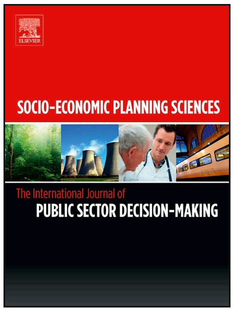

Urban expansion effects on real estate ecosystems: Identification and neutrosophic analysis of causal dynamics

Inês C. Correia, Fernando A.F. Ferreira, Constantin Zopounidis, Neuza C.M.Q.F. Ferreira

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URBAN EXPANSION EFFECTS ON REAL ESTATE ECOSYSTEMS: IDENTIFICATION AND NEUTROSOPHIC ANALYSIS OF CAUSAL DYNAMICS

Inês C. Correia
ISCTE Business School, University Institute of Lisbon
Avenida das Forças Armadas, 1649-026, Lisbon, Portugal
iccao1@iscte-iul.pt or *inesccorreia19@gmail.com*

Fernando A. F. Ferreira*
ISCTE Business School, BRU-IUL, University Institute of Lisbon
Avenida das Forças Armadas, 1649-026 Lisbon, Portugal
&
Fogelman College of Business and Economics, University of Memphis
Memphis, TN 38152-3120, USA
fernando.alberto.ferreira@iscte.pt or *fernando.ferreira@memphis.edu*

Constantin Zopounidis
School of Production Engineering and Management, Technical University of Crete
University Campus, 73100 Chania, Greece
&
Audencia Business School, Institute of Finance
8 Route de la Jonelière, 44312 Nantes, France
kostas@dpem.tuc.gr or *czopounidis@audencia.com*

Neuza C. M. Q. F. Ferreira
NECE-UBI, Research Centre for Business Sciences, University of Beira Interior
Estrada do Sineiro, 6200-209 Covilhã, Portugal
neuza.ferreira@ubi.pt

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* Corresponding author.

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ABSTRACT

Real estate ecosystems are the result of symbiotic relationships between different types of real estate, including residential, commercial, or industrial properties. Maintaining a balance among these categories is essential for these ecosystems' ability to function properly. Real estate currently is largely a product of urban expansion caused by population increases and distances from primary-sector industries. The unplanned growth of urban areas can have profound consequences for local residents' health and the environment. However, when well structured, urbanization can have a positive effect on societies' well-being. The relationship between this expansion and its impact on real estate ecosystems is an extremely complex, subjective topic, so decision makers cannot apply just one solution when making plans. This study develops a multicriteria analysis model to support decision making processes, which provides a structured understanding of urban expansion effects on real estate ecosystems and deals with the inherent subjectivity and complexity of this decision problem. Cognitive mapping and decision-making trial and evaluation laboratory (DEMATEL) technique were combined in a neutrosophic environment to incorporate uncertainty and produce a more realistic analysis system, thereby overcoming various limitations of previous research on urban expansion (*e.g.*, unclear way by which relevant factors/criteria are identified in most cases, and lack of analyses dealing with the dynamics of their causal relationships). Decision makers with professional experience in relevant areas collaborated to provide essential input used to create the proposed model. External experts validated the results, confirming the potential of our analysis system for real-life applications.

Keywords: Cognitive Mapping; Decision-Making Support; DEcision MAking Trial and Evaluation Laboratory (DEMATEL); Neutrosophic Logic; Real Estate; Urban Expansion.

1. INTRODUCTION

Urbanization first emerged due to technological developments and population increases (Tisdale, 1942), which led people to migrate from the countryside to cities and resulted in urban agglomerations and their expansion. This process can positively affect large populations by providing better infrastructure, more jobs, and higher salaries. However, many environmental disadvantages are also associated with urban expansion, such as pollution, damaged ecosystems, and higher consumption of natural resources (Firozjaei *et al.*, 2019; Rodrigues *et al.*, 2023; Wang *et al.*, 2023).

Real estate is a system that interconnects sellers and buyers who trade properties and that explores new opportunities for construction (Rybak and Shapoval, 2011; Andrade *et al.*, 2022; Huang *et al.*, 2023). It currently is largely a product of urbanization and city expansion, and properties can be divided into three different categories: residential, industrial, and commercial (Fonseca *et al.*, 2018; Soares *et al.*, 2022; Rodrigues *et al.*, 2023). Real estate units can be commercialized by renting properties or buying them. Real estate ecosystems are the result of symbiotic relationships between different types of properties and their interconnections.

Analyzing urban expansion effects on these ecosystems is a complex subjective topic as demonstrated by previous studies and their respective limitations (*cf.* Firozjaei *et al.*, 2019; Rodrigues *et al.*, 2023; Wang *et al.*, 2023). New approaches are thus needed to understand this issue. The present research used two different methodologies to develop a multicriteria model that analyses urban expansion impacts: cognitive mapping and decision-making trial and evaluation laboratory (DEMATEL) technique, which were combined in a neutrosophic environment. This model was built based on expert decision makers' experience and work-group sessions focused on collecting the necessary data through procedures that relied on a constructivist logic to produce a fuller understanding of urban expansion effects.

After the expert panel was recruited, two sessions took place online to facilitated group discussions and a deeper exploration of the topic under study. The outcomes of these meetings include a group cognitive map and an application of the DEMATEL technique to identify cause-and-effect interrelationships between determining factors. Neutrosophic logic permitted the incorporation of uncertainty, which was essential for the subsequent crispification and aggregation of values. The results were presented to two external experts to evaluate the model's practical applicability. The combined use of cognitive mapping, DEMATEL, and neutrosophic logic produced a realistic model of the subjectivity present in real estate ecosystems and a clearer understanding of the complex ways in which they are affected by urban expansion. This combination of methodologies was rooted in constructive epistemology (Belton and Stewart, 2010).

The proposed multicriteria analysis model helps structure assessments of urban expansion and its impacts on real estate ecosystems. Because this decision-support system is a mix of constructivist techniques, it increases the simplicity and transparency of results for experts seeking to examine and understand how urbanization affects these ecosystems. The model includes qualitative and quantitative analyses of the decision problem and accommodates the uncertainty associated with decision-making processes, thereby enabling specialists to identify cause-and-effect relationships between determinants. The methodological framework used also overcomes limitations of previous studies (*e.g.*, a lack of data describing population features and dependency on mathematical models).

Following this, the present study makes several notable contributions to the field of urban expansion and real estate ecosystems. First, it introduces a novel multicriteria analysis model that leverages cognitive mapping and the DEMATEL technique within a neutrosophic environment. This analysis model not only provides a structured understanding of the effects of urban expansion on real estate ecosystems but also addresses the inherent subjectivity and complexity of the decision problem at hand. Second, the incorporation of expert decision makers' input in the model development ensures practical relevance and real-world applicability. Third, the application of neutrosophic logic allows for the explicit consideration of uncertainty, overcoming limitations present in previous research. Overall, the present study offers a unique perspective on the intricate dynamics between urban expansion and real estate ecosystems, providing decision makers with valuable insights for informed planning and management.

This paper is divided into five sections that include the present introduction to the research design and contributions. The next section presents a literature review of urban expansion and real estate ecosystem studies. Section three focuses on the methodologies applied, while section four discusses the results obtained. Section five contains the conclusions, which are followed by the references and appendices containing additional calculations that support the findings.

2. LITERATURE REVIEW AND RESEARCH GAPS

Real estate can be defined as a system of seller-buyer relationships connected with both the production of new properties and the trade and exploitation of available ones. Real estate activities are based on pricing mechanisms that consider geographical, economic, judicial, and social features (Rybak and Shapoval, 2011, Huang *et al.*, 2023; Lan *et al.*, 2023). According to Fonseca *et al*. (2018), three main types of properties exist: commercial, industrial, and residential. Real estate units include, among others, factories, warehouses, mines, farms, retail stores, houses, undeveloped land, or town houses. The two main options in the real estate market are to sell or rent properties.

The decision to buy or rent real estate units depends on many factors that are not just financial but also related to households' decisions and lifestyles. This system of buyer-seller relationships is thus difficult to analyze since, in *"economic terms, it can be seen as the market where the supply of and demand for real estate meet and where real estate is traded"* (Maier and Herath, 2009, p. 7). The property market varies widely across time and space, and its activities are divided into the submarkets of sales or rentals in which property values can change over the years and prices of distinct units can differ.

Real estate ecosystems reflect symbiotic relationships between diverse types of real estate and the ways these properties interconnect with each other. Zhang *et al.* (2018) and Rodrigues *et al.* (2023) report that each municipality or region can have many industrial ecosystems with varying impacts on that urban ecosystem as a whole. The real estate sector follows the same pattern as it is connected to most industries. Disruptions in the property market can also disturb other sectors and thus positively or negatively affect multiple real estate units. All stakeholders must, therefore, work together to ensure real estate ecosystems survive and perform optimally.

The construction industry is particularly important for these ecosystems given how it alone can make urbanization happen (Zhang *et al*., 2018). Real estate is the key component of city expansion because properties are one of the main outputs of this trend. According to Ramos (2019, p. 1), *"*[t]*he production of urban space is highly tied to the rationality and stage of development of the means of production and reproduction of life"*. Real estate and urbanization are thus strongly interconnected given that this sector's growth can be a byproduct of urban property development, which expands population concentrations by multiplying the number of densely settled areas and increasing the size of these zones (Tisdale, 1942).

