7, 0.3,0.3)	4.0 (0.8, 0.1,0.1)	4.0 (0.8, 0.1, 0.1)	3.5 (0.8, 0.2,0.2)	4.0 (0.9, 0.1, 0.1)	–	3.5 (0.7, 0.2,0.2)
SC77	4.0 (0.9,0.1,0.1)	3.5 (0.7,0.1,0.3)	3.0 (0.8,0.3,0.2)	4.0 (1.0,0.1,0.0)	3.0 (0.8,0.3,0.2)	3.5 (0.9,0.1,0.1)	–

Table 15 Direct-influence matrix: organizational factors

	SC22	SC53	SC54	SC60	SC64	SC65	SC77	TOTAL
SC22	0.0	2.7	3.0	3.4	2.4	3.2	3.4	18.2
SC53	2.0	0.0	3.6	2.9	2.9	3.6	2.5	17.4
SC54	2.1	3.6	0.0	2.1	1.8	2.9	2.2	14.7
SC60	1.7	2.4	1.7	0.0	2.2	3.1	2.4	13.5
SC64	3.0	2.7	3.6	2.8	0.0	3.6	3.6	19.4
SC65	2.1	3.4	3.4	2.8	3.6	0.0	2.7	18.0
SC77	3.6	2.6	2.3	3.8	2.3	3.2	0.0	17.7
TOTAL	14.5	17.5	17.6	17.8	15.2	19.5	16.8	

Table 16 Total-relation matrix T: organizational factors

	SC22	SC53	SC54	SC60	SC64	SC65	SC77	R
SC22	0.7508	*1.0194*	*1.0334*	*1.0568*	0.9070	*1.1228*	*1.0072*	6.8973
SC53	0.8152	0.8706	*1.0273*	*1.0012*	0.8989	*1.1065*	*0.9394*	6.6590
SC54	0.7223	0.9109	0.7558	0.8549	0.7547	*0.9531*	0.8194	5.7711
SC60	0.6650	0.8082	0.7800	0.7042	0.7205	0.9034	0.7759	5.3572
SC64	*0.9340*	*1.0821*	*1.1155*	*1.0914*	0.8482	*1.2039*	*1.0698*	7.3449
SC65	0.8478	*1.0503*	*1.0524*	*1.0292*	*0.9532*	*0.9849*	*0.9773*	6.8951
SC77	0.8910	*0.9974*	*0.9846*	*1.0518*	0.8852	*1.1023*	0.8401	6.7524
C	5.6262	6.7388	6.7490	6.7895	5.9677	7.3769	6.4291	

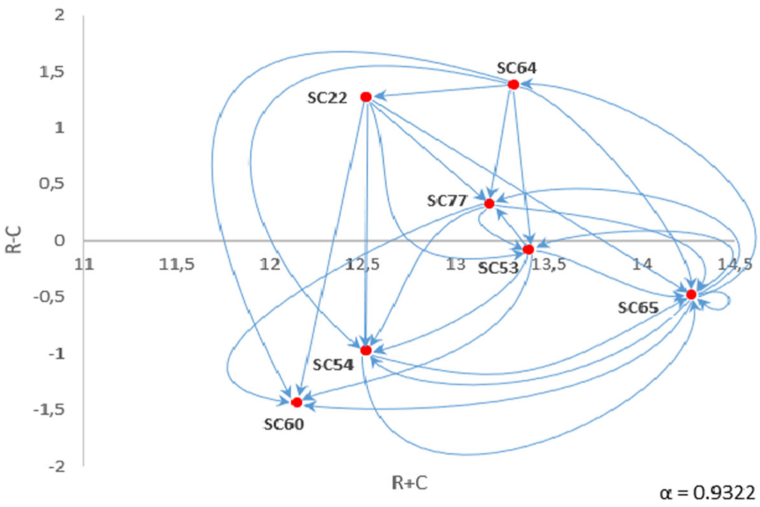

Fig. 5 Interrelationship map for organizational factors

Table 17 Most significant subcriteria: communication and engagement

Selected SCs	
SC88	More participation in public decisions
SC89	Greater input from universities and/or research centers in urban and sustainable mobility policies
SC95	Society's participation in public decisions
SC102	Streamlining of synergies between companies, organizations, and other actors by municipalities and parishes
SC108	Good ideas copied, abstracted, and adapted to local realities

