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Innovative Applications of O.R.

Rethinking urban quality of life: Unveiling causality links using cognitive mapping, neutrosophic logic and DEMATEL

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A R T I C L E I N F O

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A B S T R A C T

Quality of life (QoL) is an important issue that reflects changes around the world caused not only by human population density, growth, and related initiatives but also by crises and pandemics. Concurrently, people's increasing tendency to live in urban areas has generated growing concerns about correctly assessing city QoL to facilitate the implementation of practical measures that favor both current and future generations' well-being. Conducting accurate analyses in this context is a challenging endeavor due to the subjectivity and complexity intrinsic to QoL evaluations. Thus, this study develops a multicriteria model based on a constructivist and complementarity logic that helps decision makers evaluate urban QoL. The proposed analysis system combines cognitive mapping, neutrosophic logic, and the decision-making trial and evaluation laboratory (DEMATEL) method in order to address the limitations of previous studies. This model also enhances experts' ability to decide which determining factors should be included in assessments of urban QoL. In addition, the system developed can help decision makers cope with uncertainty during evaluations because this holistic, realistic, and complete model fosters conscious decision making in urban contexts. The practical implications, advantages, and limitations of the proposed analysis system are also discussed.

1. Introduction

Since World War II, more emphasis has been placed on attaining a good quality of life (QoL) (Owczarek, 2010; Fernandes et al., 2018). The concept of QoL is still not entirely clear as no consensus has been reached about its scope (Royuela et al., 2009; Ebrahimzadeh et al., 2016; Mouratidis, 2020). Nonetheless, individuals are deeply concerned about their QoL, and they seek to create lifestyles that meet all their requirements (Din et al., 2013; Faria et al., 2018).

Because QoL is directly related to the needs of every human being, this concept is usually seen as complex, subjective, and difficult to understand (Moroke et al., 2018). On a global level, significant transformations have been reflected in changes in human behavior and preferences, including rural populations' increasing tendency to move to cities (United Nations (UN), 2020), and thus contribute to uncontrolled urban growth. Analyzing urban QoL has, therefore, become extremely important to city officials seeking to measure and conduct accurate assessments of their residents' well-being.

Empirically rigorous QoL evaluations are not an easy endeavor (Pukelienė & Starkauskienė, 2015; Ülengin et al., 2001). The intrinsic

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complexity and multi-dimensionality of this concept makes *"measuring* [QoL] *in a city* [...] *quite difficult"* (Khalil, 2012). To guarantee an adequate QoL in urban zones, experts should also ensure their approach to this concept incorporates sustainability as QoL comprises *"social, economic and environmental aspects"* (Faria et al., 2018).

Easy solutions cannot be found for complex problems. The existing literature contains some QoL assessment studies, but most fail to identify all the relevant evaluation criteria or to define the relative importance of each criteria used to analyze QoL. Prior research has further failed to conduct dynamic analyses of the interrelationships/correlations among QoL variables (*cf.* Faria et al., 2018).

To address these gaps, the present study seeks to strengthen decision makers' ability to perceive which determining factors and respective cause-and-effect relationships should be analyzed in QoL assessments in urban areas, so that the respective aggregate QoL level can be improved accordingly. Specifically, decision conferencing (DC) was used to facilitate the application of cognitive mapping techniques. A multi-criteria evaluation technique (*i.e.*, DEcision-MAking Trial and Evaluation Laboratory (DEMATEL)) was then applied in a neutrosophic environment to help the relevant experts deal with uncertainty during their decision-making process (Abdel-Basset et al., 2018). As such, two research questions were addressed:

- How can determining factors that affect urban QoL be identified, and how are they interrelated?
- Which determining factors have a significant enough impact that they should be given priority with regard to improving urban QoL?

This study adopts a constructivist, process-oriented approach based on learning through participation. The proposed combined methodology is not applied in order to provide an optimal solution. Instead, the results offer a clear, well-informed and coherent view of the issue under analysis.

The methodologies were implemented during two group sessions—held online because of the coronavirus disease-19 (COVID-19) pandemic—with a panel of experts in urban development. These sessions promoted discussions about how to structure the decision problem of enhancing QoL in urban areas and allowing relevant input for a group cognitive map to be obtained. The DEMATEL technique subsequently enabled the decision-maker panel to examine QoL cause-and-effect relationships and conduct the respective neutrosophic assessments. Because the present study combined cognitive mapping, neutrosophic logic, and DEMATEL for the first time in an urban QoL research context, the proposed framework contributes to the literature on urban QoL assessment and operational research/management science (OR/MS), thus facilitating further investigations of the decision problem in question.

This paper is organized into five sections. The second section presents a literature review of the QoL concept and some supporting conceptualizations. Section three discusses the methodology adopted in the study. Section four focuses on the methodological application and main results. Section five concludes the paper by summarizing the insights gained and making recommendations for future research.

2. Related literature and research gap

Despite a widespread belief in its importance for all individuals, QoL is not an easily understandable concept (Moroke et al., 2018). No universal definition of QoL exists, so different experts have proposed varying descriptions (*cf.* World Health Organization (WHO), 1993; Mostafa, 2012; Din et al., 2013; Ebrahimzadeh et al., 2016) in which QoL has been related to terms such as happiness, well-being, satisfaction, and good living conditions (Pukelienė & Starkauskienė, 2015; Mouratidis, 2020). According to Shoja et al. (2015), *"urban* [QoL] *represents more than* [...] *private 'living standards' and refers to all the elements of the conditions in which people live"*.

After highlighting that QoL is a key topic in efforts to deal with the challenges of rapid urbanization, Marans (2015) further observes that the places where individuals live influence their general satisfaction so that *"the*[se] *places can be designed to improve people's* [QoL]*"*. From a social construct perspective, experts who assess QoL are still uncertain about what to evaluate (Verdugo et al., 2012; Faria et al., 2018; Reis et al., 2019). Nonetheless, strategic planning is directly related to—and an important focus in—this field.

Due to rapid globalization and rural population migrations, most of the world's people currently reside in cities and urbanized metropolitan areas. As a result, *"global population growth is expected to take place almost exclusively in* [...] *cities and towns"* (UN, 2020). Urban areas have become comparatively more developed, offering *"a higher level of public services and more job opportunities"* (UN, 2020), but urban uncontrolled expansion and the resulting crises and pandemics (*e.g.*, COVID-19) have negatively affected many people's QoL (*cf.* Wann-Ming, 2019). Thus, strategic planning is crucial in urban areas to improve residents' QoL and to define practical measures that favor both current and future generations. Goal 11 of the UN Sustainable Development Goals is a commitment to making cities inclusive, safe, resilient, and sustainable (UN, 2020). In this context, places are commonly perceived according to the presence or absence of visual attributes such as street lighting, infrastructure, and walkways (Royuela *et al.*, 2009; Etman et al., 2014). In addition, residential areas may show signs of degradation and carelessness or physical disorder (*e.g.*, graffiti and vandalism) (Mason et al., 2013; Pinto et al., 2021; Ferreira et al., 2022), which can affect residents by making them feel so insecure that they end up not going outside to stroll, exercise, or just socialize with neighbors. These aspects thus negatively affect locals' perception of their QoL. Hur and Nasar (2014) report that *"neighborhood satisfaction is related to perceived upkeep* [...] *and* [...] *fear of crime, which affect neighborhood satisfaction* [... and which] *are related to actual upkeep"*.

According to Cabrera-Barona and Merschdorf (2018), urban planning should respect the principle of low entropy, organizing public spaces to promote social cohesion and encourage cooperation among citizens. Social segregation has been linked to levels of disorder that can result in problems, such as crime or aggression, and thus worsen residents' general perception of their QoL (Cabrera-Barona & Merschdorf, 2018; Costa et al., 2021). Although achieving the perfect residential area is extremely difficult, strategic planning can improve key components by fostering a more harmonious society mainly focused on sustainability.

In terms of the triple bottom line (*i.e.*, planet, people, and profit), the relationship between sustainability and QoL should be the basis for functional urban transformation (Moroke et al., 2018; Dobrovolskienė et al., 2019). Given the growing interest in making urban areas more sustainable, city planners need to acknowledge that all residents (*i.e.*, current and future generations) seek to satisfy their needs and achieve a better QoL (*cf.* Brundtland Report, 1987; Fernandes et al., 2018; Kaklauskas et al., 2018). In the end, measuring and analyzing urban QoL is a daunting endeavor because of the large number of variables involved. However, populations' growing tendency to live in cities has made municipal authorities increasingly interested in carrying out accurate analyses and evaluations of QoL in these areas. This pressing need and the topic's impact on residents have motivated various authors to develop techniques to assess QoL. Some of these studies are summarized in Table 1.

A careful examination of QoL-related studies reveals the broad scope of previous efforts to evaluate urban QoL, but no single methodology developed is perfect since the prior research shares similar limitations (*cf.* Fernandes et al., 2018). The first issue is the unclear way in which the evaluation criteria used in most investigations (see Table 1) were identified and defined (WHO, 1993; *Monocle Magazine*, 2011; Giap et al., 2014; Shoja et al., 2015; Gavrilidis et al., 2016; Patil & Sharma, 2022). Second, most existing assessment models are not clear in how they calculate the relative importance of the assessment criteria in urban QoL contexts (*Monocle Magazine*, 2011; Giap et al., 2014; Shoja et al., 2015;

Table 1
QoL-related Studies: Contributions and Limitations.

Authors	Methods	Contributions	Limitations
WHO (1993)	WHOQoL-100	• Reflects QoL multidimensional nature. • Enables QoL assessments in diverse cultural contexts. • Offers an instrument based on 100 items hierarchically classified into six domains: (1) physical health; (2) psychological health; (3) level of independence; (4) social relationships; (5) environment; and (6) spirituality and/or personal beliefs.	• The method was limited by shortcomings, producing unclear classifications because the Likert-type scale used (*e.g.*, "sometimes", "often" and "several times") can be interpreted differently by each interviewee.
Cummins (2000)	Interactive model	• Clarifies the interactions between objective and subjective indicators based on a useful conceptual framework.	• The model has difficulty specifying the relationship between variables in terms of objective contextual factors. • The results include weak correlations between the two types of indicators (*i.e.*, objective and subjective).
Monocle Magazine (2011)	*Monocle*'s most livable cities index	• Provides a global annual ranking that identifies the most livable cities worldwide with a focus on urban lifestyles. • Classifies cities' social and economic aspects and other features that can promote happiness. • Has a prescriptive function (*i.e.*, not only collects data but suggests what each city needs to do to achieve a better ranking).	• The index does not value demographic constraints (*e.g.*, poverty). • A magazine ranking does not guarantee that the data will not be manipulated to produce convenient findings. • One indicator can be overvalued, which would affect the final ranking.
Giap et al. (2014)	Global Livable Cities Index	• Adopts the perspective of a middle-class urban resident to avoid discrepancies in evaluations (*i.e.*, avoids overvaluing data from elite groups). • Concerned about weaker indicators.	• The index includes a reduced number of dimensions regarding habitability. • This measure adopts the maximum entropy principle, setting equal weights for all categories.
Shoja et al. (2015)	Subjective assessment of urban QoL indices	• Assesses and compares—using statistical analyses—physical-environmental dimension of urban QoL. • Considers cities' local conditions and characteristics wherever studies are conducted.	• The QoL indicators selected for the study were based in theories and the related literature.
Gavrilidis et al. (2016)	Urban Landscape Quality Index	• Evaluates and draws conclusions from urban landscapes in order to improve QoL. • Involves a simple short-term application that does not require many resources.	• The index calculation was only based on urban landscape features.
Faria et al. (2018)	QoL multiple-criteria evaluation model	• Covers a large number of criteria. • Developed a multifaceted, empirically robust model. • Includes objective and subjective elements.	• The technique used (*i.e.*, measuring attractiveness by a categorical-based evaluation technique) is difficult to apply in terms of reaching a consensus on how to construct descriptors and identify reference levels.
Patil and Sharma (2022)	Urban QoL assessment of Indian cities	• Facilitates the construction of indicators that represent city relative sustainable and holistic development. • Includes gender roles in QoL assessments. • Helps urban planners by comparing urban QoL scores in order to make policy decisions that improve QoL.	• The objective method used to weigh the indicators affected the results' ability to represent all aspects of urban development. • The method required data on 29 indicators, which may not be readily available to many cities.