The concept of urbanization is challenging to define as it varies between regions and over time. Davis and Henderson (2003) observe that spreading cities translate into a shift from agriculture to urban industrial activities. Urban agglomeration growth can also be defined as a complex process of transforming rural or natural landscapes into industrialized areas (Pinto *et al*., 2021). Champion (2001) and Huang *et al.* (2023) suggest that urbanization can be understood at the physical level as an increased use of land for urban property development. This trend is also a social process because individuals traditionally embrace behaviors and lifestyles associated with cities and towns. Overall, urban expansion leads to a growing concentration of people in towns, large cities, and the surrounding ring of properties.

The origin of urbanization is unknown. However, Hauser and Schnore (1975) argue that the need for urban agglomerations can arise due to four major factors: (1) the overall population size; (2) greater control of the natural environment; (3) technological development; and (4) evolving social organization. Divergent theories have been developed about what must be present before urbanization can begin. For instance, Tisdale (1942) posits that two constantly interacting conditions have to be met for this process to start: people and technology. Urbanization is fed by a growing population and surplus goods, while technology shapes and focuses this process.

Urban expansion can be associated with varied benefits for residents, such as better infrastructure, higher employment rates, and larger incomes. Jansen (2020) analyzes the types of residential environments people prefer and concludes that most individuals prefer smaller municipalities and city edge urban centers that offer the most advantages to those living in urban areas. In addition, expanding cities increase mobility and self-employment opportunities (Jansen, 2020). However, Firozjaei *et al*. (2019) warn that urbanization can become urban sprawl, namely unplanned city property development that leaches into the surrounding areas, which has negative consequences for residents, the environment, and natural resources. Uncontrolled urban expansion contributes to a loss of biodiversity, urban heat islands (Myronidis and Ioannou, 2019; Rodrigues *et al.*, 2023), air and water pollution, climate change, increased consumption of food and energy, land and agricultural degradation, and urban residents' poorer physical and mental health (Firozjaei *et al*., 2019; Pinto *et al.*, 2021; Ferreira *et al.*, 2022). Another harmful effect is an increase in carbon dioxide emissions (Yang *et al*., 2019).

The exponential increase in urbanization has stimulated multiple researchers to study planning for sustainable growth and urban agglomeration effects on the environment and residents. *Table 1* summarizes a sample of the research on this topic, including the respective contributions and limitations. Notably, analyses of urban expansion should consider multiple variables, and different authors have differed in terms of which factors they consider the most important. For example, the research in *Table 1* evaluates urban expansion effects on croplands, the land used for urbanization, consequences for land use, people's preferred types of properties, the ways these choices affect urbanization, and policies that help control urban expansion effects. Research on this topic has evolved over decades, yet correlating studies are necessary to highlight where the reported results converge. Moreover, there is no perfect methodological approach, and all previous studies have their limitations. As no prior research has comprehensively analyzed the impact of urbanization on real estate ecosystems, understanding the limitations of these studies is crucial to identifying the methodologies that can best circumvent the reported restrictions.

Table 1. Analyses of Urban Expansion and Its Effects on Real Estate: Methods, Contributions, and Limitations

Authors	Methods	Contributions	Acknowledged Limitations
Cui *et al*. (2019)	Markov chain model	▪ The model facilitates examinations of three main areas: (1) variations in urban expansion and cropland areas; (2) croplands' contributions to urban areas; and (3) urbanization's predicted impacts on croplands.	▪ The model developed is a mathematical problem that fails to consider the impacts of other factors.
Ramos (2019)	Statistical methods	▪ The proposed approach provides a better understanding of contemporary urbanization and its socio-environmental dimensions. ▪ The methodology combines industrial ecology, urban political ecology, and urban political economy analytical tools. ▪ The results contribute to urban socio-environmental policies by providing monitoring and evaluation tools to ensure more successful, multi-scale, multi-dimension, and inclusive urban transformation.	▪ The methodology created can only be implemented with data that are difficult to obtain due to delayed responses. ▪ Data quality and quantity differed across sources, which may have diminished the validity of conclusions.
Jansen (2020)	Statistical methods	▪ The methods applied enable experts to forecast preferences related to the environment's characteristics and motivations for choosing to live in preferred urban areas.	▪ Because of the statistical methods applied, the sample does not represent the entire universe of residents. ▪ Residents were separated into groups according to their preferences—without reference to objective measures of urbanization—which also limited the results.
Varna *et al*. (2020)	Case-study method	▪ The methodology used evaluates and analyzes network development and urban growth in small cities.	▪ The data were collected over 17 years, so the research required a large number of planning applications.
Maturana *et al*. (2021)	Simulation model of the city of Temuco	▪ The study covered two points: (1) trends in land use and cover between 1985 and 2017; and (2) changes in land use and cover in Temuco.	▪ The research was handicapped by a lack of transparency and information available, which compromised the final result.
Prada-Trigo *et al*. (2021)	Spatial statistics and case-study method	▪ The research revealed how the real estate sector has prevailed over indigenous ways of life.	▪ Difficulties were encountered in building close relationships with community leaders.

While there exists an extensive body of literature in urban economics and planning, particularly focusing on real estate finance and studying the impact of urban expansion on land prices, the present study intentionally adopts a broader perspective that goes beyond the conventional focus on real estate prices. If, on the one hand, it is crucial to emphasize the significance of established theories such as the bid-rent theory and quantitative methods like the hedonic model in understanding the financial dimensions of real estate, it is essential to grasp, on the other hand, that the present study seeks to contribute to existing knowledge by examining the relationship between urban sprawl and real estate ecosystems from a multifaceted viewpoint. Instead of solely concentrating on financial implications and land prices, this study delves into the intricate dynamics of real estate ecosystems, considering symbiotic relationships between various factors, their interconnections, and the overall well-being of societies affected by urban expansion.

Methodologically, many studies have included statistical analysis in their approaches, yet one of the most significant limitations has been the available data quality because information can be difficult to obtain and samples may be too small or not representative of the research population. The available models can also focus heavily on the mathematical aspects of problems, thereby neglecting qualitative variables and analyses of cause-and-effect relationships between criteria. Furthermore, the literature has highlighted several well-known limitations of hedonic modeling in particular, including: (1) limited guidance on attribute relationships (*cf.* Bin, 2004; Ferreira *et al.*, 2016); (2) assumption of independence among attributes influencing property prices (*cf.* Dorsey *et al.*, 2010); (3) assumption of spatial independence of observations (neglecting the fact that nearby properties may share similar characteristics affecting their prices) (*cf.* Quigley 2006; Ferreira *et al.*, 2016); and the consideration of static relationships at a specific point in time (overlooking the dynamic nature of real estate markets) (*cf.* Shin *et al.*, 2011; Ferreira *et al.*, 2016).

Although different types of limitations exist, previous studies have grouped them into two major categories (*cf.* Pinto *et al.*, 2021; Ferreira *et al.*, 2022; Rodrigues *et al.*, 2023). The first involves the unclear way by which relevant factors/criteria are identified in most cases, while the second set of restrictions comprises the lack of analyses of cause-and-effect relationships among those factors, which need to include the links' dynamics. These two broad categories represent research opportunities. The present study, therefore, applied cognitive mapping to address the first group of limitations (Eden, 1988), and the DEMATEL technique to deal with the second category (Trivedi, 2018). Neutrosophic logic was also applied due to the subjective nature of the topic (Smarandache, 2007). This methodological combination is unique to this study context and aims to contribute to a more robust and nuanced understanding of the subject matter. Subsequently, we believe that our study adds value to the field by introducing a novel multicriteria analysis system and providing insights that extend beyond the conventional boundaries of real estate finance. Importantly, our intention is not to disregard established theories and methods but to offer a complementary perspective that considers the broader implications of urban expansion on real estate ecosystems.

3. METHODOLOGICAL BACKGROUND

Given the limitations of prior research, a new model is needed to explore and evaluate urban expansion effects on real estate ecosystems. This study's methodology included both cognitive mapping and DEMATEL techniques, as well as neutrosophic logic, to overcome the constraints of past investigations and accurately define the cause-and-effect relationships between variables. The following subsections discuss these methods' characteristics and applications in greater depth and present the advantages of the selected approach.

3.1 JOintly Understanding Reflecting and NEgotiating strategy (JOURNEY) Making, Cognitive Mapping, and Principles of Neutrosophic Logic

Problem-structuring methods (PSMs) can be defined *"as flexible mechanisms for addressing complex problems"* (Lami *et al.*, 2014, p. 282) that develop a structured representation of an issue in order to find innovative solutions (Mingers and Rosenhead, 2004). Decision problems are characterized by multiple actors who frequently have contrasting perspectives, objectives, interests, and uncertainties (Lami *et al.*, 2014). Structuring issues can be of strategic importance as a way to expose the fundamental components of complex problems (Mingers and Rosenhead, 2004).

JOURNEY making is the PSM selected for the present research because of its use of computer-supported group workshops as an investigative tool (Paiva *et al.*, 2021). This method comprises a procedure that helps decision makers structure complex decision problems (Shaw, 2006). This PSM specifically builds a consensual understanding among decision makers based on their personal and joint opinions about key issues. This process facilitates more informed discussions about how to define the decision problem in question and which actions should be incorporated into the solutions developed (Shaw *et al.*, 2006).