Regarding C4's causes and effects, SC123 and SC128 belong in the causes group (*i.e.*, positive *R*–*C* values), while the remaining factors (*i.e.*, SC118, SC122, and SC126) are effects (*i.e.*, negative *R*–*C* values). Figure 7 also reveals that SC123 is a core factor, SC128 is a driving factor, SC122 is an independent factor, and SC118 and SC126 are impact factors.

The C5 SCs chosen by the panel members are listed in Table 25, and the corresponding matrix of neutrosophic values is shown in Table 26. This cluster was analyzed after the direct-influence matrix was generated (see Table 27).

Table 28 reveals that SC10 is both the most influential criterion, with the highest *R* value at 4.7068, and this cluster's most important factor in the decision-support system, with an $R + C$ value of 8.9170. SC55, in contrast, is the most affected by the remaining SCs (*i.e.*, a *C* value of 4.2563). The selected SCs can be ranked by order of importance as follows: SC10 > SC136 > SC57 > SC55 > SC137.

The IRM in Fig. 8 also shows that SC10 and SC136 belong to the causes group because of their positive *R*–*C* values (*i.e.*, being a stronger influence on the other SCs versus being more affected). The effects group comprises SC55, SC57, and SC137 given their negative *R*–*C* values. Finally, the DEMATEL diagram reveals that SC10 and SC136 are core factors, SC137 is an independent factor, and SC55 and SC57 are impact factors.

As for C6, the most important SCs are presented in Table 29. The neutrosophic matrix in Table 30 was then created, as well as the initial DEMATEL matrix converted to crisp weights in Table 31.

As shown in Table 32, SC139 is the most influential factor due to its *R* value of 6.6898. SC138 is the most affected by all other factors, with a *C* value of 6.9834. SC138 also appears to be this cluster's most important criterion in the analysis system because of its $R + C$ value of 13.1055. According to Fig. 9, C6's factors should be prioritized as follows: SC138 > SC139 > SC91 > SC147 > SC141.

In addition, SC88 is the most prominent criterion, appearing the farthest to the right in Fig. 9 (*i.e.*, $R + C$ value of 5.9580). According to their *R*–*C* values, SC139 and SC141 belong to the causes group, while SC91, SC138, and SC147 are effects. Finally, the SCs' division into quartiles indicates that SC139 is a core factor, SC141 is a driving factor, SC147 is an independent factor, and SC91 and SC138 are impact factors.

The most important SCs in C7 were selected by the panel according to Table 33. The matrices for this cluster were constructed as shown in Tables 34 and 35.

Table 36 reveals that SC162 is simultaneously the determinant with the greatest influence on the others and C7's most prominent factor in the decision-support system. In contrast, SC164 is the most affected by the remaining SCs, with a *C* value of 7.7128. According to Fig. 10, decision makers should give priority to these factors in this order: SC162 > SC165

Table 18 Matrix with neutrosophic values: communication and engagement

	SC88	SC89	SC95	SC102	SC108
SC88	–	3.0 (0.8,0.3,0.1)	4.0 (0.9,0.1,0.1)	4.0 (0.9, 0.1, 0.1)	3.5 (0.9, 0.1,0.1)
SC89	3.5 (0.7, 0.4,0.3)	–	3.0 (0.8,0.2,0.2)	3.5 (0.8, 0.2,0.2)	4.0 (0.9, 0.1,0.1)
SC95	4.0 (1,0,0)	3.0 (0.8, 0.2,0.1)	–	2.0 (0.6,0.5,0.2)	3.5 (0.7, 0.3,0.2)
SC102	3.0 (0.8,0.3,0.1)	4.0 (0.9, 0.2,0.2)	3.5 (0.7,0.4,0.3)	–	4.0 (0.8, 0.1,0.1)
SC108	2.0 (0.8, 0.3,0.1)	3.0 (0.7, 0.3,0.3)	3.0 (0.8,0.2,0.1)	3.5 (0.9,0.1,0.1)	–