Faria et al., 2018; Patil & Sharma, 2022). The last issue is the failure of researchers to explore and analyze the dynamics of cause-and-effect relationships among criteria (Cummins, 2000; Giap et al., 2014; Faria et al., 2018).

QoL is a complex topic that involves multiple interrelated variables (Ülengin et al., 2001; Faria et al., 2018). Given the general limitations of prior studies, a different tool appears to be needed to fill these gaps (*i.e.*, complementary methodologies). Thus, the present research assumes a constructivist, process-oriented position based on a combination of cognitive mapping and MCDA techniques in order to analyze urban QoL. These methods enabled the development of a new decision-support model. Specifically, this study applied cognitive mapping, neutrosophic logic, and DEMATEL, which facilitated the inclusion of qualitative and quantitative aspects into decision-making processes. Cognitive mapping was used to structure and define the decision problem, thereby identifying the evaluation criteria to be included in the model (Eden, 2004). As part of the MCDA approach, DEMATEL enabled dynamic analyses of cause-effect relationships among the criteria included in the cognitive map (Gabus & Fontela, 1972).

The proposed methodological framework takes into account both indeterminacy and uncertainty in decision making (*i.e.*, neutrosophic logic), which is always affected by unpredictability and ambiguity. By integrating indeterminacy into the decision-making process, neutrosophic logic and DEMATEL combine to form a holistic, realistic model (Abdel-Basset et al., 2018; Nagarajan et al., 2020). Therefore, the analysis system for urban QoL developed in the present study overcomes limitations previously identified in the literature.

3. Methodological background

The decision-support process applied in the present study had three main phases: (1) structuring; (2) evaluation; and (3) formulation of recommendations. In the first phase, cognitive mapping techniques were used to identify and select the evaluation criteria to be included in the model. In the second phase, the DEMATEL method was applied in combination with neutrosophic logic in order to analyze the interrelationships between different criteria. The third and final phase of the study focused on the formulation of recommendations based on the structured evaluations obtained from the expert panel in the previous phase. The presence of a neutral facilitator was essential to ensure the decision-support process ran smoothly, as this person was not a specialist in urban QoL but was knowledgeable in decision analysis and the techniques applied. The facilitator guided the process and managed the information that emerged without contributing to the content or directly interfering in the development of the decision-support model (Phillips, 2002).

3.1. Decision conferencing, cognitive mapping, and neutrosophic logic

Experts struggle to solve complex decision problems involving a large set of diverse criteria (Yazdi et al., 2020). Thus, most of the time, valuable information ends up being *"under-utilized or altogether excluded"* (Angelis & Kanavos, 2017). Shortcomings of this kind can be overcome by problem-structuring methods (PSMs), which emerged as *"an alternative paradigm for problem-solving"* (Smith & Shaw, 2019). PSMs aim to bridge and address flaws in traditional quantitative methods used in OR/MS, functioning as so-called soft OR systems. Rosenhead (2006) observes that PSMs can be applied to help decision makers cope with problematic situations characterized by: (1) multiple stakeholders; (2) different perspectives; (3) conflicts of interest; (4) significant intangibles; and (5) uncertainties. PSMs are thus methodological approaches that assist groups to understand—and develop comprehensive assessments of—decision problems (Ackermann, 2012).

In the current research, DC methodology was selected to provide support for the cognitive mapping techniques applied (Phillips & Bana e Costa, 2007; Barão et al., 2021). DC is based on meetings held to solve specific real-life problems (Gonçalves et al., 2018). This methodology provides essential help when any set of key actors join together to build a model that represents all their judgments, perspectives, and data, enabling these groups to think clearly about the decision problem in question (Gonçalves et al., 2018; Barão et al., 2021).

Cognitive mapping is commonly used as a PSM during group DC (Brito et al., 2019). Cognitive maps are important tools that function as cognitive representations of how individuals or groups understand a specific decision problem (Eden, 2004; Village et al., 2013). These maps *"can bring together uncertainty, different perspectives, conflicts of interest, and multiple decision makers, allowing decision problems to be structured quite intuitively"* (Castanho et al., 2021).

As a type of directed graph, cognitive maps are usually structured into a network format composed of nodes (*i.e.*, concepts, ideas, or constructs) and directed arrows that connect concepts (Ackermann & Eden, 2001; Eden, 2004; Milici et al., 2023). The direction of each arrow reflects causality, and the arrows can be given a positive (+) or negative (–) sign depending on the type of causal relationship perceived by the decision makers involved (Eden, 2004). In this way, cognitive maps can be versatile, simple, and interactive instruments that contribute to representing problems quite realistically due to these tools' *"ability to add multiple factors* [...] *without having a preconceived (optimal) solution"* (Carayannis et al., 2018).

However, simple cognitive maps cannot incorporate the intensity of causality relationships between concepts (*i.e.*, nodes), with various researchers underlining these maps' inability to portray the *"true dynamics of real decision problems"* (Ferreira & Meidutė-Kavaliauskienė, 2019). Different theories and types of cognitive mapping (*e.g.*, based on fuzzy and neutrosophic logic) have emerged to provide greater clarity during decision-making processes (Paiva et al., 2021). Still, fuzzy logic has been shown to have a limited ability to manage and describe complex uncertainty in decision problems (*cf.* Smarandache, 2006; Uluçay & Sahin, 2019). Since the real world is full of situations with ambiguous information that cannot be converted into clear values (Ferreira & Meidutė-Kavaliauskienė, 2019; Schweizer, 2020), the present study opted to follow the principles of neutrosophic logic. This approach was first introduced by Florentine Smarandache as an extension of fuzzy logic (*cf.* Kandasamy & Smarandache, 2003; Al-Subhi et al., 2018).

According to Al-Subhi et al. (2018), applying neutrosophic logic is *"helpful* [...when] *modeling decision-making problems since it considers all aspects of decision*[-making] *such as agree, not sure, and disagree"*. Neutrosophic logic is an alternative to other available forms of logic, complementing the more common binary approach (*i.e.*, true or false). Neutrosophic logic defines each logical variable x (*i.e.*, statement and/or decision criterion) as a neutrosophic set of three components: (1) degree of truth (T); (2) degree of indeterminacy (I); and (3) degree of falsity (F) (Smarandache, 2007). In this approach, the total of the percentages of T, I, and F may differ from 100 %, and the neutrosophic components are any real standard or non-standard subset of $[^-0, 1^+]$ (*i.e.*, $T \rightarrow [^-0, 1^+]$; $I \rightarrow [^-0, 1^+]$; $F \rightarrow [^-0, 1^+]$) (*cf.* Smarandache, 2007). In practice, assigning an exact number to an expert's opinion is quite restrictive when solving multicriteria decision-making problems (Cornelis et al., 2003). Thus, neutrosophic logic allows for a more comprehensive representation of reality in which *"uncertainty exists and is not negligible"* (Schweizer, 2020).

The use of neutrosophic logic in the present study raised a point often discussed in the literature regarding the way neutrosophic values are aggregated. This extremely important issue was addressed in the empirical research stage (see Section 4.3) by incorporating the DEMATEL technique into the neutrosophic environment as a mechanism to transform the three neutrosophic components (*i.e.*, T, I, and F) into a single-value (*i.e.*, crispification). The literature provides several formulas that can be applied to achieve this purpose.

Crispification can be done using Eq. (1) so that *"each $w_k = (T_k, I_k, F_k)$ is represented by a neutrosophic number"* (Pramanik et al., 2016). The values must respect two conditions of which the first is to be greater than or equal to zero (*i.e.*, $w_k \geq 0$). The second condition is that, after crispification, the total of the neutrosophic value for weight w of all evaluation criteria must be one (*i.e.*, $\sum_{k=1}^{r} w_k = 1$). In Eq. (1), r represents the total number of evaluations and/or comparisons carried out by the decision makers involved:

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

Despite being a relatively new approach, integrating indeterminacy into decision making can arguably generate more realistic results (*cf.* Al-Subhi et al., 2018; Nagarajan et al., 2020). As a structuring tool, cognitive mapping also ensures that all the elements to be included in the model are displayed. Together with the associated neutrosophic logic, these techniques ensure that all aspects of a given decision situation (*i.e.*, truth, indeterminacy, and falsity) can be represented.

3.2. DEMATEL

DEMATEL is a multicriteria decision analysis technique that allows decision makers to specify, analyze, and verify influential relationships between variables (Si et al., 2018). Developed in the 1970s by Gabus and Fontela (1972), DEMATEL focuses on structuring and examining interconnected, complex problems (Wu, 2008; Falatoonitoosi et al., 2013; Kobryń, 2017; Abdel-Basset et al., 2018). It has been suggested as a quick and effective way to deal with limited assumptions (*i.e.*, acknowledging conceptual interdependence), and to organize key concepts according to their importance (Aghelie et al., 2016; Yazdi et al., 2020).

DEMATEL allows experts to categorize decision criteria into causes (*i.e.*, higher priority factors that overall have a greater effect on other determinants) and effects (*i.e.*, lower priority factors that are overall more influenced by others). This procedure helps decision makers identify the most feasible solutions by ranking factors from higher to lower priority (Gabus & Fontela, 1972). Traditionally, factors' impacts are evaluated on a scale ranging from 0 to 4 (0 = "no influence"; 1 = "little influence"; 2 = "medium influence"; 3 = "strong influence"; and 4 = "very strong influence") (Gabus & Fontela, 1972; Falatoonitoosi et al., 2013; Kobryń, 2017; Si et al., 2018), after which five steps have to be completed (*cf.* Wu, 2008; Sivakumar et al., 2018).

3.2.1. Step one

Direct-influence matrix Z is calculated after a group of specialists E evaluates and finds solutions for a complex problem involving n factors or criteria. The experts start by making pairwise comparisons of the influence between factors using the aforementioned five-point scale. Notably, prior studies (*e.g.*, Milici et al., 2023; Guo et al., 2024) have used intermediary values with 1+ significant digits within the initial 0–4 point scale as a nuanced approach to capture more subtle distinctions in the evaluation process. The result is a non-negative matrix n x n expressed as $Z = [a_{ij}]\ n \times n$ and represented as shown in Eq. (2):

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

where a_{ij} stands for the degree of influence that criterion C_i has on criterion C_j.

3.2.2. Step two

The initial direct-influence matrix is normalized to generate a normalized direct-influence matrix or matrix X. This procedure is done using 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 normalization constant representing the maximum effect that the total of lines i of matrix Z has on other factors, as well as the maximum effect that the total of columns j of matrix Z receives from the remaining factors. Each element in matrix X has values within the range of [0,1].

3.2.3. Step three

The total-relation matrix T is calculated in this step. Matrix $Tn \times n$ is constructed using Eq. (5):

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

in which X^h is the degree of influence of the h^{th} factor, I is denoted as an identity matrix, and the sum of $X, X^2, \ldots, X^h$ results in the variables' total ratio. Essentially, matrix T provides information about how one factor affects another. It is constructed by adding the value of the direct and indirect effects, and reflects the total degree of influence in the relationships between each pair of factors.

3.2.4. Step four

The totals of the lines and of the columns of matrix T are then calculated. These total values are denoted as vectors R and C, respectively. These vectors are represented by Eqs. (6) and (7):

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

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

Thus, matrix *[r_i]* represents the factors' driving power, and *[c_j]'*—as a transposed matrix—represents their dependence. Given that $i = j$ and i, $j \in \{1, 2, \ldots n\}$, the $R + C$ value is designated as "prominence" (*i.e.*, the degree of importance that a factor has in the analysis system). The $R - C$ value, in turn, is termed "relation" or "relationship" (*i.e.*, a factor's degree of influence in the system). These values are used to divide the factors into two groups: (1) causes (*i.e.*, donors); and (2) effects (*i.e.*, receivers).