Cognitive mapping is the baseline tool used in JOURNEY making because it generates maps of what people think about an issue (Eden, 2004). Cognitive maps represent cause-and-effect relationships between variables as a system of nodes and arrows, in which the latter show the direction of causal links between the former (Marques *et al.*, 2022). The arrows can include causal signs so that a positive link to the first-level concept is indicated by a plus sign (+), and a negative connection is shown by a minus sign (–) (Ferreira *et al.*, 2017; Vieira *et al.*, 2022).

Eden (2004) observes that these maps reflect the decision makers' beliefs about causality and organize the connections between concepts into a three-level hierarchy. The top level represents the decision makers' objectives. The strategic issues appear in the middle level. The bottom level comprises the actions that could address the main decision problem (Rosário *et al.*, 2021). The decision makers' analysis system reflects their mutual trust and shared professional experience dealing with the topic under discussion, which strengthens their confidence in the map's reliability. The solutions will thus depend on these policymakers having faith in the model-building process and concurring that the JOURNEY making process is a faster way to discuss complex issues with other experts (Eden and Ackermann, 2004).

Neutrosophic logic can be incorporated into cognitive mapping to allow uncertainty to be incorporated into the decision-support model. Experts' realities include much uncertainty and information that cannot be quantified as sharp values (Uluçay and Sahin, 2019). Fuzzy set theory has long been an effective tool to deal with uncertainty, but this approach can only be used in random processes. Researchers have developed various other solutions based on decision-making theories (Uluçay and Sahin, 2019), but these techniques cannot cope with the full range of uncertainties in decision problems (*e.g.*, imprecise and erratic data) (Uluçay and Sahin, 2019). To fill this gap, Smarandache (2007) proposed neutrosophic logic as an extension of fuzzy logic.

According to Schweizer (2020), neutrosophy started out as a new approach within philosophy that adds a third option of neutrality to the traditional choices of positive and negative, thereby complementing classical logic's true or false with a neutral response. Smarandache (2007, p. 91) defines neutrosophic logic as a system *"in which each proposition is estimated to have the percentage of truth in a subset T, the percentage of indeterminacy in a subset I, and the percentage of falsity in a subset F"*. In other words, instead of simple intervals, these subsets can be *"any sets (e.g., discrete, continuous, open or closed or half-open/half-closed interval, intersections or unions of the previous sets)* [determined] *by the given proposition"* (Smarandache, 2007, p. 91). Statistically, T, I, and F are, therefore, considered subsets. Their value can also be designated as functions that are defined by known or unknown parameters. In this way, neutrosophic logic makes a distinction between relative and absolute truth. Specifically, T, I, and F are expressed as the unitary non-standard interval [–0, +1], which is the only restriction of this logic, and $0 \leq T + I + F \leq 3^{+}$ when the components are independent (Smarandache, 2007; Vaz-Patto *et al.*, 2023).

Cognitive maps represent experts' opinions about decision problems. When questioned, k decision makers can use neutrosophic logic to define the level of truth (T_k), indeterminacy (I_k), and falsity (F_k) of their own statements (Uluçay and Sahin, 2019). This logic thus portrays opinions in a form that matches how the human mind expresses judgements (Shadrach and Kandasamy, 2021). Neutrosophic cognitive maps (NCMs) can capture indeterminacy to represent human thinking more closely because they are directed graphs of causal relationships between factors (Shadrach and Kandasamy, 2021).

Neutrosophic matrix $N(E)$ based on the NCM generated by k decision makers is constructed by assigning each node an input vector for which $A = (a_1, a_2, \ldots, a_n)$ and $a_i \in \{0, 1, I\}$. The matrix contains the values produced by neutrosophic evaluations of the cause-and-effect relationships between n variables, with the diagonal values always equal to 0 because the concepts do not affect themselves. Using NCMs in decision making is beneficial as they can represent neutral criteria that have no effect on the other factors. This approach gives policymakers the freedom to decide that evaluation criteria have an indeterminate impact on other factors, adding another option to the basic choices of a positive, negative, or null effect (Smarandache, 2007). As mentioned previously, neutrosophic logic can be incorporated into cognitive maps and other methodologies.

The present study applied the DEMATEL technique in a neutrosophic environment to reflect the degree of indeterminacy inherent to the decision makers' judgements. To apply this logic to the DEMATEL technique, the neutrosophic T, I, and F values should be converted into a single number (*i.e.*, a crisp value) (Abdel-Basset *et al.*, 2018). To find this value, k decision makers, with $1 \leq k \leq m$, define each neutrosophic weight, which is expressed as $w_k = (T_k, I_k, F_k)$. Equation (1) is used to obtain crisp weights (Pramanik *et al.*, 2016):

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

in which $w_k \geq 0$.

By quantifying the decision makers' disagreement and considering the truth, indeterminacy, and falsity inherent to decision-making processes, the combined use of neutrosophic logic and DEMATEL reveals information previously unknown to experts who are unsure about their preferences (Abdel-Basset *et al.*, 2018).

3.2 DEMATEL

Gabus and Fontela (1972) developed DEMATEL at the Battelle Memorial Institute to analyze the relationships between criteria and structure complex decision problems (Abdel-Basset *et al.*, 2018). This technique has increasingly been applied in various fields due to its widely recognized advantages as a tool to solve extremely complicated decision problems (Braga *et al.*, 2021; Costa *et al.*, 2021). The DEMATEL methodology can be divided into six different steps (Sivakumar *et al.*, 2018).

3.2.1 Step One

The first step is to construct group direct-influence matrix Z in order to determine the relationships between n factors F given that the decision-making process will use k experts, with $1 \leq k \leq m$, in decision group E to determine the degree of direct influence the analyzed factors have on each other. Using a scale from 0 to 4 (0 = "No influence"; 1 = "Weak influence"; 2 = "Medium influence"; 3 = "Strong influence"; 4 = "Very strong influence"), the decision makers attribute a value to the level of influence that factor F_i has on F_j. The results of this procedure are used to generate individual direct-influence matrix $Z = [zij]\ n \times n$, in which all diagonal elements are equal to 0 and the value of z_{ij} represents the experts' joint decision. The experts can construct the matrix with Equation (2):

$$z_{ij} = \frac{1}{m}\sum_{k=1}^{m} z_{ij}^{k}, i, j = 1, 2, \dots, n \tag{2}$$

3.2.2 Step Two

The second step is to compute normalized direct-influence matrix *X* based on normalized direct-influence matrix *Z* by using Equation (3):

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

The value of λ is the normalized constant that corresponds to the maximum effect of each determinant on other factors, which is obtained with Equation (4), namely by adding up the values in matrix *Z*'s row *i*:

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

The total of column *j* is, in turn, the maximum effect a determinant receives from the other factors. After the normalized constant λ is applied, the elements of matrix *X* should all have values falling within the interval [0, 1].

3.2.3 Step Three

The third step is to generate total-influence matrix *T* using normalized direct-influence matrix *X*. Total-influence matrix *T* $n \times n$ is the total of all direct and indirect effects as estimated by Equation (5):

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

Thus, matrix *T* describes the relationship between each pair of factors.

3.2.4 Step Four

The fourth step is to add up rows and columns of total-influence matrix *T* to create vectors *R* and *C* by using Equations (6) and (7), respectively:

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

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

The r_i values represent the total of the i^{th} row in matrix T and show factor F_i's total indirect and direct effects on the other factors. The total of the j^{th} column is, in turn, denoted as c_j, which is factor F_j's total direct and indirect effects received from the remaining factors. When $i = j \in \{1, 2, \ldots, n\}$, the $R + C$ value corresponds to "prominence" of the relevant factor. This value is presented on the horizontal axis, which represents a criterion's degree of importance in the analysis system. The $R - C$ value denotes the "relationship" of each factor. This value appears on the vertical axis and indicates the level of influence of a given factor on the system. As a result, two possible situations can arise. If $r_i - c_j$ is positive, F_i has a net influence on the other factors, and this criterion belongs to the causes group. If $r_i - c_j$ is negative, F_j is overall more influenced by the remaining factors, so it belongs to the effects group.

3.2.5 Step Five

The fifth step is to establish the limit value—also known as the threshold or α value—by applying Equation (8):

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

Decision makers can use this limit to identify the most critical factors and eliminate the least significant elements from the system. The α value is defined by averaging all the elements of matrix T.

3.2.6 Step Six

The last step is to create an interrelationship map (IRM) by diagraming the dataset ($R + C$, $R - C$). As mentioned previously, $R + C$ values are placed along the horizontal axis and $R - C$ values are shown on the vertical one. In this way, the IRM representing the cause-and-effect relationships can be divided into four quadrants to which the factors or criteria are allocated (see *Figure 1*).

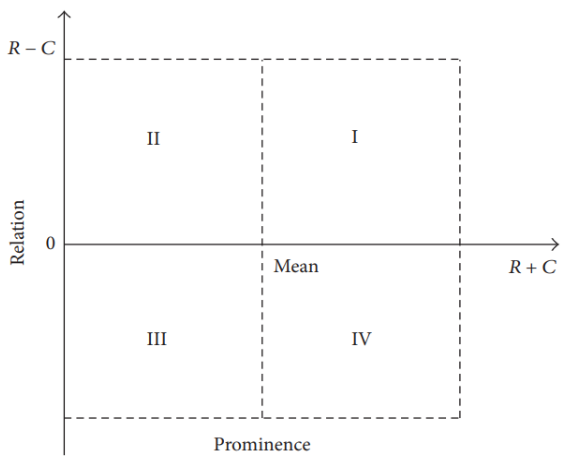

Figure 1. Four-Quadrant Interrelationship Map

Source: Si *et al.* (2018)

In *Figure 1*, quadrant I (QI) contains the core factors (*i.e.*, cause factors perceived as central to the system). Quadrant II (QII) embraces the driving factors (*i.e.*, cause factors associated with perceived risks). Quadrant III (QIII) comprises the independent factors (*i.e.*, effect factors linked with perceived risks). Finally, quadrant IV (QIV) encloses the impact factors (*i.e.*, effect factors connected with perceived benefits) (Si *et al.*, 2018).