Table 19 Direct-influence matrix: communication and engagement

	SC88	SC89	SC95	SC102	SC108	TOTAL
SC88	0.0	2.4	3.6	3.6	3.2	12.7
SC89	2.3	0.0	2.4	2.8	3.6	11.1
SC95	4.0	2.5	0.0	1.2	2.6	10.3
SC102	2.4	3.3	2.3	0.0	3.4	11.4
SC108	1.6	2.1	2.5	3.2	0.0	9.3
Total	10.2	10.2	10.8	10.8	12.7	

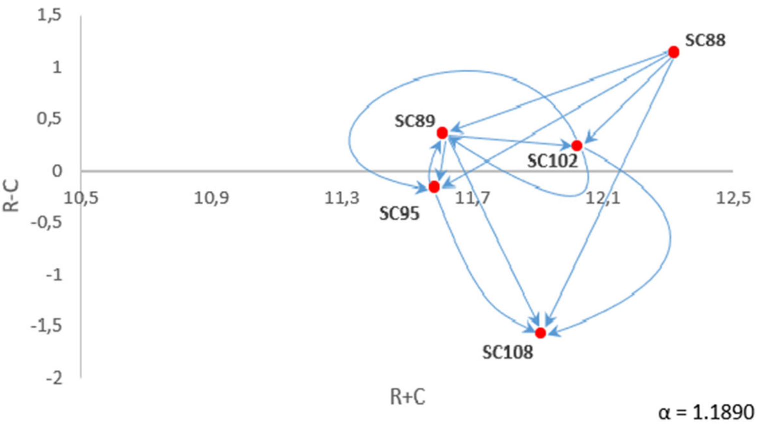

Fig. 6 Interrelationship map for communication and engagement

Table 20 Total-relation matrix T: communication and engagement

	SC88	SC89	SC95	SC102	SC108	R
SC88	1.1184	*1.2791*	*1.3942*	*1.3953*	*1.5411*	6.7281
SC89	1.1421	0.9972	*1.1993*	*1.2281*	*1.4184*	5.9851
SC95	*1.1944*	1.1106	1.0013	1.0974	*1.3063*	5.7101
SC102	1.1671	*1.2288*	*1.2197*	1.0734	*1.4395*	6.1284
SC108	0.9704	1.0069	1.0608	1.1008	1.0340	5.1728
C	5.5924	5.6226	5.8753	5.8949	6.7392	

> SC163 > SC164 > SC167. SC162, SC163, and SC167 belong to the causes group, while SC164 and SC165 comprise the effects group. The IRM shows that SC162 is a core factor, SC163 and SC167 are driving factors, SC164 is an independent factor, and SC165 is an impact factor.

After the evaluation phase was completed, a consolidation session was scheduled with two experts on smart, sustainable ecosystems who were not present in the previous sessions. The goal was to obtain a neutral opinion on the multicriteria analysis model developed.

Table 21 Most significant subcriteria: environmental sustainability

Selected SCs	
SC118	City planning based on sustainable behavior-change policies
SC122	Priority given to investments in transportation networks to the detriment of more vehicle acquisitions
SC123	Sustainability defined as a public policy priority
SC126	Promotion of more efficient public transportation systems reflecting distances to jobs
SC128	Circular economy

4.3 Consolidation, expert discussion, and recommendations

The consolidation session was held with representatives of the Lisbon City Council Urban Management and Intelligence Center, who were responsible for promoting a management culture that includes monitoring and analyzing urban ecosystems. This meeting took place in person at the center's facilities and lasted approximately one hour. The interviewees contributed ideas that complement the results of the previous phases, thereby ensuring greater credibility.