3.2.5. Step five

The fifth step is to calculate a threshold (α) value in order to identify the most critical factors in the decision-support system and to construct an impact relationship map (IRM). The α value is defined as the average value of all elements present in matrix T, which are added and then divided by the total number of elements ($N = n^2$). Eq. (8) is used to calculate the α value:

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

This last step eliminates the least significant factors in matrix T, thereby making interpreting the IRM easier for decision makers. DEMATEL IRMs are constructed based on the coordinate sets ($r_i + c_i$, $r_j - c_j$). As shown in Fig. 1, the IRM is divided into four quartiles (QI–QIV), which separate the determinants or factors into: (1) core factors in QI; (2) driving factors in QII; (3) independent factors in QIII; and (4) impact factors in QIV, depending on the position of their coordinates.

In general, DEMATEL is a powerful tool that can help experts to identify and analyze practical solutions to complex decision problems (Falatoonitoosi et al., 2013). This approach requires decision makers to assess factors based on scores (see step one in Section 3.2.1), yet, as previously mentioned, assigning only one number to each expert's opinion is extremely restrictive. The results also are not always useful to decision makers. For this reason, the present study opted to combine DEMATEL with neutrosophic logic.

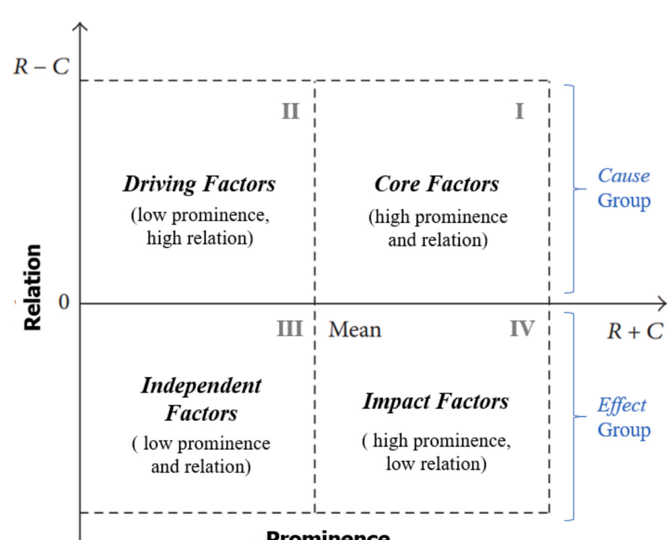

Fig. 1. Impact Relationship Map for DEMATEL Analysis, Source: Adapted from Si et al. (2018).

4. Application and results

4.1. Expert selection and panel composition

The main research goal is to develop a multicriteria analysis system to facilitate decision making by identifying and analyzing determining factors of urban QoL. To this end, cognitive mapping techniques were applied (*i.e.*, structuring phase), followed by DEMATEL combined with neutrosophic logic (*i.e.*, evaluation phase). These techniques required a panel of specialists to be created. The participants were *"decision-makers* [… with] *experience in the field"* (Abdel-Basset et al., 2018), who were available to attend two group work sessions lasting a total of eight hours. Authors have suggested that the ideal is *"a decision-making group of 5–7 experts and other key-players"* (Bana e Costa et al., 2002) or *"a small number* [… of from] *three to ten persons"* (Eden & Ackerman, 2001). Thus, the present study's panel comprised eight professionals specializing in areas directly related to urban QoL.

Specifically, the group included two environmental engineers, one of whom was an environmental sanitation engineer working for the Water and Waste Services Regulation Authority. Two other experts were a senior technical architect with the Lisbon City Council, and a deputy senior landscape architect with the Secretary of State for the Environment. A fifth specialist was a senior technician from the Lisbon Municipal Mobility and Parking Company, while a sixth was the division head of the Cascais Municipal Council Sustainability Policies and Climate Action Department. The last two panel members were a senior technician working for the Portuguese Institute for Mobility and Transportation, and the president of the Quinta da Carreira Residents Association, who represented the residents' perspective. The eight experts expressed an active interest in participating and analyzing the decision problem of urban QoL, affirming that they were available to share their experience and knowledge in the group work sessions.

The COVID-19 pandemic restrictions required social distancing. Thus, both sessions were conducted entirely through online platforms. As mentioned previously, a facilitator (*i.e.*, one of the authors of this study) guided the online meetings, helping to create an environment that encouraged interactions. In this sense, the latter participant did not directly interfere in the model development. The panel work produced findings that reflect the methodology's constructivist orientation and strong focus on process. Overall, the objective was not to achieve representativeness or optimal solutions (*cf.* Bana e Costa et al., 2002; Ormerod, 2020). The methodological procedures followed in the current study are presented in Fig. 2.

4.2. Structuring phase: collective cognitive map

To define the decision problem, the first session comprised the structuring phase. According to Belton and Stewart (2010), this phase provides *"a rich description of the problem from which an appropriate multicriteria model may be derived"*. The session lasted for about three and a half hours, and it was attended by the decision makers, facilitator, and a technical assistant responsible for registering the outcomes.

The session started with a brief overview of the concepts underlying the methodologies to be applied to ensure the expert panel would be well informed before starting the decision-making process. The Miro platform (http://www.miro.com) was used in this session to enable simultaneous virtual interactions between all the specialists, which allowed them to complete all the steps of structuring the decision problem in an organized manner. To start the process, the facilitator asked the panel a trigger question: *"Based on your values and professional experience, what determinants or factors affect QoL in urban areas?"*. Ribeiro et al. (2017) specify that, *"during this phase of the process, the panel members* [… should be] *invited to share opinions, perceptions, experiences and values"*, in this case regarding urban QoL.

The experts' exchange of information was made possible by the "post-its technique" (Ackermann & Eden, 2001). To apply this technique online, digital post-it notes were made available via the Miro platform to all the decision makers, which enabled them to write relevant criteria—one on each post-it note—that answered the trigger question. Depending on the criterion's impact on urban QoL, a plus (*i.e.*, a positive influence) or minus sign (*i.e.*, a negative influence) was added to the digital post-it note.

This process had to be *"repeated until the decision makers demonstrated satisfaction with the quantity and depth of the revealed criteria"* (Ferreira et al., 2016), ensuring the results included multiple determinants or factors related to the decision problem. Criteria that were repeated or

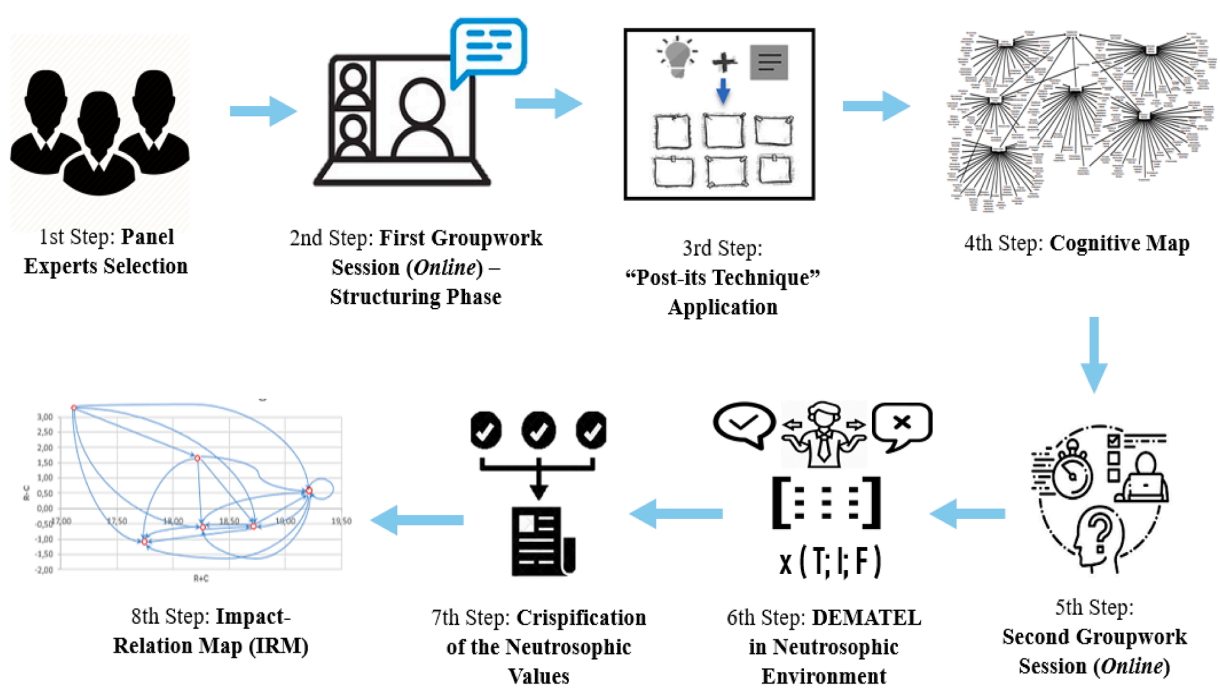

Fig. 2. Procedures Followed in the Empirical Research.

too similar were eliminated or rewritten. After identifying all the significant criteria, the experts were invited to work together to divide the criteria into areas of concern (*i.e.*, clusters). All the criteria were placed in six clusters, which were given the following labels: (1) *Public Spaces*; (2) *Transportation and Mobility*; (3) *The Environment and Health*; (4) *Participation, Citizenship, and Governance*; (5) *City Policy and Urbanism*; and (6) *Facilities and Services*.

The final step completed in this first session was to organize the criteria according to their importance inside each cluster so that the most significant appeared at the top and the least important at the bottom. Based on the information collected (*i.e.*, criteria and clusters identified), a group cognitive map was generated using the *Decision Explorer* software (http://www.banxia.com). The panel members then collectively reviewed, analyzed, and validated the map at the beginning of the second group session. The decision makers also were given the chance to adjust the decision criteria, clusters, and the cognitive structure shape. The final version of the group cognitive map contains approximately 150 criteria, as shown in Fig. 3 (size restrictions prevent a better visualization, but an editable version of the entire map can be obtained from the corresponding author upon request).

The map presented in Fig. 3 provided the decision-maker panel with a holistic view of the decision problem under analysis, and a better understanding of the causal relationships among the factors that affect urban QoL. Once the group's knowledge was garnered and the structuring phase completed, the second session could focus on applying DEMATEL combined with neutrosophic logic.

4.3. Evaluation phase: DEMATEL in neutrosophic context

The second online meeting with the decision makers relied on the DEMATEL technique paired with neutrosophic logic to facilitate their participation in the evaluation phase. The combined methodology was briefly explained to the experts, including emphasizing that the two approaches together offer advantages since they *"depict […] the disagreement of decision makers and experts"* (Abdel-Basset *et al.*, 2018). The panel members were then invited to conduct an analysis of the clusters' degree of influence on each other using the traditional DEMATEL scale (*i.e.*, 0 = "no influence"; 4 = "very strong influence").

The decision makers were also asked to identify the probability of their judgment being either true (*T*), uncertain (*I*), or false (*F*) in the form of percentages (*i.e.*, the neutrosophic values of the inter-cluster relationships). The value assigned to each relationship was given as $x(T, I, F)$, which gave the experts the freedom to express the meaning of their judgments more accurately. The panel was further informed that, in neutrosophic logic, the total of the percentages given to *T*, *I*, and *F* can be different from 100%.

After the neutrosophic values were incorporated into the process, the first task was to carry out the crispification of the values obtained in order to define the initial input needed to apply DEMATEL. To this end, an extra calculation had to be done using Eq. (1) (see Section 3.1) to achieve crispification of all the matrix cells $x(T, I, F)$ produced during the session (*i.e.*, all the values assigned by the decision makers to each relationship under analysis). The crisp values were then used to complete all the DEMATEL steps (see Section 3.2).

The analysis focused on the relationships between the clusters identified (see Table 2). The second group work session produced the matrix shown in Table 3, which includes the neutrosophic values given by the decision makers. For example, the panel members decided that the influence of C3 on C4 is 1.50 (*i.e.*, between "little influence" and

Table 2
Clusters Identified.