In comparison to other multiple-criteria decision analysis (MCDA) methods, this technique can clarify more fully criteria's direct and indirect influence on each other and provide a deeper understanding of their complex cause-and-effect links (*cf.* Si *et al.*, 2018). Thus, DEMATEL IRMs provide a visualization of the relationships between the factors identified by decision makers, thereby revealing each criterion's impact on the other factors (Yazdi *et at.*, 2020). Despite its many advantages, DEMATEL is not free from limitations. One significant restriction is that experts' opinions can be biased and imprecise. Decision makers may also try to manipulate the criteria to obtain the desired results (*cf.* Luthra *et al.*, 2017; Chen *et al.*, 2020; Zhou, 2020). However, the benefits of using DEMATEL evidently surpass its limitations.

4. APPLICATION AND RESULTS

The methodologies presented in *Section 3* facilitate the creation of a decision-support model—with the assistance of an expert panel—that can be used to analyze the effects of urban expansion on real estate ecosystems. This type of panel is usually composed of specialists with experience in controlling, managing, or understanding issues related to the topic under study and the associated organizational performance in varied settings (Yaman and Polat, 2009). According to Salmeron (2009), expert panels should include between 5 to 18 members.

Based on this recommendation, our expert panel comprised eight specialists in the selected topic. One panel member was an investment consultant specializing in hotel investments. Another was an architect who owned a company. A third was a real estate consultant who had worked in one of the largest real estate companies operating in Portugal for the last 11 years. A fourth member was a civil engineer, while a fifth was a real estate constructor specializing in sustainable construction. The final three experts were another real estate consultant who owned a real estate agency, another architect with several years of experience in sustainable construction, and a sustainable energy production and distribution specialist. Although respecting the guidelines and recommendations presented in the literature (*cf.* Belton and Stewart, 2010), is worth noting that the present study is process-oriented, so representativeness was not—and did not have to be—a point of concern. Bell and Morse (2013) note that the objective of the selected methodologies is not to make generalizations but rather to maintain a strong focus on process.

4.1 Group Cognitive Map

The group sessions took place online to guarantee a safe environment for all the participants because of the pandemic-related restrictions and rising number of coronavirus disease-19 cases in Portugal in January 2022. The first session started with a short presentation of each panel member and an explanation of the session purpose. Brief explanations were also provided of the baseline concepts and methodologies to ensure the panel members understood the procedures.

This meeting was coordinated by a facilitator (*i.e.*, one of the authors of the present paper). In addition, two technical assistants provided logistical support, as well as being responsible for recording the sessions. The Miro platform (www.miro.com) was used to allow the participants to complete the first-session tasks. The facilitator next presented a trigger question to the panel members: *"Based on your experience and/or professional knowledge, what effects and/or impacts can urban expansion have on real estate ecosystems?"*. The panel members' answers were given by applying the "post-its technique" (Ackermann and Eden, 2001) and using virtual post-it notes provided by the Miro platform. The decision makers were invited to write the criteria they considered relevant on these notes (Azevedo and Ferreira, 2019). The participants were informed that each note could only contain one idea and that they should add a plus (+) or minus (–) sign according to the type of causal relationship associated with the concepts (Faria *et al.*, 2018). That is, if the urban-expansion criterion positively influences real estate ecosystems, the note should include a plus (+) sign. Conversely, if a factor harms these ecosystems, a negative (–) sign should be added. The decision makers presented multiple criteria that they felt were related to the trigger question. According to Eden (2004), decision problems are best represented by large cognitive maps with more than 100 nodes. In the present study, the panel identified over 150 criteria.

The second part of the first session started with an analysis of the factors identified. The objective was to create groups of closely related criteria (Castanho *et al.*, 2019). Five clusters—or areas of concern—were formed that reflect urban expansion effects on real estate ecosystems, with the following labels: *Tourism* (C1); *Mobility* (C2); *Society* (C3); *Sustainability* (C4); and *Economy* (C5).

The last part of the first group session focused on developing a hierarchy of criteria within each cluster. To do this, the experts organized the factors by levels of importance so that the most significant criteria were placed at the top of their cluster while the least important were at the bottom. Any intermediate factors were situated appropriately in between these extremes. The data generated during the first session were combined to create a group cognitive map using the *Decision Explorer* software (www.banxia.com). The second group session also took place online via Zoom and started with the panel members' analysis, discussion, and validation of the cognitive map. The decision makers could voice their opinions about what had previously been done, and reformulate the contents when they considered this necessary (Brito *et al.*, 2019). *Figure 2* presents the map's approved final version.

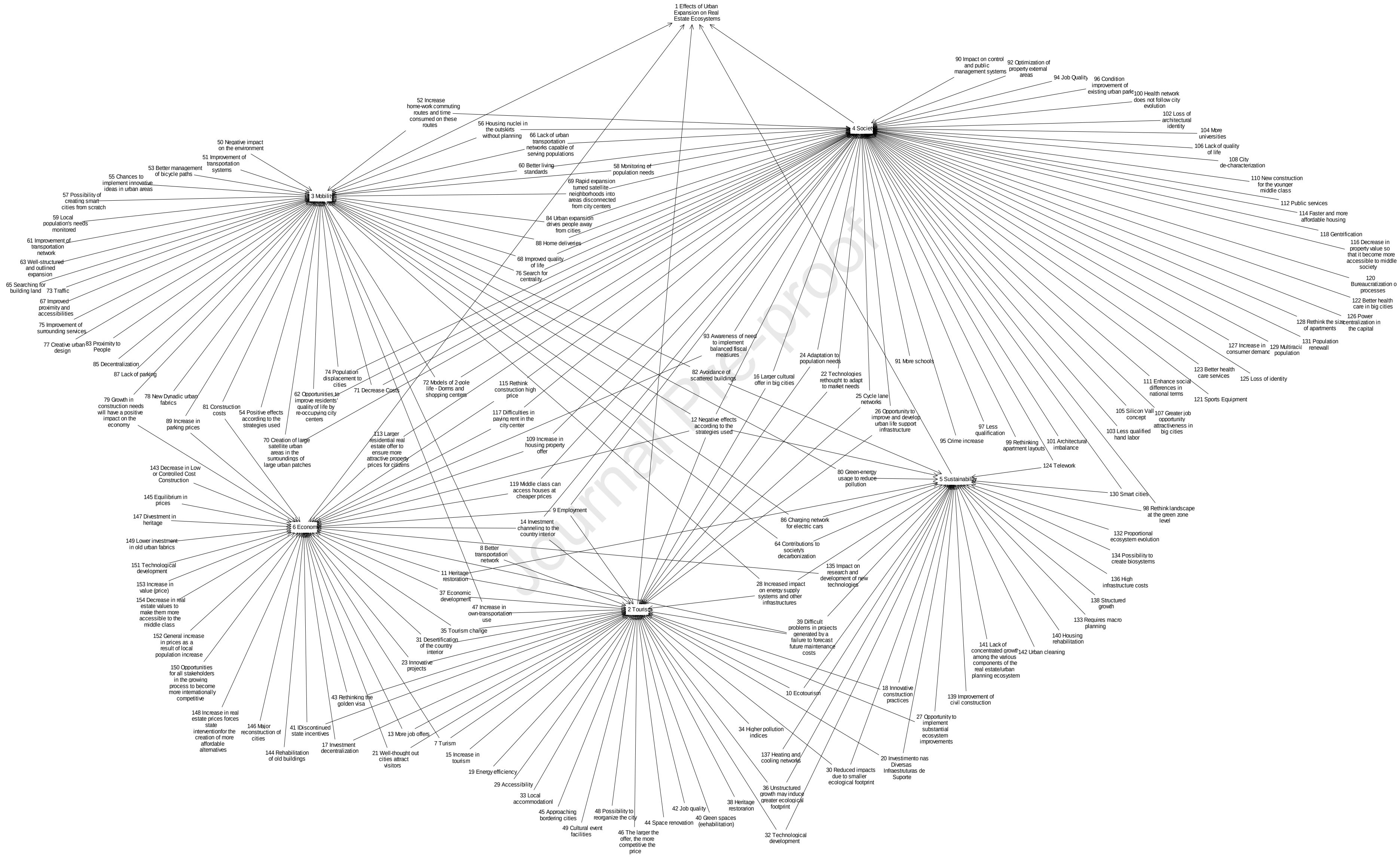

Figure 2. Group Cognitive Map

As shown in *Figure 2*, each arrow in the map represents a cause-and-effect relationship between two criteria. Some factors belong to more than one cluster, and the urban-expansion criteria that negatively influence real estate ecosystems are associated with a negative sign (–) at the head of the corresponding arrow. Once the cognitive map was completed, the panel could move on to the quantitative analysis based on an application of the DEMATEL technique in a neutrosophic environment.