The session began with a brief overview of the topic and the methodologies applied, which emphasized that the proposed model was based on a constructivist logic and thus each panel members' knowledge, experience, and values. Next, the facilitator presented the cognitive map, as well as the matrices and diagrams generated with the DEMATEL technique. The experts expressed concern about the study's qualitative component, specifically the *"abundance of information"* in the cognitive map (in their words). However, after cognitive mapping was explained, the interviewees became interested in analyzing each part of the map more carefully since this methodology has been shown to facilitate greatly the structuring of complex decision problems. Regarding the evaluation phase, one specialist underlined the importance of proceeding to a diagnosis of real urban-ecosystem priorities.

Overall, these experts concurred that the methodologies applied in this second phase were quite suitable for the research topic. The interviewees also commented that the model's practical applicability was enhanced by the diverse measures, initiatives, and challenges included in the group cognitive map. This aspect could be one of the main advantages of the proposed model because, if any restriction/limitation is present to prevent any criterion's application, the decision makers will have other alternative approaches to achieving the same goal. These specialists concluded that the model has strong potential when adapted to the local realities of each urban ecosystem, and that the indeterminacy incorporated provides fundamental support to decision-making processes as neutrosophic logic produces a closer approximation to reality and thus better results. By the end of the session, the experts were pleased with the empirically robust outcomes obtained with the selected tools and were in agreement regarding the potential applicability of the decision-support system developed in this study.

The consolidation session was an essential step in the present research as the two interviewees' feedback strengthened the transparency of results and facilitated their interpretation. However, the complementary perspective of the present research means that the objective was not to replace previous methods or models but instead to augment their usefulness. The expert panel members had previously noted that, because the proposed approach permits decision

Table 22 Matrix with neutrosophic values: environmental sustainability

	SC118	SC122	SC123	SC126	SC128
SC118	–	3.5 (0.8,0.1,0.2)	4.0 (0.9, 0.1,0.1)	3.5 (0.9,0.1,0.1)	3.5 (0.9,0.1,0.1)
SC122	4.0 (0.9,0.2,0.1)	–	3.5 (0.7, 0.4,0.3)	4.0 (0.8,0.3,0.2)	2.5 (0.7,0.4,0.2)
SC123	4.0 (0.9,0.1,0.1)	4.0 (0.9,0.1,0.1)	–	4.0 (0.9,0.1,0.1)	3.5 (0.8,0.3,0.2)
SC126	4.0 (0.8,0.2,0.1)	4.0 (0.9,0.1,0.1)	3.5 (0.9,0.1,0.1)	–	2.5 (0.7, 0.4,0.2)
SC128	3.5 (0.8,0.2,0.2)	4.0 (0.9, 0.4,0.1)	4.0 (0.9,0.1,0.1)	3.5 (0.9,0.4,0.1)	–

Table 23 Direct-influence matrix: environmental sustainability

	SC118	SC122	SC123	SC126	SC128	TOTAL
SC118	0.0	2.9	3.6	3.2	3.2	12.8
SC122	3.4	0.0	2.3	3.0	1.7	10.5
SC123	3.6	3.6	0.0	3.6	2.7	13.5
SC126	3.3	3.6	3.2	0.0	1.7	11.8
SC128	2.8	3.0	3.6	2.6	0.0	12.1
TOTAL	13.1	13.1	12.7	12.4	9.3	

Table 24 Total-relation matrix T: environmental sustainability

	SC118	SC122	SC123	SC126	SC128	R
SC118	*1.8682*	*2.0345*	*2.0024*	*1.9768*	1.5806	9.4626
SC122	1.7896	1.5755	1.6668	1.7013	1.2958	8.0290
SC123	*2.1490*	*2.1370*	*1.8550*	*2.0646*	1.6055	9.8110
SC126	*1.9351*	*1.9377*	*1.8503*	1.6620	1.4075	8.7926
SC128	*1.9519*	*1.9521*	*1.9164*	*1.8668*	1.3246	9.0119
C	9.6939	9.6368	9.2909	9.2715	7.2139	