Clusters	
C1	Public Spaces
C2	Transportation and Mobility
C3	The Environment and Health
C4	Participation, Citizenship, and Governance
C5	City Policy and Urbanism
C6	Facilities and Services

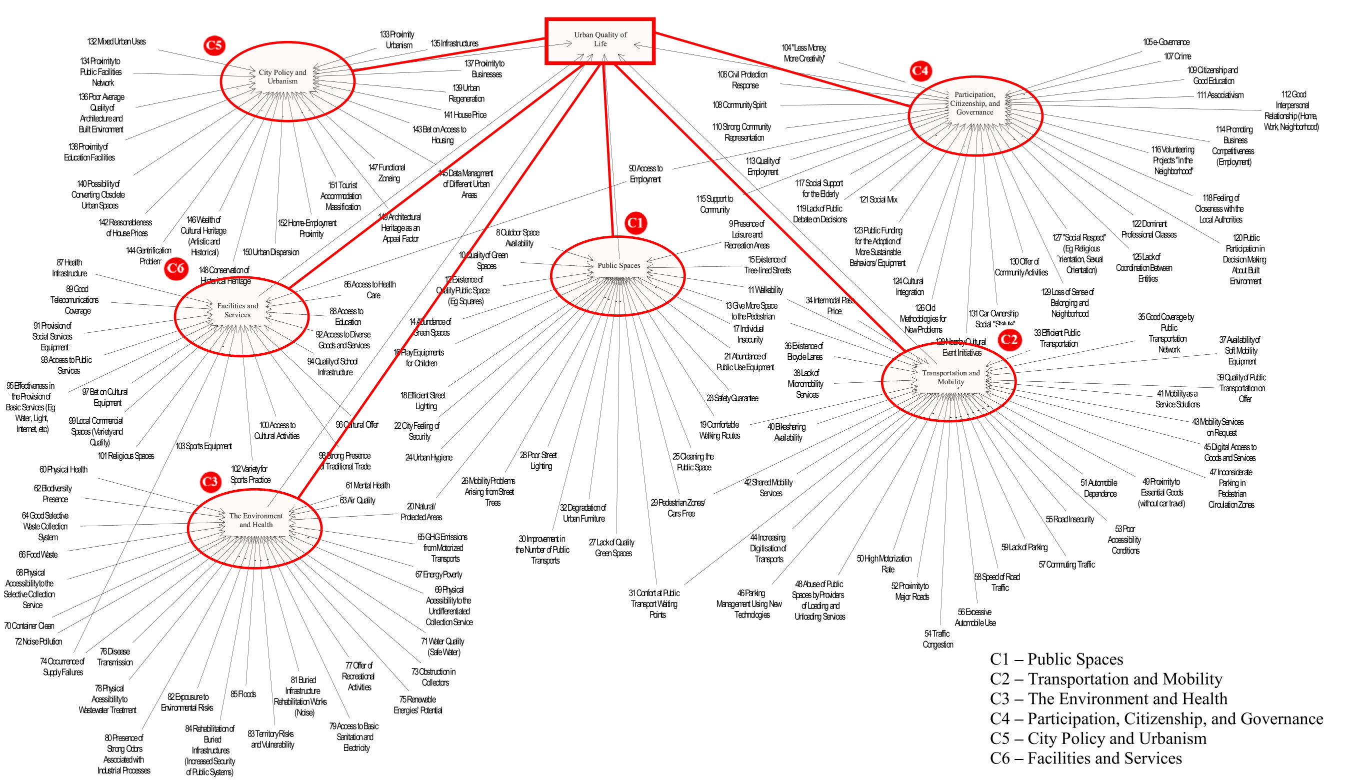

Fig. 3. Group Cognitive Map.

Table 3
Group matrix with neutrosophic values for clusters.

	C1	C2	C3	C4	C5	C6
C1	–	2.00 (0.80; 0.25; 0.10)	3.50 (0.70; 0.30; 0.10)	2.50 (0.75; 0.40; 0.10)	0.50 (0.70; 0.40; 0.20)	1.50 (0.80; 0.20; 0.10)
C2	4.00 (0.90; 0.10; 0.00)	–	4.00 (0.95; 0.00; 0.00)	1.00 (0.90; 0.10; 0.05)	2.50 (0.80; 0.20; 0.10)	1.50 (0.80; 0.20; 0.10)
C3	4.00 (0.95; 0.10; 0.00)	1.00 (0.80; 0.25; 0.10)	–	1.50 (0.80; 0.50; 0.10)	3.00 (0.80; 0.20; 0.10)	1.00 (0.70; 0.30; 0.10)
C4	4.00 (0.80; 0.20; 0.00)	2.00 (0.70; 0.30; 0.20)	3.50 (0.80; 0.20; 0.10)	–	4.00 (0.95; 0.10; 0.10)	1.50 (0.50; 0.50; 0.20)
C5	4.00 (0.99; 0.00; 0.00)	4.00 (0.95; 0.07; 0.00)	4.00 (0.95; 0.05; 0.00)	3.00 (0.70; 0.40; 0.10)	–	4.00 (0.90; 0.10; 0.00)
C6	2.50 (0.60; 0.30; 0.20)	3.00 (0.90; 0.10; 0.00)	1.00 (0.60; 0.45; 0.20)	2.50 (0.80; 0.20; 0.10)	2.50 (0.70; 0.40; 0.20)	–

“medium influence”), and that the probability of their judgment being true is 80%, 10% that it is false, and that the degree to which they are not sure is 50%. In neutrosophic notation, this is expressed as 1.50 (0.80; 0.50; 0.10) (the sum does not necessarily equal 1) (*cf.* Smarandache, 2007).

Specifically, the degrees of influence and respective neutrosophic values were directly provided by the panel members—and validated by them—after intense collective discussion and negotiation. Although this procedure is non-linear and inherently subjective, an important feature is that it allows for an interactive exploration of changes in the inputs to the model, such that the impact of such changes can be seen immediately, offering opportunities for further discussion.

Due to its recursive nature, this procedure is also versatile and can accommodate new information at any time. As noted by Belton and Stewart (2010), the importance of group dynamics and negotiation should be highlighted here, because the interactive nature of MCDA methods allows individuals to confront different opinions and to reach more consensual solutions. The neutrosophic matrix values were then subjected to crispification. The results of this step are given in Table 4.

As can be seen in Table 4, the final values used to construct the DEMATEL direct-influence matrix (see Table 5) were obtained by multiplying the crispified neutrosophic value (*i.e.*, the crispification equation numerator) by the degree of influence assigned by the decision makers (*i.e.*, DEMATEL scale value (x) determined for each causal relationship). For example, the final value for the relationship between C1 and C2 (*i.e.*, 1.61 in the last column of Table 4) is the product of the

Table 5
Group direct-influence matrix Z for clusters.

	C1	C2	C3	C4	C5	C6	Total
C1	0.00	1.61	2.62	1.80	0.34	1.24	7.62
C2	3.67	0.00	3.88	0.91	2.07	1.24	11.78
C3	3.74	0.81	0.00	1.03	2.48	0.75	8.80
C4	3.35	1.46	2.89	0.00	3.65	0.86	12.20
C5	3.98	3.80	3.84	2.12	0.00	3.67	17.41
C6	1.72	2.76	0.63	2.07	1.72	0.00	8.90
TOTAL	16.46	10.43	13.86	7.93	10.26	7.76	

Table 4
Crisp neutrosophic values for clusters.

	Rela-tion-ships ana-lyzed	DEMATEL Scale (X)	Neutrosophic values (T, I, F)			Neutrosophic crispification		
			T	*I*	*F*	Crispifi-cation equation numera-tor	Crisp weight W	Final value in matrix Z
Clusters Matrix	C1-C2	2.00	0.80	0.25	0.10	0.8063	0.03	1.61
	C1-C3	3.50	0.70	0.30	0.10	0.7483	0.03	2.62
	C1-C4	2.50	0.75	0.40	0.10	0.7216	0.03	1.80
	C1-C5	0.50	0.70	0.40	0.20	0.6891	0.03	0.34
	C1-C6	1.50	0.80	0.20	0.10	0.8268	0.03	1.24
	C2-C1	4.00	0.90	0.10	0.00	0.9184	0.04	3.67
	C2-C3	4.00	0.95	0.00	0.00	0.9711	0.04	3.88
	C2-C4	1.00	0.90	0.10	0.05	0.9134	0.04	0.91
	C2-C5	2.50	0.80	0.20	0.10	0.8268	0.03	2.07
	C2-C6	1.50	0.80	0.20	0.10	0.8268	0.03	1.24
	C3-C1	4.00	0.95	0.10	0.00	0.9355	0.04	3.74
	C3-C2	1.00	0.80	0.25	0.10	0.8064	0.03	0.81
	C3-C4	1.50	0.80	0.50	0.10	0.6838	0.03	1.03
	C3-C5	3.00	0.80	0.20	0.10	0.8268	0.03	2.48
	C3-C6	1.00	0.70	0.30	0.10	0.7483	0.03	0.75
	C4-C1	4.00	0.80	0.20	0.00	0.8367	0.03	3.35
	C4-C2	2.00	0.70	0.30	0.20	0.7292	0.03	1.46
	C4-C3	3.50	0.80	0.20	0.10	0.8268	0.03	2.89
	C4-C5	4.00	0.95	0.10	0.10	0.9134	0.04	3.65
	C4-C6	1.50	0.50	0.50	0.20	0.5757	0.02	0.86
	C5-C1	4.00	0.99	0.00	0.00	0.9942	0.04	3.98
	C5-C2	4.00	0.95	0.07	0.00	0.9503	0.04	3.80
	C5-C3	4.00	0.95	0.05	0.00	0.9592	0.04	3.84
	C5-C4	3.00	0.70	0.40	0.10	0.7056	0.03	2.12
	C5-C6	4.00	0.90	0.10	0.00	0.9184	0.04	3.67
	C6-C1	2.50	0.60	0.30	0.20	0.6891	0.03	1.72
	C6-C2	3.00	0.90	0.10	0.00	0.9184	0.04	2.76
	C6-C3	1.00	0.60	0.45	0.20	0.6337	0.03	0.63
	C6-C4	2.50	0.80	0.20	0.10	0.8268	0.03	2.07
	C6-C5	2.50	0.70	0.40	0.20	0.6891	0.03	1.72
$\sum_{k=1}^{r} w_k^c = 1.00$, complies with Eq. (1)'s conditions					Crispification equation denominator	24.4160	1.00	

crispification equation numerator (*i.e.*, 0.8063) and the respective DEMATEL value (*i.e.*, 2.00 in second column in Table 4) (*cf.* Smarandache, 2007; Pramanik et al., 2016). The results (*i.e.*, the final crisp weights) were used to complete the direct-influence matrix Z (*i.e.*, DEMATEL step one (see Section 3.2.1)), which is presented in Table 5. This step allowed the panel to proceed to the remaining steps (i.e., steps two through five in Section 3.2).

In step two, the normalized direct-influence matrix X was obtained based on Eqs. (3) and (4) (see Section 3.2.2). Table 6 displays the results of this second step.

The next step (*i.e.*, step three in Section 3.2.3) comprised the construction of total-relation matrix T. This matrix was calculated using Eq. (5) after the three required matrices (*i.e.*, matrix I, $I-X$, and $I-X^{-1}$) were obtained. The results are shown in Table 7.

In matrix T (see Table 7), column R is the totals of each line estimated using Eq. (6), and row C is the totals of each column calculated using Eq. (7) in step four (see Section 3.2.4) of the DEMATEL application. Specifically, the R values reflect each cluster's overall influence on the remaining clusters. The results reveal that C5 has an influence of 2.4579 over the others. In contrast, C1 has the smallest impact on the other clusters given its R value of 1.1428. A C value, in turn, indicates the total influence of all the remaining clusters on the cluster in question. For instance, the C value for how much C1 is influenced by the remaining clusters is 2.4131, which confirms that C1 is the most affected by all the other clusters with the analysis system.

The α value of 0.2763 was also calculated using Eq. (8) (see Section 3.2.5). Because this value is the average of all values in matrix T, α highlights the more significant relationships affecting urban QoL (*i.e.*, values in green in matrix T). This significance was reflected in the IRMs constructed since only the links considered important were included in the analyses. Other essential values taken into account were the addition and subtraction of the R and C values. Table 8 shows the combination of these values, which provides a fuller understanding of the clusters' significance.