4.2 Neutrosophic Logic, Crispification, and DEMATEL Application

The present research incorporated neutrosophic logic into the DEMATEL scale used to measure the cause-and-effect relationships between variables. Díaz *et al.* (2020, p. 24) observe that: *"indeterminacy is part of daily life, which is why* […] *neutrosophic DEMATEL allows* [for] *the study of complex cause-effect relationships,* […] *includ*[ing] *indeterminacy and the use of linguistic terms* [… that are] *the* [most] *natural form of communication for human beings"*.

The second expert panel session started out with the facilitator's explanation of this technique and its advantages for model-building processes. This meeting was attended by 5 of the 8 initial participants. This situation has occurred in prior studies, which found that it does not jeopardize the results as long as the minimum number of participants is present (*cf.* Salmeron, 2009; Azevedo and Ferreira, 2019). At the beginning of this session, the panel members determined which criteria were more important in each cluster by using the nominal group technique (NGT) and multi-voting. This step was essential to the decision-making process because an analysis of the large number of criteria in each cluster would have been extremely challenging. The two techniques applied benefited from the participants' previous interactions during the meetings, which had allowed them to share their knowledge.

4.2.1 Inter-Cluster Analysis

The second group session allowed for the construction of 6 matrices (*i.e.*, 1 inter-cluster and 5 intra-cluster matrices), in which each cell contains 4 values: the DEMATEL value and the neutrosophic *T*, *I*, and *F* values. To apply the DEMATEL technique, the three neutrosophic values assigned by the panel members had to be converted into a single crisp value that reflected the *T*, *I*, and *F* levels. The first matrix represented the inter-relationships between clusters (*i.e.*, *Tourism* (C1); *Mobility* (C2); *Society* (C3); *Sustainability* (C4); and *Economy* (C5)) with neutrosophic values (see *Table 2*). *Table 3* lists the values after crispification, with which the final DEMATEL matrix could be completed and an IRM generated. *Table 4* is the DEMATEL matrix with crisp values. After this step, Equations (3) and (4) (see *Subsection 3.2.2*) were used to carry out auxiliary calculations (see *Table 5*) and the normalized direct matrix presented in *Table 6*. The remaining computations were done to produce matrix *T* (see *Table 7*).

Table 2. Inter-Cluster Matrix Constructed with Neutrosophic Values

	C1	C2	C3	C4	C5
C1	–	2(0.65, 0.5, 0.1)	3.5(0.9, 0.05, 0)	3.5(0.9, 0.05, 0)	4(0.95, 0, 0)
C2	4(0.95, 0, 0)	–	4(0.95, 0, 0)	2.5(0.8, 0.2, 0.15)	3(0.65, 0.75, 0.15)
C3	3(0.8, 0.15, 0.05)	3(0.9, 0.05, 0)	–	3.5(0.9, 0.05, 0)	4(0.95, 0, 0)
C4	2.5(0.7, 0.2, 0.15)	2.5(0.8, 0.2, 0.15)	3(0.8, 0.15, 0.05)	–	3(0.8, 0.15, 0.05)
C5	3(0.7, 0.2, 0.15)	3(0.7, 0.2, 0.15)	3(0.7, 0.2, 0.15)	2.5(0.8, 0.15, 0.1)	–

Table 3. Inter-Cluster Crispification of Neutrosophic Values

	Relationship Analyzed	**DEMATEL Scale (x)**	**Neutrosophic Values (T, I, F)**			**Neutrosophic Crispification**		
			T	I	F	Crispification on Formula Numerator	Neutrosophic Weight w Crispified	Final Value for DEMATEL Matrix $x(T,I,F)\rightarrow x$
Inter-Cluster Matrix	C1–C2	2.0	0.65	0.50	0.10	0.6429	0.0380	1.29
	C1–C3	3.5	0.90	0.05	0.00	0.9355	0.0553	3.27
	C1–C4	3.5	0.90	0.05	0.00	0.9355	0.0553	3.27
	C1–C5	4.0	0.95	0.00	0.00	0.9711	0.0574	3.88
	C2–C1	4.0	0.95	0.00	0.00	0.9711	0.0574	3.88
	C2–C3	4.0	0.95	0.00	0.00	0.9711	0.0574	3.88
	C2–C4	2.5	0.80	0.20	0.15	0.8152	0.0482	2.04
	C2–C5	3.0	0.65	0.75	0.15	0.5144	0.0304	1.54
	C3–C1	3.0	0.80	0.15	0.05	0.8528	0.0504	2.56
	C3–C2	3.0	0.90	0.05	0.00	0.9355	0.0553	2.81
	C3–C4	3.5	0.90	0.05	0.00	0.9355	0.0553	3.27
	C3–C5	4.0	0.95	0.00	0.00	0.9711	0.0574	3.88
	C4–C1	2.5	0.70	0.20	0.15	0.7745	0.0458	1.94
	C4–C2	2.5	0.80	0.20	0.15	0.8152	0.0482	2.04
	C4–C3	3.0	0.80	0.15	0.05	0.8528	0.0504	2.56
	C4–C5	3.0	0.80	0.15	0.05	0.8528	0.0504	2.56
	C5–C1	3.0	0.70	0.20	0.15	0.7745	0.0458	2.32
	C5–C2	3.0	0.70	0.20	0.15	0.7745	0.0458	2.32
	C5–C3	3.0	0.70	0.20	0.15	0.7745	0.0458	2.32
	C5–C4	2.5	0.80	0.15	0.10	0.8445	0.0499	2.11
If $\Sigma = 1$, Equation (1) (see subsection 3.1) conditions are satisfied.					Crispification formula denominator	16.9151	1.0000	

Table 4. Inter-Cluster Direct-Influence Matrix

	C1	C2	C3	C4	C5	Total
C1	0.0	1.3	3.3	3.3	3.9	11.7
C2	3.9	0.0	3.9	2.0	1.5	11.3
C3	2.6	2.8	0.0	3.3	3.9	12.5
C4	1.9	2.0	2.6	0.0	2.6	9.1
C5	2.3	2.3	2.3	2.1	0.0	9.1
Total	10.7	8.5	12.0	10.7	11.9	

Table 5. Auxiliary Calculations

Max	12.0	12.5
1/max	0.083126	0.079872
1/s	**0.079872204**	

Table 6. Normalized Direct-Influence Matrix *X*

	C1	C2	C3	C4	C5
C1	0.0000	0.1030	0.2612	0.2612	0.3099
C2	0.3099	0.0000	0.3099	0.1629	0.1230
C3	0.2045	0.2244	0.0000	0.2612	0.3099
C4	0.1550	0.1629	0.2045	0.0000	0.2045
C5	0.1853	0.1853	0.1853	0.1685	0.0000

Table 7. Matrix *T*

	C1	C2	C3	C4	C5	*R*
C1	1.0823	1.0195	1.4046	1.3258	1.4771	6.3094
C2	1.3541	0.9339	1.4707	1.2848	1.3760	6.4195
C3	1.3261	1.1599	1.2759	1.3899	1.5432	6.6950
C4	1.0304	0.8970	1.1577	0.9166	1.1803	5.1821
C5	1.0562	0.9134	1.1497	1.0643	1.0136	5.1971
C	5.8491	4.9237	6.4586	5.9813	6.5902	

Table 8 lists the *R* and *C* values and the *R* + *C* and *R* – *C* values that became the IRM axes. The clusters were divided into two groups. If *R* – *C* < 0, the cluster belongs to the effects group and has a weak relationship with the other clusters. If *R* – *C* > 0, the cluster is part of the causes group and directly influences the remaining clusters. The *R* + *C* value represents the total effect a cluster receives from or gives to the others, and this number defines the IRM horizontal axis. The vertical axis is the *R* – *C* value, which reveals the degree of influence (*i.e.*, relationship) a given cluster has within the analysis system. The level of importance of each cluster can be measured by the *R* + *C* value because it reflects the total prominence of that cluster within the model.

Table 8. Inter-Cluster Interactions

	R	*C*	*R* + *C*	*R* – *C*
C1	6.3094	5.8491	12.1585	0.4603
C2	6.4195	4.9237	11.3432	1.4957
C3	6.6950	6.4586	13.1536	0.2363
C4	5.1821	5.9813	11.1634	–0.7992
C5	5.1971	6.5902	11.7873	–1.3931

In this specific case, the most important cluster is C3. With the lowest *R* + *C* value, C4 is the least prominent cluster. The clusters' order of importance according to their *R* + *C* values is as follows: C3 > C1 > C5 > C2 > C4. The prominence of C3 as the most pivotal cluster in our study results from a nuanced interplay of various factors and key considerations. The invaluable input and insights of decision makers played a decisive role in the meticulous process of weighting and prioritizing criteria, thereby enhancing the robustness of our analytical model. In this regard, the prominence of C3 signifies a consensus among these experts regarding the substantial impact of societal factors in shaping the dynamics of urban expansion. This cluster emerged as the most significant, likely due to the nuanced and multifaceted nature of societal influences, encompassing a broad spectrum of perspectives, values, and cultural considerations. Examples include an emphasis on preserving social inclusivity during urban expansion, promoting community engagement, policies that foster the integration of various cultural communities, and the creation of an urban environment conducive to well-being. These facets are integral to the complex dynamics at play. Our comprehensive approach, informed by the diverse insights of decision makers, effectively captured the intricate interconnections and diverse dimensions characterizing the societal impact on urban expansion and real estate ecosystems. This comprehensive understanding reinforces the significance of C3 in our study, highlighting its central role in shaping the outcomes and underscoring the importance of societal factors in the broader context of urban expansion dynamics. *Figure 3* shows the IRM generated for the inter-cluster analysis, which reveals that C4 and C5 have a negative $R - C$ value and belong to the effects group. C1, C2, and C3 are part of the causes group with a positive $R - C$ value. This map also divides the clusters into three different quartiles: QI, in which C1 and C3 contain core factors; QII, in which C2 comprises driving factors; and QIII, in which C4 and C5 encompass independent factors.