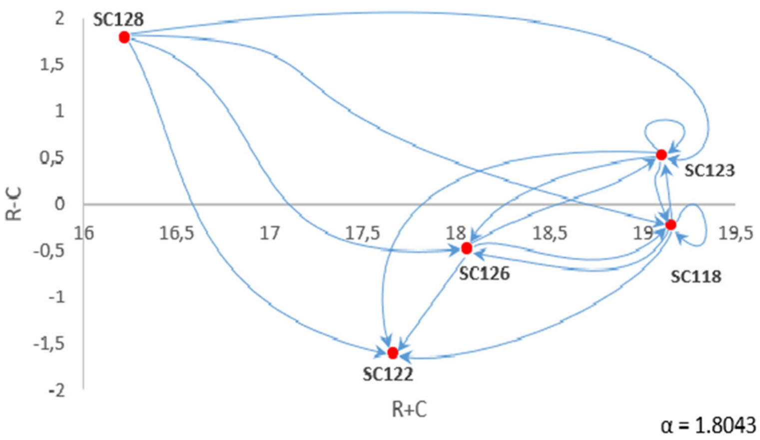

Fig. 7 Interrelationship map for environmental sustainability

Table 25 Most significant subcriteria: well-being and quality of life

Selected SCs	
SC10	Opportunities for change
SC55	Efficient services
SC57	Effective services
SC136	Data usage
SC137	Unsustainable human behavior

Table 26 Matrix with Neutrosophic Values: Well-Being and Quality of Life

	SC10	SC55	SC57	SC136	SC137
SC10	–	3.5 (0.9, 0.3,0.1)	3.5 (0.9, 0.3,0.1)	3.5 (0.9, 0.3,0.1)	4.0 (0.9,0.1,0.1)
SC55	3.0 (0.8,0.2,0.2)	–	3.0 (0.8,0.2,0.2)	3.5 (0.7, 0.3, 0.3)	2.5 (0.7, 0.3,0.3)
SC57	3.5 (0.8,0.2,0.2)	3.5 (0.8,0.2,0.2)	–	3.0 (0.7,0.3,0.3)	2.5 (0.8, 0.2,0.1)
SC136	3.5 (0.9,0.3,0.2)	4.0 (0.9,0.1,0.1)	4.0 (0.9,0.1,0.1)	–	2.5 (0.4,0.5,0.5)
SC137	3.5 (0.7, 0.3,0.3)	2.0 (0.6,0.4,0.3)	2.0 (0.6,0.4,0.3)	2.0 (0.5,0.5,0.3)	–

Table 27 Direct-influence matrix: well-being and quality of life

	SC10	SC55	SC57	SC136	SC137	Total
SC10	0.0	2.8	2.8	2.8	3.6	12.1
SC55	2.4	0.0	2.4	2.5	1.8	9.0
SC57	2.8	2.8	0.0	2.1	2.1	9.8
SC136	2.7	3.6	3.6	0.0	1.2	11.1
SC137	2.5	1.3	1.3	1.1	0.0	6.1
Total	10.4	10.5	10.1	8.5	8.6	

Table 28 Total-relation matrix T: well-being and quality of life

	SC10	SC55	SC57	SC136	SC137	R
SC10	*0.8318*	*1.0267*	*0.9991*	*0.8980*	*0.9512*	4.7068
SC55	*0.8375*	0.6828	*0.8257*	0.7455	0.7058	3.7973
SC57	*0.9013*	*0.9102*	0.6977	0.7606	0.7635	4.0334
SC136	*0.9954*	*1.0605*	*1.0320*	0.6999	0.7897	4.5776
SC137	0.6441	0.5760	0.5605	0.4955	0.4186	2.6946
C	4.2102	4.2563	4.1151	3.5994	3.6287	