The fifth step involved producing a DEMATEL diagram (*i.e.*, IRM) that represents the final results of the cluster analysis. This IRM (see Fig. 4) presents the distribution of the six clusters identified in the cognitive map along two axes, as well as the cause-and-effect relationships among them. Given that $R + C$ values reflect the total effects given and received by each cluster, the $R + C$ axis reveals the clusters' prominence in the decision-support system. A greater value on this horizontal axis corresponds to a greater impact on the model under analysis. According to the specialist panel, C5 is the most important in the model, with the highest $R + C$ value (*i.e.*, 3.9502). The lowest $R + C$ value (*i.e.*, 2.6023) was assigned to C6, making it the least important due to its lesser impact within the analysis system. The clusters can be ranked overall by order of importance as C5 > C1 > C3 > C2 > C4 > C6.

The $R – C$ value reveals the degree of influence that each criterion's relationships have on the system, thereby dividing the clusters into two groups: causes (*i.e.*, when $R – C > 0$), and effects (*i.e.*, when $R – C < 0$). The clusters can be classified based on their position on the $R – C$ axis (see Fig. 4). C2, C4, C5, and C6 have positive R – C values, signifying that these clusters are causes and that they affect others more than they are affected. In the effects group with negative $R – C$ values, C1 and C3 fall below the $R + C$ axis, so they are overall more affected by the other clusters. Finally, based on the IRM four quartiles (see Fig. 1 in Section 3.2.5), C5 is a core factor; C2, C4, and C6 are driving factors; and C1 and C3 are impact factors.

Next, each of the six clusters considered in the proposed model were subjected to similar analyses following the same logic (*i.e.*, $x(T, I, F)$) and the five DEMATEL steps. Before these analyses could begin, the decision makers had to select the most important criteria within each cluster because of the large number of criteria identified. Nominal group and multi-voting techniques were used to facilitate the selection process. All the subsequent initial DEMATEL matrices (*i.e.*, group direct-influence matrix Z) include crisp weights that were estimated using the same equations as in the inter-cluster analysis (*i.e.*, crispification of the neutrosophic values). Thus, the intra-cluster analyses followed the same sequence of procedures based on more realistic values to construct matrix T and the final IRM for each cluster.

The panel members selected the most important criteria from C1 (see Table 9). These factors are referred to as specific criterion (SC) to differentiate them from the six clusters. The neutrosophic values estimated during the second session underwent crispification (see Table 10) so that group direct-influence matrix Z could be filled in with crisp values (see Table 11) and the final results could be generated. These two matrices clearly reflect the uncertainty incorporated into the degrees of influence assigned by the decision makers.

According to Table 12, the most influential criterion is SC24, with an R value of 5.7540. In contrast, SC11 is the most influenced by the other selected criteria, followed by SC22, with C values of 6.1233, and 5.8257, respectively. Based on the $R + C$ values, the IRM in Fig. 5 reveals that the C1 criteria's overall prioritization by importance is SC22 > SC11 > SC24 > SC10 > SC9. SC22 is the most important SC in the present analysis as this criterion has the highest $R + C$ value (11.2726).

As can be seen in Fig. 5, SC9, SC10, and SC24 fall above the $R – C$ axis (*i.e.*, criteria with a positive value), so they comprise the causes group. In contrast, SC11 and SC22 appear at the bottom of the DEMATEL diagram (*i.e.*, with a negative $R – C$ value), making them effect criteria, namely the most affected by the remaining SCs. The IRM in Fig. 5 also reveals that SC24 is a core factor, SC10 and SC9 are driving factors, and SC11 and SC22 are impact factors.

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

As Table 16 shows, SC35 was identified as the factor that not only most influences the other criteria, with an R value of 3.1604, but also is most influenced by the remaining criteria, with the highest C value of 2.6619. These values indicate that SC35 is the most important criterion (*i.e.,* $R + C$ value is 5.8223) as opposed to SC34, which is the least significant as it has the lowest $R + C$ value (0.5146) and which appears to the IRM's far left side (see Fig. 6). By order of importance, these criteria can be ranked as follows: SC35 > SC39 > SC33 > SC47 > SC34.

Regarding the two groups revealed by the $R – C$ values, SC47 has a negative value, so it is an effect criterion, while the other criteria under analysis (*i.e.*, SC33, SC34, SC35, and SC39) make up the cause or influencer group. Based on the SCs' positions in the diagram (see Fig. 6), the most important links (*i.e.*, green matrix T cells) between the other criteria indicate that the criteria should be categorized as follows: SC33, SC35, and SC39 as core factors; and SC47 as an independent factor.

C3 was analyzed by following all the same steps. The most significant SCs in this cluster were also selected (see Table 17). Table 18 shows the neutrosophic value matrix created by the panel, while Table 19 presents the results after crispification. The latter table lists the degrees of influence assigned to the five selected SCs.

Table 6
Normalized direct-influence matrix X for clusters.

Max.	16.46	17.41				
1/max.	0.0607	0.0574				
1/s	0.0574					
	C1	C2	C3	C4	C5	C6
C1	0.0000	0.0926	0.1505	0.1036	0.0198	0.0712
C2	0.2110	0.0000	0.2232	0.0524	0.1187	0.0712
C3	0.2150	0.0463	0.0000	0.0589	0.1425	0.0430
C4	0.1923	0.0838	0.1660	0.0000	0.2097	0.0494
C5	0.2286	0.2184	0.2204	0.1216	0.0000	0.2110
C6	0.0990	0.1583	0.0364	0.1187	0.0990	0.0000

Table 7
Total-relation matrix *T* for clusters.

	C1	C2	C3	C4	C5	C6	*R*
C1	0.1854	0.1931	0.2887	0.1849	0.1411	0.1495	1.1428
C2	0.4560	0.1682	0.4273	0.1901	0.2683	0.2001	1.7099
C3	0.4004	0.1856	0.1907	0.1702	0.2506	0.1542	1.3517
C4	0.4705	0.2708	0.4103	0.1554	0.3624	0.2040	1.8735
C5	0.5831	0.4334	0.5223	0.3087	0.2389	0.3715	2.4579
C6	0.3176	0.2858	0.2399	0.2223	0.2312	0.1131	1.4099
C	2.4131	1.5369	2.0793	1.2317	1.4924	1.1924	

Table 8
Given and received influence between clusters.

	R	*C*	*R* + *C*	*R* – *C*
C1	1.1428	2.4131	3.5559	–1.2703
C2	1.7099	1.5369	3.2468	0.1730
C3	1.3517	2.0793	3.4309	–0.7276
C4	1.8735	1.2317	3.1051	0.6418
C5	2.4579	1.4924	3.9502	0.9655
C6	1.4099	1.1924	2.6023	0.2176

The IRM in Fig. 7 reflects the values listed in Table 20. SC82 is the criterion that most influences the other determinants, with a total *R* value of 1.4876 (*i.e.*, the highest). In contrast, SC60 is the most affected by all the other criteria, with a *C* value of 1.4876. The *R* + *C* values reveal that SC60 is the most important factor in this cluster, appearing the farthest to the right in the map, while SC71 is the least important. The values of these SCs are 1.8209 and 0.9073, respectively. By order of importance, the SCs can be ranked as follows: SC60 > SC82 > SC61 > SC63 > SC71.

Regarding the division into causes or effects, SC63, SC71, and SC82 belong to the cause group (*i.e.*, a positive *R* – *C* value). SC60 and SC61 have negative *R* – *C* values, so they form the effect group influenced by the causes. An examination of the IRM quartiles (see Fig. 7) confirmed that SC82 is a core factor, SC63 and SC71 are driving factors, and SC60 and SC61 are impact factors.

In the fourth cluster, the panel members selected the criteria presented in Table 21. The crispification formula had been previously applied, so the panel was able to transform the group neutrosophic matrix (see Table 22) into the group direct-influence matrix shown in Table 23.

Table 24 shows that SC109 has the most influence on all the criteria, with an *R* value of 7.3912. In turn, the highest *C* value (7.2068) makes SC120 the one that receives the most effects from the remaining criteria. Thus, this determinant is the most strongly influenced. With the highest *R* + *C* value, SC109 is also overall the most important criterion, closely followed by SC120 and SC108. These three criteria have extremely similar *R* + *C* values of 14.3274, 14.2259, and 14.1376, respectively. SC105 is at the opposite extreme of the diagram, with an *R* + *C* value of 7.1288. This SC was not included in the DEMATEL diagram (see Fig. 8) because it has no significant relationships with the remaining SCs under analysis, as confirmed by all the red cells in Table 24 (*i.e.*, values below

Table 9
Most significant criteria: public spaces cluster.

Selected criteria	
SC9	Presence of leisure and recreation areas
SC10	Quality of green spaces
SC11	Walkability
SC22	City feeling of security
SC24	Urban hygiene

Table 10
Group matrix with neutrosophic values: public spaces cluster.

	SC9	SC10	SC11	SC22	SC24
SC9	–	3.00 (0.80; 0.20; 0.10)	4.00 (0.90; 0.10; 0.00)	2.00 (0.70; 0.30; 0.10)	2.00 (0.70; 0.30; 0.10)
SC10	4.00 (0.90; 0.10; 0.00)	–	2.50 (0.70; 0.30; 0.10)	3.00 (0.80; 0.20; 0.10)	2.50 (0.70; 0.30; 0.10)
SC11	2.00 (0.70; 0.30; 0.20)	2.00 (0.70; 0.30; 0.20)	–	3.50 (0.80; 0.20; 0.05)	3.00 (0.80; 0.20; 0.10)
SC22	2.50 (0.70; 0.30; 0.10)	2.50 (0.60; 0.40; 0.30)	4.00 (0.95; 0.00; 0.00)	–	3.50 (0.70; 0.30; 0.10)
SC24	1.00 (0.90; 0.10; 0.05)	4.00 (0.95; 0.00; 0.00)	2.50 (0.70; 0.30; 0.10)	4.00 (0.90; 0.10; 0.00)	–

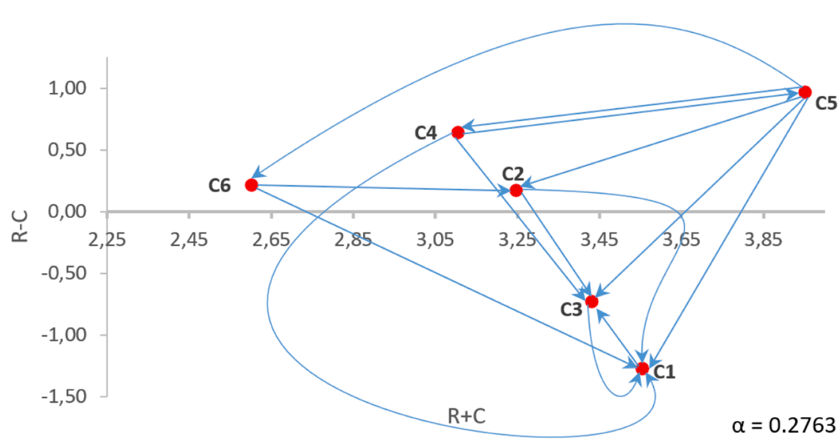

Fig. 4. IRM for DEMATEL Analysis of Clusters.

Table 11
Group direct-influence matrix Z: public spaces cluster.

	SC9	SC10	SC11	SC22	SC24	Total
SC9	0.00	2.48	3.67	1.50	1.50	9.14
SC10	3.67	0.00	1.87	2.48	1.87	9.90
SC11	1.46	1.46	0.00	2.92	2.48	8.32
SC22	1.87	1.58	3.88	0.00	2.62	9.95
SC24	0.91	3.88	1.87	3.67	0.00	10.34
TOTAL	7.92	9.39	11.30	10.57	8.47	

or equal to α).

Regarding the causes and effects in C4, SC108 and SC109 fall above the $R - C$ axis (*i.e.*, positive values). Thus, these SCs form the cause group. In contrast, SC105, SC120, and SC128 have negative values, making them part of the effect group. Fig. 8 also reveals that SC108 and SC109 are core factors, SC128 is an independent factor, and SC120 is an impact factor.