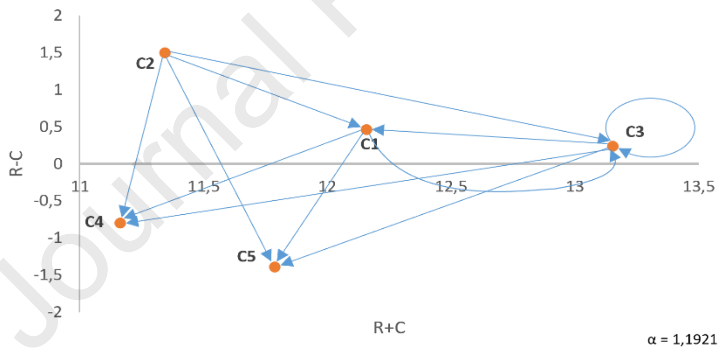

Figure 3. Inter-Cluster Interrelationship Map

Importantly, only the causal relationships with intensity above the average value of matrix T (*i.e.*, $\alpha = 1.1921$) are represented in the IRM (*cf.* Gabus and Fontela, 1972; Sivakumar *et al.*, 2018). This association is visually reflected in *Figure 3*, where the lines exclusively represent the green values in the matrix T presented in *Table 7*. Each cluster was subsequently analyzed separately to ensure a more comprehensive evaluation and conclusive results.

4.2.2 Intra-Cluster Analyses

The intra-cluster analyses used only the most significant criteria (hereafter, subcriteria (SCs)) that the panel had selected to complete the DEMATEL matrixes. The equations and auxiliary calculations were the same as those used for the inter-cluster analysis. The decision makers first analyzed C1. *Table 9* lists the C1 SCs selected by the panel as the most important. *Table 10* shows the DEMATEL and neutrosophic values associated with the experts' opinions regarding C1, and *Table 11* presents the crisp values.

Table 9. Selected Subcriteria for Tourism Cluster

Subcriteria in Tourism Cluster	
SC11	Heritage restoration
SC13	More job offers
SC23	Innovative projects
SC37	Economic development
SC39	Difficult problems in projects generated by a failure to forecast future maintenance costs
SC44	Space renovation
SC49	Cultural event facilities

Table 10. Tourism Cluster with Neutrosophic Values

	SC11	SC13	SC23	SC37	SC39	SC44	SC49
SC11	--	3(0.9, 0.1, 0.1)	2(0.70, 0.3, 0.15)	3.5(0.9, 0.1, 0.1)	3(0.8, 0.1, 0.1)	4(0.9, 0.1, 0.1)	4(0.9, 0.1, 0.1)
SC13	1.5(0.7, 0.7, 0.15)	--	1.5(0.7, 0.7, 0.15)	3(0.9, 0.1, 0.1)	0(1, 0, 0)	1.5(0.7, 0.7, 0.15)	1.5(0.7, 0.7, 0.15)
SC23	2.5(0.7, 0.1, 0.1)	2.5(0.7, 0.1, 0.1)	--	3(0.8, 0.2, 0.15)	2.5(0.7, 0.1, 0.1)	2.5(0.7, 0.1, 0.1)	3.5(0.8, 0.2, 0.1)
SC37	3(0.7, 0.2, 0.15)	4(0.95, 0.05, 0)	3.5(0.8, 0.2, 0.1)	--	2(0.75, 0.2, 0.15)	3(0.7, 0.2, 0.15)	3(0.7, 0.2, 0.15)
SC39	3(0.8, 0.2, 0.15)	3(0.8, 0.2, 0.15)	2(0.75, 0.2, 0.2)	3(0.8, 0.2, 0.15)	--	3(0.8, 0.2, 0.15)	3(0.8, 0.2, 0.15)
SC44	3(0.8, 0.2, 0.15)	3.5(0.9, 0.1, 0.1)	1.5(0.8, 0.2, 0.15)	3.5(0.9, 0.1, 0.1)	3.5(0.9, 0.1, 0.1)	--	3(0.8, 0.2, 0.15)
SC49	3.5(0.7, 0.7, 0.15)	1.5(0.7, 0.7, 0.15)	3.5(0.8, 0.2, 0.1)	2.5(0.8, 0.15, 0.1)	2.5(0.8, 0.15, 0.1)	3.5(0.8, 0.2, 0.1)	--

Table 11. Tourism Cluster Direct-Influence Matrix

	SC11	SC13	SC23	SC37	SC39	SC44	SC49	Total
SC11	0.00	2.70	1.48	3.15	2.58	3.60	3.60	17.1
SC13	0.83	0.00	0.83	2.70	0.00	0.83	0.83	6.0
SC23	2.02	2.02	0.00	2.45	2.02	2.02	2.89	13.4
SC37	2.32	3.84	2.89	0.00	1.59	2.32	2.32	15.3
SC39	2.45	2.45	1.56	2.45	0.00	2.45	2.45	13.8
SC44	2.45	3.15	1.22	3.15	3.15	0.00	2.45	15.6
SC49	1.93	0.83	2.89	2.11	2.11	2.89	0.00	12.8
Total	12.0	15.0	2.4	16.0	11.5	14.1	14.5	

With the information provided by *Table 12*, the most significant SCs in C1 could be analyzed in greater depth. SC11 has the highest *R* value. The SC with the highest *C* value is SC37, which is also the most prominent criterion in this cluster due to its $R + C$ value of 7.9565. Taken together, SC11 and SC37 highlight how much decision makers value the importance of heritage restoration to the cultural richness and historical significance of urban spaces. This emphasis aims at attracting visitors and fostering a sense of pride and identity within the community, ultimately contributing to increased economic development. The least important is SC49, with the lowest *R* + *C* value. The C1 SCs can be ranked as follows: SC37 > SC11 > SC39 > SC23 > SC13 > SC49 > SC44.

Table 12. Tourism Cluster: Interactions Between Subcriteria

	R	***C***	***R* + *C***	***R* – *C***
SC11	4.4048	3.1777	7.5825	1.2271
SC13	1.7050	3.9398	5.6448	–2.2348
SC23	3.5458	2.9637	6.5095	0.5820
SC37	3.8257	4.1308	7.9565	–0.3051
SC39	3.6269	3.0145	6.6413	0.6124
SC44	3.9829	0.0000	3.9829	3.9829
SC49	3.5160	0.0000	3.5160	3.5160

Figure 4 shows the IRM for this cluster. SC11, SC23, SC39, SC44, and SC49 present positive *R* – *C* values, so they belong to the causes group. SC13 and SC37 are part of the effect group and are more influenced by the other factors. The subdivision of *Figure 4* into quartiles places SC11, SC23, and SC39 in QI (*i.e.*, core factors). The driving factors in QII are SC44 and SC49. The only independent factor in QIII is SC13. Finally, SC37 can be considered an impact factor as it appears in QIV.

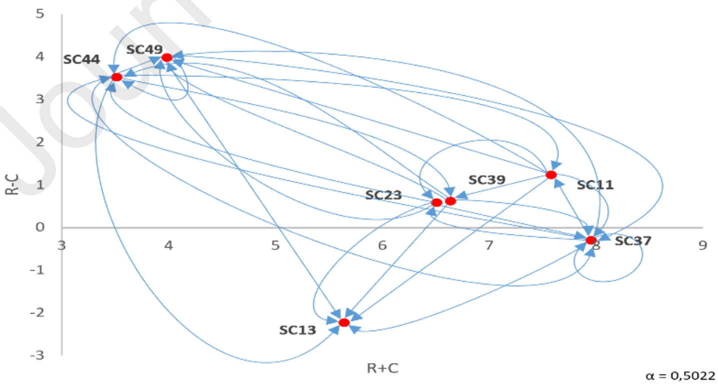

Figure 4. Tourism Cluster Interrelationship Map

C2 was analyzed next based on the SCs presented in *Table 13*. *Table 14* displays the DEMATEL and neutrosophic values associated with the decision makers' choices, while *Table 15* lists the crisp values.