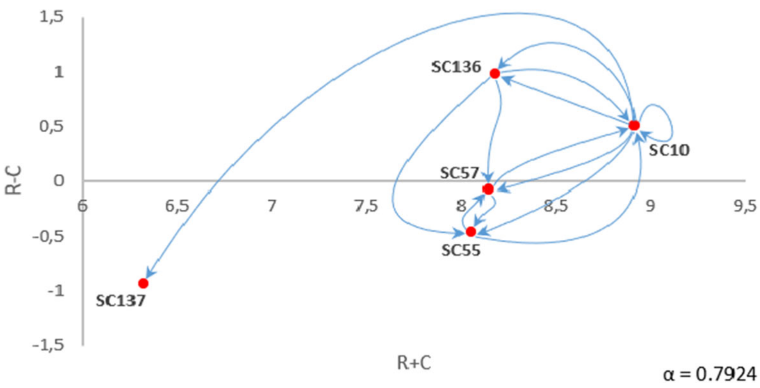

Fig. 8 Interrelationship map for well-being and quality of life

Table 29 Most significant subcriteria: information, training, and knowledge

Selected SCs	
SC91	Partnerships with research and teaching institutions
SC138	Empowerment of existing human resources with a new smart city vision
SC139	Reinforcement of municipalities with public human resources companies focused on smart cities
SC141	Identification of target audiences' real needs
SC147	Empowered, smart residents needed to develop smart cities

Table 30 Matrix with Neutrosophic Values: Information, Training, and Knowledge

	SC91	SC138	SC139	SC141	SC147
SC91	–	3.5 (0.8,0.3,0.1)	3.5 (0.7,0.5,0.2)	2.5 (0.6,0.3,0.3)	3.5 (0.8,0.2,0.1)
SC138	4.0 (0.9,0.2,0.1)	–	3.0 (0.6, 0.3,0.1)	3.0 (0.8,0.4,0.2)	3.5 (0.7,0.3,0.3)
SC139	3.5 (0.7,0.3,0.2)	4.0 (0.9,0.1,0.1)	–	3.0 (0.8,0.3,0.2)	3.5 (0.8,0.2,0.2)
SC141	3.0 (0.8,0.2,0.2)	3.5 (0.9,0.1,0.1)	3.5 (0.9,0.1,0.1)	–	3.0 (0.8,0.2,0.2)
SC147	3.5 (0.8,0.2,0.1)	3.5 (0.7,0.4,0.2)	3.0 (0.8,0.2,0.1)	2.5 (0.7,0.4,0.2)	–

Table 31 Direct-influence matrix: information, training, and knowledge

	SC91	SC138	SC139	SC141	SC147	TOTAL
SC91	0.0	2.7	2.3	1.7	2.9	9.6
SC138	3.4	0.0	2.1	2.2	2.5	10.2
SC139	2.6	3.6	0.0	2.3	2.8	11.2
SC141	2.4	3.2	3.2	0.0	2.4	11.1
SC147	2.9	2.4	2.5	1.7	0.0	9.5
TOTAL	11.3	11.9	10.0	7.8	10.5	

Table 32 Total-relation matrix T: information, training, and knowledge

	SC91	SC138	SC139	SC141	SC147	*R*
SC91	1.1292	*1.3426*	1.1525	0.9420	*1.2547*	5.8211
SC138	*1.4121*	1.2156	1.1969	1.0127	*1.2848*	6.1221
SC139	*1.4745*	*1.5642*	1.1420	1.1028	*1.4063*	6.6898
SC141	*1.4594*	*1.5375*	1.3504	0.9400	*1.3798*	6.6672
SC147	*1.3219*	*1.3235*	1.1642	0.9446	1.0579	5.8121
C	6.7971	6.9834	6.0061	4.9421	6.3835	