The C5 criteria chosen by the panel members are listed in Table 25. The matrix with neutrosophic values is presented in Table 26. After the crispification of these values, this cluster could be analyzed starting with the group direct-influence matrix (see Table 27).

Table 28 reveals that SC139 is the most influential criterion since it has the highest R value at 2.5262. SC142, in contrast, is the most affected by the remaining criteria, with the lowest C value (2.1512). According to the $R + C$ values, SC142 is clearly the most important criterion (4.4422). Thus, it appears the farthest to the right in the IRM (see Fig. 9). With the lowest $R + C$ value (2.6785), SC136 has the weakest relationships with the other determining factors. The ranking of the selected SCs by order of importance is as follows: SC142 > SC139 > SC134 > SC137 > SC136.

In addition, the IRM in Fig. 9 shows that SC139 and SC142 are core

Table 13
Most significant criteria: transportation and mobility cluster.

Selected criteria	
SC33	Efficient public transportation
SC34	Intermodal pass price
SC35	Good coverage by public transportation network
SC39	Quality of public transportation on offer
SC47	Inconsiderate parking in pedestrian circulation zones

Table 14
Group matrix with neutrosophic values: transportation and mobility cluster.

	SC33	SC34	SC35	SC39	SC47
SC33	–	0.00 (0.95; 0.00; 0.00)	4.00 (0.95; 0.00; 0.00)	3.00 (0.70; 0.30; 0.10)	3.00 (0.60; 0.40; 0.15)
SC34	0.00 (0.95; 0.00; 0.00)	–	0.50 (0.75; 0.25; 0.10)	0.50 (0.90; 0.10; 0.00)	2.00 (0.60; 0.40; 0.20)
SC35	4.00 (0.95; 0.00; 0.00)	0.00 (0.95; 0.00; 0.00)	–	4.00 (0.95; 0.00; 0.00)	3.00 (0.70; 0.40; 0.20)
SC39	2.50 (0.70; 0.30; 0.10)	0.00 (0.95; 0.00; 0.00)	4.00 (0.95; 0.00; 0.00)	–	3.00 (0.70; 0.30; 0.10)
SC47	0.50 (0.55; 0.35; 0.10)	0.00 (0.95; 0.00; 0.00)	0.50 (0.70; 0.30; 0.10)	0.50 (0.70; 0.30; 0.10)	–

Table 15
Group direct-influence matrix: transportation and mobility cluster.

	SC33	SC34	SC35	SC39	SC47	Total
SC33	0.00	0.00	3.88	2.25	1.99	8.11
SC34	0.00	0.00	0.39	0.46	1.31	2.16
SC35	3.88	0.00	0.00	3.89	2.25	10.01
SC39	1.87	0.00	3.88	0.00	2.25	8.00
SC47	0.33	0.00	0.37	0.37	0.00	1.08
TOTAL	6.08	0.00	8.53	6.96	7.78	

Table 12
Total-relation matrix T: public spaces cluster.

	SC9	**SC10**	**SC11**	**SC22**	**SC24**	***R***
SC9	0.7477	1.0164	1.2622	1.0828	0.9281	5.0373
SC10	1.0655	0.9121	1.2477	1.2129	1.0130	5.4511
SC11	0.8132	0.9145	0.9595	1.1239	0.9500	4.7610
SC22	0.9372	1.0339	1.3575	1.0495	1.0686	5.4468
SC24	0.9466	1.2265	1.2965	1.3566	0.9277	5.7540
C	4.5103	5.1035	6.1233	5.8257	4.8874	

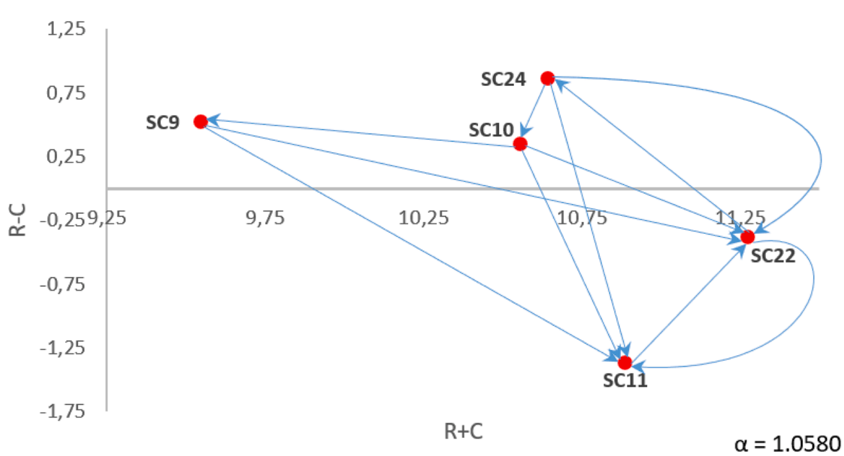

Fig. 5. IRM for Public Spaces Cluster.

Table 16
Total-relation matrix *T*: transportation and mobility cluster.

	SC33	SC34	SC35	SC39	SC47	*R*
SC33	0.4898	0.0000	0.8721	0.6968	0.6474	2.7061
SC34	0.0758	0.0000	0.1218	0.1176	0.1993	0.5146
SC35	0.8455	0.0000	0.6952	0.8754	0.7443	3.1604
SC39	0.6300	0.0000	0.8487	0.4950	0.6506	2.6244
SC47	0.1047	0.0000	0.1241	0.1118	0.0737	0.4143
C	2.1459	0.0000	2.6619	2.2966	2.3153	

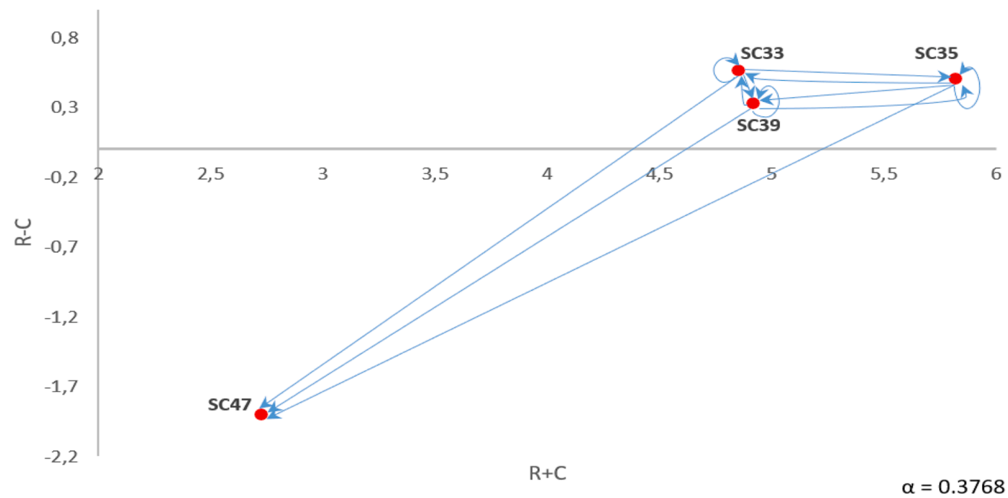

Fig. 6. IRM for Transportation and Mobility Cluster.

Table 17
Most significant criteria: the environment and health cluster.

Selected criteria	
SC60	Physical health
SC61	Mental health
SC63	Air quality
SC71	Water quality (*i.e.*, safe water)
SC82	Exposure to environmental risks

Table 18
Group matrix with neutrosophic values: the environment and health cluster.

	SC60	SC61	SC63	SC71	SC82
SC60	–	4.0 (0.95; 0.00; 0.00)	0.00 (0.95; 0.00; 0.00)	0.00 (0.95; 0.00; 0.00)	0.00 (0.95; 0.00; 0.00)
SC61	4.00 (0.95; 0.00; 0.00)	–	0.00 (0.95; 0.00; 0.00)	0.00 (0.95; 0.00; 0.00)	0.00 (0.95; 0.00; 0.00)
SC63	4.00 (0.95; 0.00; 0.00)	2.50 (0.60; 0.40; 0.15)	–	0.50 (0.80; 0.20; 0.10)	1.50 (0.80; 0.20; 0.15)
SC71	4 00 (0.95; 0.00; 0.00)	0.50 (0.95; 0.00; 0.00)	0.00 (0.95; 0.00; 0.00)	–	1.50 (0.80; 0.20; 0.15)
SC82	4.00 (0.95; 0.00; 0.00)	4.00 (0.95; 0.00; 0.00)	4.00 (0.95; 0.00; 0.00)	4.00 (0.95; 0.00; 0.00)	–

factors. These two SCs have a positive *R* – *C* value, which also means they comprise the cause group (*i.e.*, have a stronger influence on the other criteria as opposed to being more affected). SC134, SC136, and SC137 are independent factors, and, given their negative *R* – *C* values, they constitute the effect group.

Finally, in order to analyze C6, the expert panel selected its most significant criteria (see Table 29). By following the same logic and crispification procedures, the decision makers could move from the neutrosophic matrix in Table 30 to the initial DEMATEL matrix with crisp weights in Table 31.

Table 19
Group direct-influence matrix: the environment and health cluster.

	SC60	SC61	SC63	SC71	SC82	Total
SC60	0.00	3.88	0.00	0.00	0.00	3.88
SC61	3.88	0.00	0.00	0.00	0.00	3.88
SC63	3.88	1.66	0.00	0.41	1.22	7.18
SC71	3.88	0.49	0.00	0.00	1.22	5.59
SC82	3.88	3.88	3.88	3.88	0.00	15.54
TOTAL	15.54	9.91	3.88	4.30	2.45	

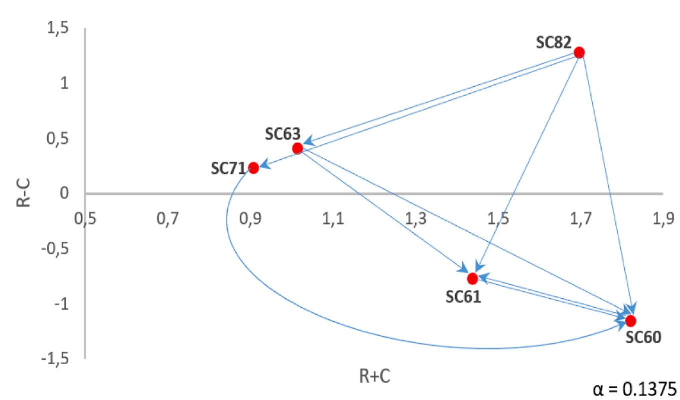

Fig. 7. IRM for The Environment and Health Cluster.

The *R* values (see Table 32) reflect the total influence of each criterion, confirming that SC88 is the factor that most affects the others, with an *R* of 2.9487. SC88, with the highest *C* (3.0093), is also the most influenced by all the remaining SCs. Thus, SC88 is the most important criterion, appearing the farthest to the right in Fig. 10 and showing an *R*

Table 20
Total-relation matrix *T*: the environment and health cluster.

	SC60	SC61	SC63	SC71	SC82	*R*
SC60	0.0667	0.2667	0.0000	0.0000	0.0000	0.3333
SC61	0.2667	0.0667	0.0000	0.0000	0.0000	0.3333
SC63	0.3426	0.2169	0.0210	0.0482	0.0842	0.7129
SC71	0.3142	0.1332	0.0205	0.0210	0.0820	0.5708
SC82	0.4975	0.4209	0.2604	0.2673	0.0415	1.4876
C	1.4876	1.1043	0.3019	0.3365	0.2077	

Table 21
Most significant criteria: participation, citizenship, and governance cluster.

Selected criteria	
SC105	E-governance
SC108	Community spirit
SC109	Citizenship and good education
SC120	Public participation in decision making about built environment
SC128	Nearby cultural event initiatives

Table 22
Group matrix with neutrosophic values: participation, citizenship, and governance cluster.