Table 13. Selected Subcriteria for Mobility Cluster

Subcriteria in Mobility Cluster	
SC51	Improvement of transportation systems
SC53	Better management of bicycle paths
SC55	Chances to implement innovative ideas in urban areas
SC59	Local population's needs monitored
SC62	Opportunities to improve residents' quality of life by re-occupying city centers
SC77	Creative urban design
SC80	Green-energy usage to reduce pollution

Table 14. Mobility Cluster Matrix with Neutrosophic Values

	SC51	**SC53**	**SC55**	**SC59**	**SC62**	**SC77**	**SC80**
SC51	--	3(0.8, 0.2, 0.1)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	3.5 (0.8, 0.2, 0.1)	3.5 (0.8, 0.2, 0.1)
SC53	3(0.8, 0.2, 0.1)	--	3.5 (0.8, 0.2, 0.1)	3(0.8, 0.2, 0.1)	3.5 (0.9, 0.1, 0.05)	3.5 (0.8, 0.2, 0.1)	4 (0.9, 0.1, 0.1)
SC55	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	--	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)
SC59	4 (0.9, 0.1, 0.1)	3 (0.8, 0.2, 0.1)	4 (0.9, 0.1, 0.1)	--	4 (0.9, 0.1, 0.1)	3.5 (0.8, 0.2, 0.1)	3.5 (0.8, 0.2, 0.1)
SC62	3.5 (0.9, 0.1, 0.1)	3.5 (0.9, 0.1, 0.1)	3.5 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	--	3.5 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)
SC77	3.5 (0.9, 0.1, 0.1)	3.5 (0.9, 0.1, 0.1)	4 (1, 0, 0)	3.5 (0.9, 0.1, 0.1)	3.5 (0.9, 0.1, 0.1)	--	3.5 (0.9, 0.1, 0.1)
SC80	3.5 (0.8, 0.2, 0.1)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	3.5 (0.8, 0.2, 0.1)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	--

Table 15. Mobility Cluster Direct-Influence Matrix

	SC51	**SC53**	**SC55**	**SC59**	**SC62**	**SC77**	**SC80**	**Total**
SC51	0.0	2.5	3.6	3.6	3.6	2.9	2.9	19.1
SC53	2.5	0.0	2.9	2.5	3.2	2.9	3.6	17.5
SC55	3.6	3.6	0.0	3.6	3.6	3.6	3.6	21.6
SC59	3.6	2.5	3.6	0.0	3.6	2.9	2.9	19.1
SC62	3.2	3.2	3.2	3.6	0.0	3.2	3.6	19.8
SC77	3.2	3.2	4.0	3.2	3.2	0.0	3.2	19.8
SC80	2.9	3.6	3.6	2.9	3.6	3.6	0.0	20.2
Total	18.9	18.5	20.8	19.3	20.8	19.0	19.7	

Table 16 provides the information needed to evaluate the most important C2 SCs. SC55 has the most influence on the other factors (*i.e.*, R = 10.6641). This SC also has the highest C value, so it receives more influence from the other factors.

Table 16. Mobility Cluster: Interactions Between Subcriteria

	R	***C***	***R* + *C***	***R* – *C***
SC51	9.6046	9.5077	19.1123	0.0969
SC53	8.9127	9.3303	18.2430	–0.4175
SC55	10.6641	10.3389	21.0030	0.3252
SC59	9.6046	9.7097	19.3143	–0.1051
SC62	9.8947	10.3113	20.2060	–0.4166
SC77	9.9013	9.5733	19.4746	0.3281
SC80	10.0665	9.8775	19.9440	0.1890

As shown in *Figure 5*, the most prominent SC is SC55, with an *R* + *C* value of 21.0030. This demonstrates how much decision makers recognize the importance of seizing opportunities to implement innovative ideas and prioritize criteria that foster a dynamic and forward-thinking urban mobility landscape. Based on the *R* + *C* axis, the C2 SCs can be ranked by importance as follows: SC55 > SC62 > SC80 > SC77 > SC59 > SC51 > SC53. The SCs ranked the highest give and receive more influence. The SCs that have positive *R* – *C* values are part of the causes group, which is divided into core factors (*i.e.*, SC55 and SC80) in QI and driving factors (*i.e.*, SC51 and SC77) in QII. The effects group (*R* – *C* < 0) is, in turn, divided into independent factors (*i.e.*, SC53 and SC59) in QIII and impact factors (*i.e.*, SC62) in QIV.

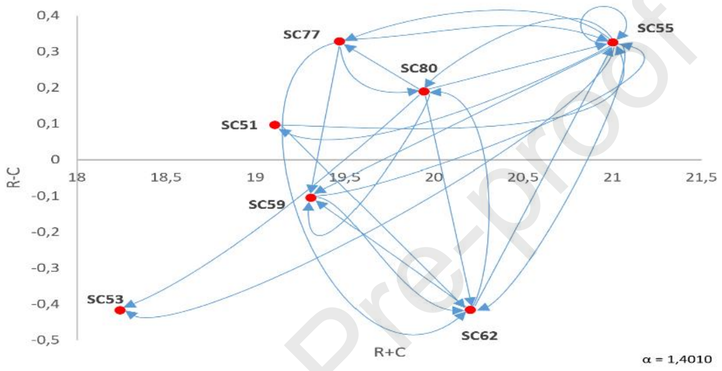

Figure 5. Mobility Cluster Interrelationship Map

The SCs selected for the analysis of C3 are listed in *Table 17*. The decision makers' subsequent choices are reflected in *Tables 18* and *19*.

Table 17. Selected Subcriteria for Society Cluster

Subcriteria in Society Cluster	
SC9	Employment
SC22	Technologies rethought to adapt to market needs
SC68	Improved quality of life
SC93	Awareness of need to implement balanced fiscal measures
SC112	Public services
SC113	Larger residential real estate offer to ensure more attractive property prices for citizens
SC131	Smart cities

Table 18. Society Cluster Matrix with Neutrosophic Values

	SC9	SC22	SC68	SC93	SC112	SC113	SC131
SC9	--	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	3.5 (0.8, 0.2, 0.15)	3.5 (0.8, 0.2, 0.15)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)
SC22	4 (0.9, 0.1, 0.1)	--	4 (0.9, 0.1, 0.1)	3.5 (0.8, 0.2, 0.15)	2.5 (0.7, 0.5, 0.3)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)
SC68	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	--	0 (1, 0, 0)	0 (1, 0, 0)	0 (1, 0, 0)	2 (0.7, 0.5, 0.3)
SC93	4 (0.9, 0.1, 0.1)	2 (0.7, 0.5, 0.3)	4 (0.9, 0.1, 0.1)	--	1 (0.7, 0.5, 0.3)	4 (0.9, 0.1, 0.1)	2 (0.7, 0.5, 0.3)
SC112	1 (0.9, 0.1, 0.1)	2 (0.7, 0.5, 0.3)	4 (0.9, 0.1, 0.1)	2 (0.7, 0.5, 0.3)	--	1 (0.9, 0.1, 0.1)	3.5 (0.9, 0.7, 0.1)
SC113	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	2 (0.7, 0.5, 0.3)	1 (0.7, 0.5, 0.3)	--	4 (0.9, 0.1, 0.1)
SC131	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	--

Table 19. Society Cluster Direct-Influence Matrix

	SC9	SC22	SC68	SC93	SC112	SC113	SC131	Total
SC9	0.0	3.6	3.6	2.9	2.9	3.6	3.6	20.1
SC22	3.6	0.0	3.6	2.9	1.6	3.6	3.6	18.8
SC68	3.6	3.6	0.0	0.0	0.0	0.0	1.2	8.4
SC93	3.6	1.2	3.6	0.0	0.6	3.6	1.2	13.9
SC112	0.9	1.2	3.6	1.2	0.0	0.9	2.1	9.9
SC113	3.6	3.6	3.6	1.2	0.6	0.0	3.6	16.3
SC131	3.6	3.6	3.6	3.6	3.6	3.6	0.0	21.6
Total	18.9	16.9	21.6	11.8	9.2	15.3	15.3	

The cause-and-effect relationships between selected C3 SC are presented in *Table 20*, which shows the influence of the different factors on each other. SC131 has the strongest effect on the other SCs (R = 3.5438). SC68 is the most influenced by the others, with the highest C value. SC9 overall gives and receives more influence, so this factor is the most important in C3, with the highest $R + C$ value.

Table 20. Society Cluster: Interactions Between Subcriteria

	R	*C*	*R* + *C*	*R* – *C*
SC9	3.3631	3.2596	6.6227	0.1035
SC22	3.2256	3.0086	6.2343	0.2170
SC68	1.6923	3.5438	5.2361	-1.8515
SC93	2.4074	2.0621	4.4695	0.3453
SC112	1.6650	1.6528	3.3177	0.0122
SC113	2.9096	2.6105	5.5201	0.2991
SC131	3.5438	2.6694	6.2133	0.8744

As shown in *Figure 6*, the most important SCs are on the right side of the diagram. Thus, when these factors are ranked by importance, the result is as follows: SC9 > SC22 > SC131 > SC113 > SC68 > SC93 > SC112. The importance of SC9 reflects the recognition by decision makers of its pivotal role in shaping urban societal dynamics. Emphasizing employment goes beyond economic considerations, aligning with broader societal values that prioritize meaningful work for the well-being, social inclusivity, and prosperity of communities. Decision makers within C3 understand that robust employment opportunities contribute not only to financial stability but also play a vital role in fostering social cohesion, reducing inequality, and building resilient urban communities. This emphasis on employment influences policy decisions and initiatives aimed at creating a dynamic employment landscape, contributing significantly to the overall health and vibrancy of urban societies. The IRM quadrants include SC9, SC22, SC113, and SC131 as core factors in QI; SC93 and SC112 as driving factors in QII; and SC68 as the only independent factor in QIII.

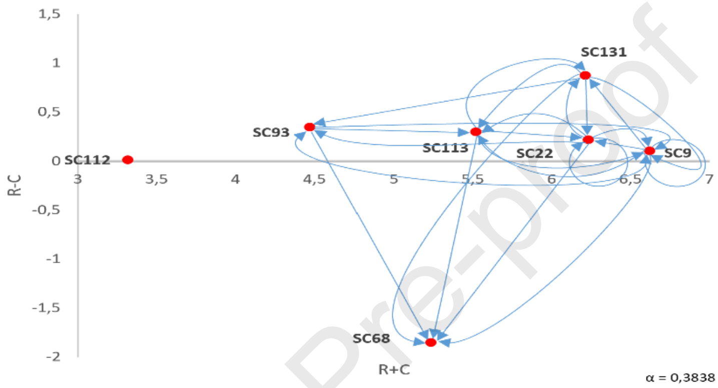

Figure 6. Society Cluster Interrelationships Map

Table 21 lists the SCs chosen for C4. *Table 22* then presents the DEMATEL and neutrosophic values for this cluster, while *Table 23* shows the crisp values. Finally, *Table 24* reflects the interactions between the C4 SCs.