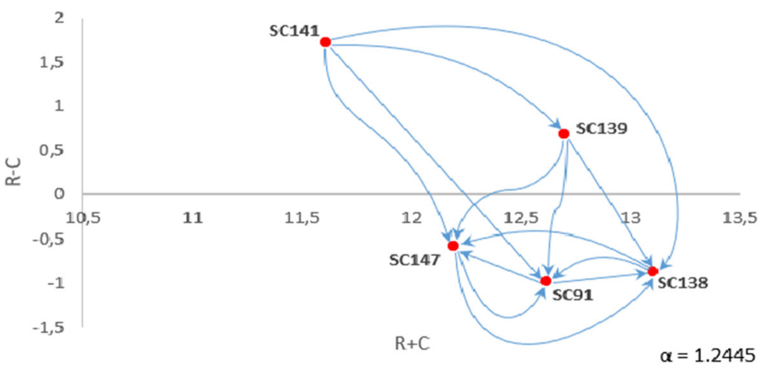

Fig. 9 Interrelationship map for information, training, and knowledge

Table 33 Most significant subcriteria: funding sources

Selected SCs	
SC162	Support used to fund innovative projects or the creation of added value
SC163	Recovery and Resilience Plan and other funds available to accelerate digitalization
SC164	Start-up investment using national and European funds and contributing to smart city creation
SC165	Companies and residents' investments
SC167	Return on investment with regard to the implementation of sustainability strategies

Table 34 Matrix with neutrosophic values: funding sources

	SC162	SC163	SC164	SC165	SC167
SC162	–	3.5 (0.8,0.3,0.1)	4.0 (0.8,0.3,0.1)	4.0 (0.8,0.3,0.1)	3.0 (0.7,0.2,0.1)
SC163	4.0 (0.8,0.3,0.1)	–	3.5 (0.8,0.2,0.1)	3.0 (0.7,0.3,0.2)	3.0 (0.8,0.3,0.2)
SC164	3.0 (0.8,0.2,0.2)	2.5 (0.7,0.5,0.4)	–	3.0 (0.8,0.3,0.2)	3.0 (0.8,0.2,0.2)
SC165	3.0 (0.7,0.3,0.1)	4.0 (0.8,0.4, 0.2)	3.5 (0.8,0.2,0.1)	–	3.0 (0.7,0.6,0.3)
SC167	3.5 (0.8,0.2,0.1)	3.0 (0.7,0.4,0.2)	3.0 (0.7,0.4,0.2)	3.5 (0.8,0.3,0.2)	–

Table 35 Direct-influence matrix: funding sources

	SC162	SC163	SC164	SC165	SC167	TOTAL
SC162	0.0	2.7	3.1	3.1	2.4	11.4
SC163	3.1	0.0	2.9	2.2	2.3	10.5
SC164	2.4	1.5	0.0	2.3	2.4	8.6
SC165	2.2	2.9	2.9	0.0	1.7	9.7
SC167	2.9	2.1	2.1	2.7	0.0	9.7
TOTAL	10.7	9.2	11.0	10.3	8.8	

Table 36 Total-relation matrix T: funding sources

	SC162	SC163	SC164	SC165	SC167	R
SC162	1.4845	1.5115	1.7570	1.6679	1.4424	7.8633
SC163	1.6186	1.2414	1.6557	1.5316	1.3679	7.4152
SC164	1.3522	1.1640	1.2208	1.3212	1.1834	6.2416
SC165	1.4740	1.3615	1.5608	1.2767	1.2542	6.9273
SC167	1.5185	1.3235	1.5184	1.4775	1.1253	6.9631
C	7.4477	6.6019	7.7128	7.2750	6.3732	