	SC105	SC108	SC109	SC120	SC128
SC105	–	0.50 (0.90; 0.10; 0.00)	2.50 (0.70; 0.30; 0.10)	3.50 (0.80; 0.20; 0.10)	1.00 (0.60;0.40; 0.10)
SC108	0.50 (0.90; 0.10; 0.00)	–	4.00 (0.95; 0.00; 0.00)	4.00 (0.95; 0.00; 0.00)	4.00 (0.95; 0.00; 0.00)
SC109	2.00 (0.80; 0.20; 0.00)	4.00 (0.95; 0.00; 0.00)	–	4.00 (0.95; 0.00; 0.00)	4.00 (0.95; 0.00; 0.00)
SC120	2.50 (0.60; 0.40; 0.20)	4.00 (0.95; 0.00; 0.00)	4.00 (0.95; 0.00; 0.00)	–	3.50 (0.80; 0.10; 0. 00)
SC128	3.50 (0.60; 0.40; 0.20)	4.00 (0.95; 0.00; 0.00)	3.50 (0.75; 0.25; 0.10)	3.50 (0.75; 0.25; 0.10)	–

Table 23
Group direct-influence matrix: participation, citizenship, and governance cluster.

	SC105	SC108	SC109	SC120	SC128	Total
SC105	0.00	0.46	1.87	2.89	0.67	5.89
SC108	0.46	0.00	3.88	3.88	3.88	12.11
SC109	1.67	3.88	0.00	3.88	3.88	13.33
SC120	1.63	3.88	3.88	0.00	3.05	12.45
SC128	2.29	3.88	2.76	2.76	0.00	11.69
TOTAL	6.05	12.11	12.40	13.42	11.49	

$+ C$ value of 5.9580. In contrast, SC87 was classified as the least significant determinant in the present analysis based on its lowest $R + C$ value (1.7905). According to the IRM (see Fig. 10), the criteria in C6 can be prioritized in the following order: SC88 > SC100 > SC91 > SC92 > SC87.

Based on their position in relation to the $R – C$ vertical axis, SC87, SC91, and SC100 form the cause group (*i.e.*, R – C > 0), which influences the effect group composed of SC88 and SC92 (*i.e.*, R – C < 0). Finally, Fig. 10 reveals that SC91 and SC100 are core factors, SC87 is a determining factor, SC92 is an independent factor, and SC88 is an impact factor.

After all six clusters and their main SCs were analyzed, the information presented here could be used to determine the most effective strategies regarding urban QoL. The results can help decision makers to understand more clearly which criteria need to be prioritized, thereby ensuring that the most important determinants of urban QoL are improved in order to obtain positive results for residents.

4.4. Consolidation by independent experts

To elicit feedback and expert opinions regarding the relevance of this study approach and results based on the proposed combined methodology, a consolidation session was held with specialists who had not participated in the previous group work. Two senior representatives of the Lisbon Metropolitan Area (AML in Portuguese) participated in this final session, one of whom was responsible for drafting the area's *"Metropolitan Strategy for Innovation and Competitiveness"*.

Formed as an association, AML is a Portuguese inter-municipality entity that develops initiatives addressing various issues to promote the common interests of its 18 municipalities. The AML's mission is defined by Law 75/2013, namely to contribute to more sustainable, integral development, to regional and socioeconomic cohesion, and to better QoL in the member municipalities (AML, 2021). This session enhanced the present study's findings and strengthened its credibility because opinions were elicited from experts working for AML, which represents about one-fourth of the Portuguese population. The organization covers a geographical area that has the strongest concentration of economic activities and people in Portugal.

The consolidation session lasted approximately an hour, and the meeting was also held online via the Microsoft Teams platform. The session began with a brief explanation of the QoL topic and the research goal, followed by a description of the methodologies used (*i.e.*, cognitive mapping, neutrosophic logic, and DEMATEL). Next, the results were presented and explained to the interviewees (*i.e.*, group cognitive map, main matrices, and IRMs).

Regarding the methods, the interviewees expressed interest in how cognitive mapping was used to outline the decision makers' collective cognitive representations based on group brainstorming. The two experts further agreed that the criteria appeared adequate in terms of the existing urban QoL research. One of the interviewees said that, *"when we talk about QoL, we have to balance our concerns,* […] *and here we see both material and non-material practices, which makes a lot of sense"* (in the interviewee's words). In general, the experts concurred that cognitive mapping is useful for structuring the decision problem as this method can incorporate multiple dimensions. The interviewees also voiced their satisfaction regarding the combination of neutrosophic logic and DEMATEL and its results. One of the experts pointed out that this *"model has a lot of merit and* […] *has a lot of potential"* (also in the interviewee's words). In addition, these specialists emphasized that the proposed model is able to *"clarify some shortcomings that can be difficult to capture, and thus it could generate positive change"* (again, in the interviewee's words), allowing decision makers to identify more easily the challenges

Table 24
Total-relation matrix *T*: participation, citizenship, and governance cluster.

	SC105	SC108	SC109	SC120	SC128	*R*
SC105	0.3600	0.7516	0.8154	0.8957	0.7247	3.5474
SC108	0.7593	1.4373	1.6202	1.6650	1.5905	7.0722
SC109	0.8547	1.7145	1.4529	1.7278	1.6413	7.3912
SC120	0.8132	1.6392	1.6058	1.4294	1.5316	7.0192
SC128	0.7944	1.5228	1.4420	1.4889	1.2359	6.4840
C	3.5815	7.0654	6.9362	7.2068	6.7240	

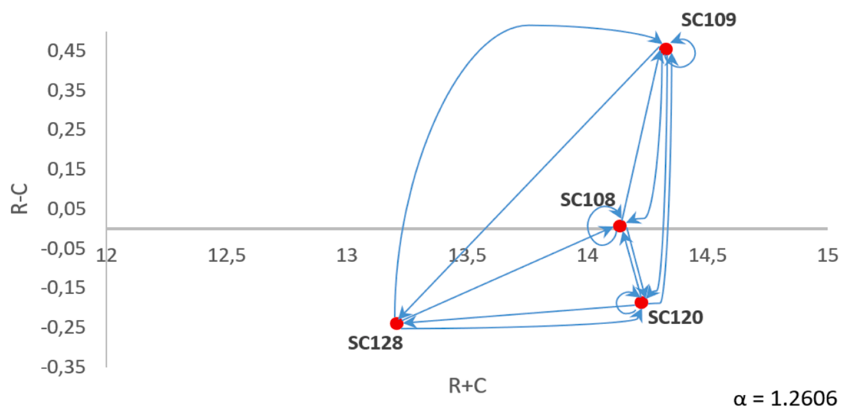

Fig. 8. IRM for Participation, Citizenship, and Governance Cluster.

Table 25
Most significant criteria: city policy and urbanism cluster.

Selected criteria	
SC134	Proximity to public facilities network
SC136	Poor average quality of architecture and built environment
SC137	Proximity to businesses
SC139	Urban regeneration
SC142	Reasonableness of house prices

Table 26
Group matrix with neutrosophic values: city policy and urbanism cluster.

	SC134	SC136	SC137	SC139	SC142
SC134	–	0.00 (0.95; 0.00; 0.00)	3.50 (0.90; 0.10; 0.00)	2.50 (0.80; 0.20; 0.10)	3.50 (0.90; 0.10; 0.00)
SC136	0.00 (0.95; 0.00; 0.00)	–	0.00 (0.95; 0.00; 0.00)	3.50 (0.80; 0.20; 0.10)	3.50 (0.90; 0.10; 0.00)
SC137	1.00 (0.90; 0.10; 0.05)	0.00 (0.95; 0.00; 0.00)	–	1.50 (0.70; 0.30; 0.10)	3.00 (0.80; 0.20; 0.10)
SC139	4.00 (0.95; 0.00; 0.00)	4.00 (0.95; 0.00; 0.00)	4.00 (0.95; 0.00; 0.00)	–	4.00 (0.95; 0.00; 0.00)
SC142	3.50 (0.90; 0.10; 0.00)	3.50 (0.90; 0.10; 0.00)	3.50 (0.90; 0.10; 0.00)	4.00 (0.95; 0.00; 0.00)	–

Table 27
Group direct-influence matrix: city policy and urbanism cluster.

	SC134	SC136	SC137	SC139	SC142	Total
SC134	0.00	0.00	3.21	2.07	3.21	8.50
SC136	0.00	0.00	0.00	2.89	3.21	6.10
SC137	0.91	0.00	0.00	1.12	2.48	4.51
SC139	3.88	3.88	3.88	0.00	3.88	15.54
SC142	3.21	3.21	3.21	3.88	0.00	13.53
TOTAL	8.01	7.10	10.31	9.96	12.79	

that municipalities may face.

The interviewees' final conclusion was that, given the ability of the analysis system to incorporate indeterminacy into the decision-making process, this tool can be used not only in strategic planning but also in any complex situation encountered by decision makers. Therefore, the consolidation session proved essential for the present study as the experts' feedback reinforced the transparency of results, and facilitated the interpretation of the proposed model, as well as validating the decision-support system and its results in real-life contexts.

4.5. Discussion of results and recommendations

The methodological approach in this study combines cognitive mapping, neutrosophic logic, and DEMATEL to analyze urban QoL and understand the causal links between its determinants in a structured and practical manner. It aligns with well-established research streams in OR/MS, including problem structuring, multi-methodology approaches, and Community OR.

In the context of problem structuring, including systems mapping, Mingers (2000), Belton and Stewart (2002), Rosenhead (2006) and Midgley et al. (2018) emphasize the importance of problem structuring as a critical step in decision making that involves defining the decision problem, determining its causes and effects, and exploring potential solutions. In this study, we used cognitive mapping, neutrosophic logic, and DEMATEL to facilitate the exchange of ideas and experiences among the expert panel members, deepen the understanding of the decision problem, and uncover perceived cause-and-effect relationships related to QoL determinants. Our approach follows the steps of a DC process that encourages interactive learning and a fruitful analysis of relevant factors, which are common characteristics of PSMs (*cf.* Belton & Stewart, 2002; Ferreira et al., 2022). Regarding systems mapping, it involves constructing causal models to better understand decision problems and

Table 28
Total-relation matrix *T*: city policy and urbanism cluster.

	SC134	SC136	SC137	SC139	SC142	*R*
SC134	0.1964	0.1717	0.4192	0.3294	0.4322	1.5489
SC136	0.1860	0.1736	0.2120	0.3595	0.4046	1.3357
SC137	0.1781	0.1106	0.1475	0.2002	0.2929	0.9292
SC139	0.5022	0.4686	0.5724	0.3528	0.6302	2.5262
SC142	0.4483	0.4183	0.5110	0.5221	0.3912	2.2910
C	1.5110	1.3428	1.8622	1.7639	2.1512	

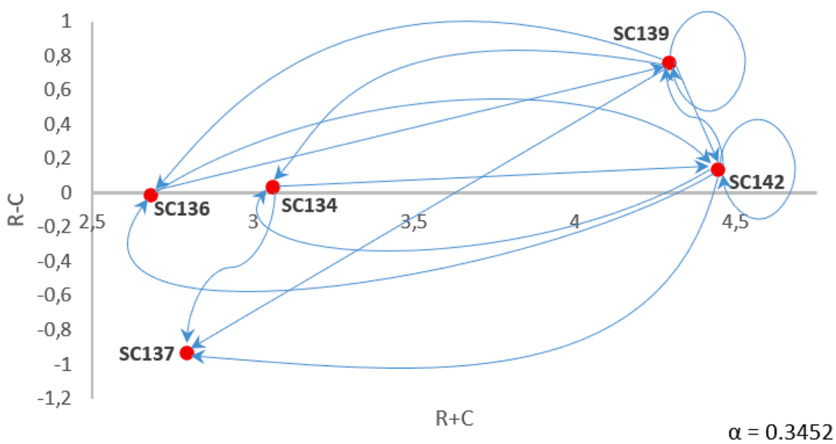

Fig. 9. IRM for City Policy and Urbanism Cluster.

Table 29
Most significant criteria: facilities and services cluster.

Selected criteria	
SC87	Health infrastructure
SC88	Access to education
SC91	Provision of social services equipment
SC92	Access to diverse goods and services
SC100	Access to cultural activities

Table 30
Group matrix with neutrosophic values: facilities and services cluster.

	SC87	SC88	SC91	SC92	SC100
SC87	–	0.50 (0.70; 0.40; 0.10)	3.00 (0.70; 0.30; 0.10)	2.00 (0.70; 0.30; 0.10)	0.00 (0.95; 0.00; 0.00)
SC88	0.50 (0.70; 0.40; 0.10)	–	2.50 (0.75; 0.25; 0.10)	3.00 (0.85; 0.10; 0.10)	3.50 (0.80; 0.20; 0.00)
SC91	0.50 (0.70; 0.40; 0.10)	2.50 (0.75; 0.25; 0.10)	–	1.50 (0.70; 0.30; 0.15)	2.50 (0.60; 0.40; 0.15)
SC92	0.00 (0.95; 0.00; 0.00)	2.00 (0.80; 0.20; 0.10)	0.50 (0.70; 0.40; 0.10)	–	0.50 (0.70; 0.40; 0.10)
SC100	0.00 (0.80; 0.20; 0.00)	3.75 (0.90; 0.10; 0.05)	1.50 (0.70; 0.30; 0.10)	2.50 (0.60; 0.40; 0.15)	–

Table 31
Group direct-influence matrix: facilities and services cluster.

	SC87	SC88	SC91	SC92	SC100	Total
SC87	0.00	0.35	2.25	1.50	0.00	4.10
SC88	0.35	0.00	1.97	2.64	2.93	7.89
SC91	0.35	1.97	0.00	1.11	1.66	5.09
SC92	0.00	1.65	0.35	0.00	0.35	2.36
SC100	0.00	3.43	1.12	1.66	0.00	6.20
TOTAL	0.71	7.40	5.69	6.91	4.94	

assess the impact of different interventions using mathematical and simulation models (Barbrook-Johnson & Penn, 2022). This approach includes methods such as fuzzy cognitive maps, Bayesian networks and system dynamics, which share similar principles with our approach (*e.g.*, problem structuring, visual representation of system structure, and informed analysis of results).

Multi-methodology is a thriving field in OR/MS research. Mingers (2000), Belton and Stewart (2002) and Marttunen et al. (2017) highlight the benefits of combining methods, including improved decision-making, better problem understanding, increased flexibility, enhanced visualization, and improved stakeholder engagement. By combining OR/MS methods, our study leverages the advantages of multi-methodology approaches and provides a novel toolset that deepens our understanding of urban QoL and its determinants. As recognized by the expert panel members, our methodological combination can ultimately enhance decision-making in this specific context.

Our methodological combination is also in line with the principles of Community OR, which emphasizes collaboration and engagement with communities to tackle complex decision problems and develop practical solutions using OR methods and interdisciplinary approaches (Midgley et al., 2018). Although our study mostly involves experts (with only one panel member representing the residents' perspective), we have incorporated the core principles of Community OR. This has allowed us to bring a sense of realism to our framework, as our methodological combination has provided new insights based on the expertise of the panel members involved. In fact, as recognized by the independent experts during the consolidation session, one of the main advantage of the methodology used is its ability to capture the decision makers' expertise, which was a key aspect in the context of the addressed problem.

We acknowledge that the methodological processes followed in this study may seem complex to those unfamiliar with the techniques employed. However, our approach is based on inclusive and participatory methods that aim to reduce misunderstandings among expert panel

Table 32
Total-relation matrix *T*: facilities and services cluster.

	SC87	SC88	SC91	SC92	SC100	*R*
SC87	0.0349	0.3466	0.4337	0.4233	0.2384	1.4769
SC88	0.1006	0.6606	0.5902	0.8208	0.7764	2.9487
SC91	0.0883	0.6785	0.2965	0.5410	0.5477	2.1520
SC92	0.0278	0.4187	0.2032	0.2271	0.2528	1.1297
SC100	0.0621	0.9048	0.4831	0.6904	0.4678	2.6081
C	0.3137	3.0093	2.0068	2.7026	2.2831	

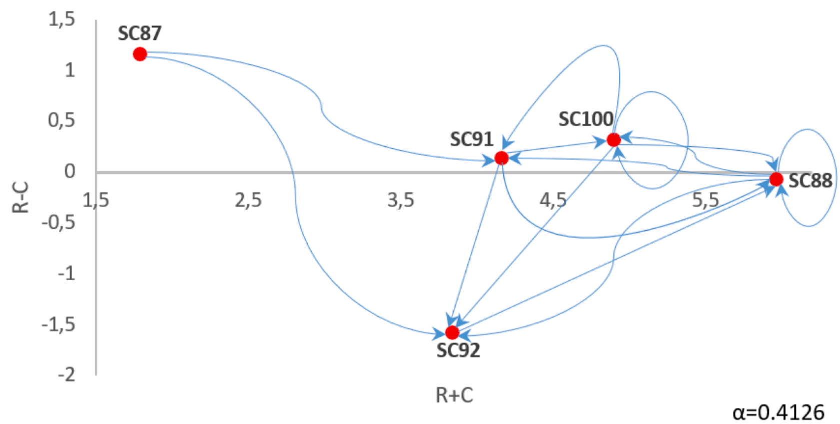

Fig. 10. IRM for Facilities and Services Cluster.

members and enhancing their understanding of both the decision problem (*i.e.*, urban QoL) and the methodologies employed for its analysis. Initially, the expert panel members were unfamiliar with the techniques used, but with the guidance of a facilitator, they were able to successfully apply these techniques. By the end of the group meetings, they agreed that the methodological combination, although initially appearing complex, is more straightforward than it seems. In fact, they no longer require the assistance of a facilitator, having learned the methods through active participation in the study. Overall, our inclusive, participatory approach has proven to be effective in enhancing the understanding of the panel members and ensuring the successful application of the methodologies used.

Although following a different methodological approach, our findings are consistent with the results of Faria et al. (2018) and Kaklauskas et al. (2018) in what pertains to the importance of strategic planning, socio-economic factors, community engagement, and transportation and mobility to achieve higher levels of urban QoL. While many criteria in our analysis are not new, the completeness of the cognitive structure we created enabled us to uncover important details that might otherwise be overlooked. Community spirit, citizenship, good education, and coordination between entities, for instance, can be easily overlooked due to their subjectivity, but can significantly affect QoL assessment and subsequent decisions. In fact, it was generally agreed among the panel members that some of the criteria included in the cognitive map are seldom considered in current urban QoL assessment frameworks. However, the methodological processes employed in this study allowed for their identification, reducing the omission of determinants and their cause-and-effect relationships (as acknowledged by the expert panel members). Similar to the study by Milici et al. (2023), the mapping process we conducted with the panel members proved highly valuable, fostering an extensive exchange of values, opinions, and experiences. Moreover, due to the incorporation of both objective and subjective elements, our combined use of cognitive mapping, neutrosophic logic, and DEMATEL facilitated a transparent, comprehensive, and realistic analysis of urban QoL (as acknowledged by the expert panel members). The model also accounted for decision makers' uncertainty by including neutrosophic logic, thereby enabling more informed decision-making.

Because urban policies play an important role in sustainable QoL management (*cf.* Faria et al., 2018), the implementation of our OR/MS methodology in real-world contexts can provide strategic support for the development of urban QoL policies, fostering greater public awareness, promoting changes in practice, and facilitating active cooperation with societal stakeholders. The communication of results can then explore the resulting cognitive maps and DEMATEL diagrams to gain insights into the factors influencing QoL within urban systems. Decision makers and other stakeholders can utilize these findings to inform their decision-making processes, prioritize interventions, develop targeted strategies, and engage in informed discussions. This enhanced capability for long-term planning can ultimately support the development and implementation of sustainable and impactful urban public policies aimed to improve residents' QoL.

Due to the process-oriented nature of the methodology, it is worth noting that results generally are not applicable from one urban area to another and, in some respects, the actual results may not be as critical as the process. As Bell and Morse (2013) explain, *"there is less emphasis on outputs per se and more focus on process"* in this type of methodological approach. Naturally, we are aware that there may be other decision makers wishing to apply our framework to their own urban area or specific jurisdiction. Although they may not understand the "process", they may like to know our final recommendation(s). In this case, we recommend that these decision makers study both at the cognitive map (Fig. 3) and DEMATEL diagrams (Figs. 4–10), and to select the QoL improvement initiatives that best fit their unique situation. We could prioritize what items may have the largest impact for their particular situation. However, this would have to be done on a casuistic basis due to specific characteristics of each city/area/location.

5. Conclusion

Assessments of urban QoL are important, especially at the residential neighborhood level. This topic is challenging due to its intrinsic subjectivity and complexity. Thus, the current research's main goal was to develop a multicriteria analysis system to support decision making in urban areas.

The proposed combined methodology provides a holistic view of the decision problem, allowing experts to identify determining factors that affect urban QoL, as well as their cause-and-effect relationships and respective importance. Using this approach, specialists can engage in conscious decision making in urban areas to achieve improvements in residents' QoL. In this way, the results answer the two research questions defined (*i.e.*, "How can determinants and/or factors that affect urban QoL be identified, and how are they interrelated?" and "Which determining factors have a significant enough impact that they should be given priority with regard to improving QoL in urban areas?"). Specifically, the findings include that urban QoL can be divided into six areas of concern: public spaces; transportation and mobility; the environment and health; participation, citizenship, and governance; city policy and urbanism; and facilities and services.

Despite its many advantages, this methodology also has limitations that need to be highlighted. Because it is constructivist in nature, the proposed framework depends heavily on the context in which it is used, and the findings cannot, therefore, be generalized to other contexts without appropriate adjustments. Given other participants and/or a different panel of experts, the evaluation criteria identified could have been different, which is true also of each assigned degree of influence and neutrosophic value. Two long group work sessions were needed to define the large number of components and their influence on each other and to quantify the experts' judgments (*i.e.*, the probability of an opinion being true, uncertain, or false). Finally, due to the COVID-19 pandemic-related restrictions, the group sessions were carried out remotely via Zoom and Microsoft Teams, which partially affected the work done (*e.g.*, Wi-Fi connection problems). However, this adjustment constitutes a significant innovation given that it confirmed that the proposed methodology can be applied through digital channels.

A new approach to urban QoL was developed, and the results of the combination of methodologies adopted are quite promising. To address some common shortcomings of previous QoL assessment studies, the present research introduced an innovative tool comprising constructivist methods based on the MCDA approach, which provided a clear, well-structured, and holistic view of urban QoL (as recognized by the expert panel members). As a result, the findings make multiple contributions to this field of study. First, the methodology applied provides a decision-support model that incorporates uncertainty into decision making. Second, using neutrosophic values in analyses may produce more authentic results in this specific type of context. Third, the multiple experts contributed different (*i.e.*, professional and personal) values and opinions to the process, thereby generating a group cognitive map with a large number of determining factors. Fourth, the model was developed in a neutrosophic environment, so it may reflect human reasoning more closely. The proposed system effectively reflects the decision-problem particularities, highlighting the dimensions with the greatest and least impact on urban QoL, and provides decision makers with a more realistic view of the areas that need improvement (as also recognized by the expert panel members). This means that the adopted procedures focus on supporting interactive learning and a fruitful elaboration of recommendations for QoL improvement initiatives. Last, the methodological combination is new as no evidence was found of studies using cognitive mapping, neutrosophic logic, and DEMATEL simultaneously to analyze QoL in urban areas. This research's novel approach can thus be assumed to add value to the QoL and OR/MS fields and to experts involved in improving urban QoL.

The current study can provide a springboard for future research. Further studies using neutrosophic logic combined with other methods could bring additional benefits. One possible approach is to use fuzzy cognitive mapping to represent the causal relationships between variables, and then use neutrosophic logic to handle uncertainty in the model. The resulting model can then be simulated using system dynamics to analyze the behavior of the system over time. Overall, there are several ways to combine these approaches, and the best approach will depend on the specific problem being addressed and the data available. Naturally, it is important to carefully consider the strengths and weaknesses of each methodological combination and choose the one that is most appropriate for the problem at hand. A potentially interesting challenge would also be to apply the proposed methodology to specific urban areas and compare the findings with current public policies. QoL in urban areas is an almost inexhaustible topic. Thus, any new contributions and procedures can promote empirical research progress toward a deeper understanding of QoL, providing additional benefits that will always be welcomed by both researchers and practitioners.

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