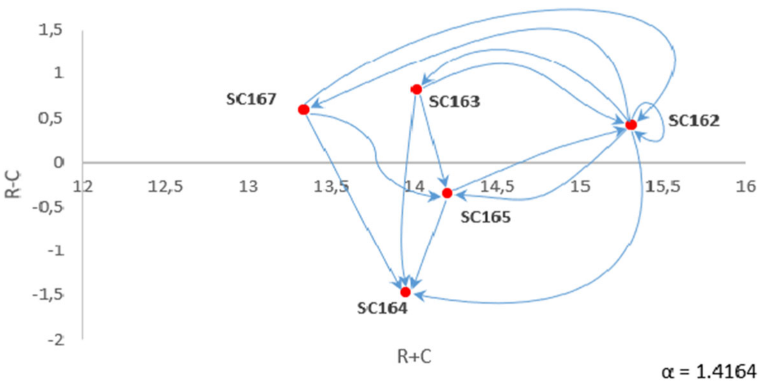

Fig. 10 Interrelationship map for funding sources

makers to add new information at any time, the analysis model is both empirically robust and versatile. Therefore, the use of combined methodologies ensured that the decision-support system developed is different from—yet complements—the existing models.

5 Conclusion

One of the main reasons for developing urban ecosystems is the urgent need to create smart, sustainable solutions for cities. Analyses of these ecosystems must be conducted to understand more fully what contributes to their success. The most important result in the present study was a model to support decisions regarding how to promote smart, sustainable urban ecosystems, which was produced by a combination of cognitive mapping and DEMATEL in a neutrosophic environment. These methodologies together generated a complete model of the problem under analysis that integrates objective and subjective elements and incorporates indeterminacy, thereby resulting in an analysis system of more evaluation criteria that reflect reality more closely. In addition, the model simplifies decision-making processes as it identifies which areas to prioritize and what should be done to support the conceptualization and analysis of smart, sustainable urban ecosystems. This study relied on specialists' knowledge. The expert panel's findings highlight that the construction of these ecosystems involves seven areas of concern, namely: *technological factors* (C1); *organizational factors* (C2); *communication and engagement* (C3); *environmental sustainability* (C4); *well-being and quality of life* (C5); *information, training, and knowledge* (C6); and *funding sources* (C7).

The research included the definition of a set of measures essential to developing smart, sustainable urban ecosystems. By identifying key initiatives and challenges, the proposed model helps decision makers identify more clearly what contributes to the creation of these ecosystems. The DEMATEL technique was applied in a neutrosophic environment to determine which determining factors should be prioritized in related analyses. This methodology considered the element of uncertainty in order to expand the conceptualization of smartness and urban sustainability and obtain more credible, transparent results.

Regardless of the many advantages of the selected approach, this study was not free of limitations. The first was the proposed model's dependency on the context in which it was developed, which means the results cannot be generalized to other settings without first making appropriate adaptations. The second limitation is that the methodologies required the participants to be fully dedicated and available for hours at a time. Thus, the recruitment of the decision-maker panel and harmonization of agendas proved challenging. The last restriction was that the chosen experts' profiles influenced the results since their different knowledge and experience shaped their judgement regarding neutrosophic priorities and values. The proposed model must, as a result, be adjusted to reflect the reality and/or vision found in other contexts in which the analysis system is applied. Nonetheless, the methodological tools adopted facilitated the design of a decision-support model that brings greater empirical robustness and clarity to the subject under analysis. The findings thus provide city planners with a better understanding of smart, sustainable urban ecosystems. The above results highlight the great potential of multicriteria methodologies for structuring and solving complex decision problems related to these ecosystems. The combination of methods enables more complete analyses, so these techniques offer advantages in terms of conceptualizing smartness and urban sustainability.

The aforementioned limitations suggest further lines of research. First, other multicriteria assessment techniques could be applied in combination with neutrosophic logic in order to produce more credible, transparent results. Second, researchers need to follow the same procedures with different expert panels. Last, additional analyses could be carried out in specific contexts to compare the results and identify divergences from the present proposed model. The construction of smarter and more sustainable urban ecosystems is clearly a topic with great potential for future research, and any new contributions that ensure more empirically robust findings will always offer significant benefits.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest. Informed consent was obtained from all individual participants included in the study.

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