Table 21. Selected Subcriteria for Sustainability Cluster

Subcriteria in Sustainability Cluster	
SC18	Innovative construction practices
SC30	Reduced impacts due to smaller ecological footprint
SC64	Contributions to society’s decarbonization
SC82	Avoidance of scattered buildings
SC138	Structured growth

Table 22. Sustainability Cluster Matrix with Neutrosophic Values

	SC18	SC30	SC64	SC82	SC138
SC18	–	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	0 (1, 0, 0)	4 (0.9, 0.1, 0.1)
SC30	2 (0.7, 0.5, 0.3)	–	4 (0.9, 0.1, 0.1)	0 (1, 0, 0)	0 (1, 0, 0)
SC64	2 (0.7, 0.5, 0.3)	4 (0.9, 0.1, 0.1)	–	0 (1, 0, 0)	4 (0.9, 0.1, 0.1)
SC82	0 (1, 0, 0)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	–	4 (0.9, 0.1, 0.1)
SC138	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	–

Table 23. Sustainability Cluster Direct-Influence Matrix

	SC18	SC30	SC64	SC82	SC138	Total
SC18	0.0	3.6	3.6	0.0	3.6	10.8
SC30	1.2	0.0	3.6	0.0	0.0	4.8
SC64	1.2	3.6	0.0	0.0	3.6	8.4
SC82	0.0	3.6	3.6	0.0	3.6	10.8
SC138	3.6	3.6	3.6	3.6	0.0	14.4
Total	6.1	14.4	14.4	3.6	10.8	

Table 24. Sustainability Cluster: Interactions Between Subcriteria

	R	*C*	*R + C*	*R – C*
SC18	2.0717	1.3720	3.4437	0.6997
SC30	0.9317	2.6860	3.6177	–1.7543
SC64	1.6689	2.6860	4.3549	–1.0171
SC82	2.0717	0.7372	2.8089	1.3345
SC138	2.6860	1.9488	4.6348	0.7372

SC138 has the highest *R* value (*i.e.*, 2.6860). In contrast, SC30 and SC64 are the most influenced, with the same *C* value of 2.6860. As can be seen in *Figure 7*, SC138 is the most prominent SC in this cluster. This strategic focus on structured growth within C4 influences decision-making processes, guiding policies and initiatives aimed at creating resilient, eco-friendly, and socially inclusive urban environments that promote long-term sustainability. The ranking by importance is as follows: SC138 > SC64 > SC30 > SC18 > SC82.

When these SCs are divided into the IRM quartiles, SC138 is a core factor in QI, SC18 and SC82 are driving factors in QII, SC30 is an independent factor in QIII, and SC64 is an impact factor in QIV (see *Figure 7*).

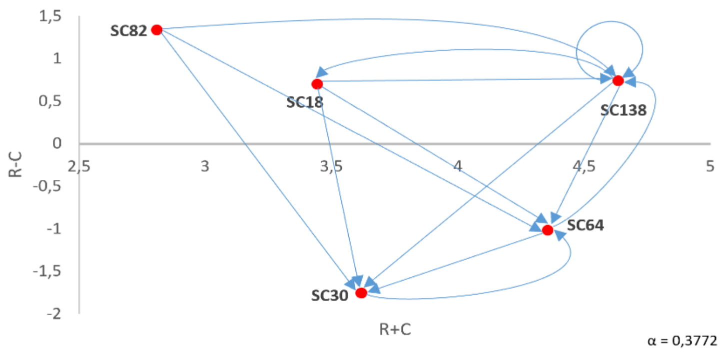

Figure 7. Sustainability Cluster Interrelationship Map

The last cluster to be analyzed was C5. *Table 25* shows the SCs selected for this cluster. *Tables 26* and *27* are the matrixes constructed in the second session for C5.

Table 25. Selected Subcriteria for Economy Cluster

Subcriteria in Economy Cluster	
SC13	More job offers
SC17	Investment decentralization
SC37	Economic development
SC93	Awareness of need to implement balanced fiscal measures
SC154	Decrease in real estate values to make them more accessible to the middle class

Table 26. Economy Cluster Matrix with Neutrosophic Values

	SC13	SC17	SC37	SC93	SC154
SC13	–	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)
SC17	4 (0.9, 0.1, 0.1)	–	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	2.5 (0.7, 0.2, 0.1)
SC37	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	–	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)
SC93	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	–	4 (0.9, 0.1, 0.1)
SC154	0 (1, 0, 0)	2(0.7, 0.5, 0.3)	4 (0.9, 0.1, 0.1)	4 (0.9, 0.1, 0.1)	–

Table 27. Economy Cluster Direct-Influence Matrix

	SC13	SC17	SC37	SC93	SC154	Total
SC13	0.0	3.6	3.6	3.6	3.6	14.4
SC17	3.6	0.0	3.6	3.6	2.0	12.8
SC37	3.6	3.6	0.0	3.6	3.6	14.4
SC93	3.6	3.6	3.6	0.0	3.6	14.4
SC154	0.0	1.2	3.6	3.6	0.0	8.4
Total	10.8	12.0	14.4	14.4	12.8	

In this cluster, SC37 and SC93 have the highest values for *R* and *C*, respectively (see *Table 28*). This shows that decision makers within C5 recognize that prioritizing economic criteria reflects a commitment to creating a robust and dynamic economic landscape that benefits the community at large. Simultaneously, the results highlight the significance of maintaining fiscal equilibrium, ensuring sustainable economic practices that consider long-term stability and resilience. This dual focus aligns with the broader economic goals within the cluster, aiming for both growth and fiscal responsibility. The C5 factors' order by importance is SC37 = SC93 > SC17 = SC13 > SC154. As shown in *Figure 8*, only two factors are part of the causes group (*i.e.*, SC13 and SC17). Notably, SC37 and SC93 do not belong to either the causes or effects group because their relationship values are 0 (*i.e.*, $R - C = 0$).

Table 28. Economy Cluster: Interactions Between Subcriteria

	R	*C*	*R* + *C*	*R* – *C*
SC13	9.3976	7.4847	16.8823	1.9129
SC17	8.7563	8.1436	16.8999	0.6127
SC37	9.3976	9.3976	18.7952	0.0000
SC93	9.3976	9.3976	18.7952	0.0000
SC154	6.0389	8.5645	14.6034	–2.5256

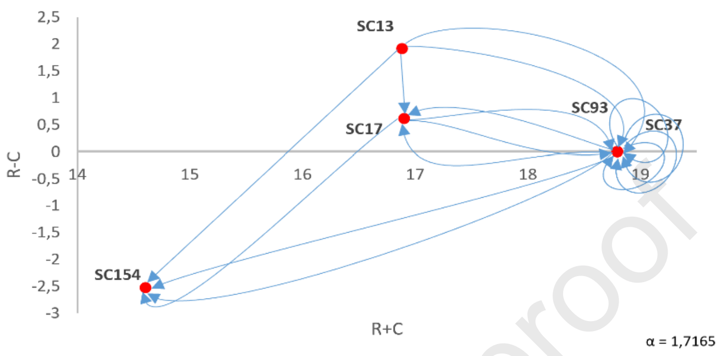

Figure 8. Economy Cluster Interrelationship Map

The group work in the second session completed the evaluation phase, after which the results were consolidated with the help of external, impartial experts. The findings and recommendations of this final session are discussed in the next subsection.

4.3 Consolidation of Results, Limitations, and Recommendations

The procedures and results presented in the previous subsections facilitated an analysis of urban expansion effects on real estate ecosystems. The proposed model provides a hierarchy of determining factors, and thus an indication of which should be given priority in terms of where to act first and how best to improve urbanization processes. In addition, the combination of qualitative and quantitative methodologies supported the decision-maker panel's group work, which produced a more realistic, transparent model that integrates uncertainty and generates objective measures.

To strengthen these results, an in-person consolidation session was organized with two representatives of the *Centro de Gestão e Inteligência Urbana de Lisboa* (Lisbon City Council Center for Management and Urban Intelligence). These experts were considered neutral and independent because they had not participated in the previous panel sessions. This final meeting started with a brief explanation of the research topic and methodologies, followed by the findings. Both experts then analyzed the results and expressed their opinions about the model's advantages and limitations. The meeting lasted for approximately 40 minutes. Even though the emphasis was primarily on the experts' qualitative expressions, the quantitative elements detailed in *Section 4.2* played a vital role in the experts' evaluation during the consolidation session. Specifically, by adopting a triangulation procedure, the experts meticulously reviewed and analyzed both the qualitative and quantitative outputs generated during the previous group meetings with decision makers. It is important to note that the validation did not entail the production of new data by these external experts; instead, it centered on their critical evaluation of the existing results. Furthermore, the validation procedures followed align with the guidelines employed by José *et al.* (2023) and Santos *et al.* (2023), underscoring our commitment to ensuring the robustness of our approach.

The specialists were surprised by the amount of information included in the map and remarked on its great detail. However, they found the information to be overly general and non-specific to any city. Each metropolis is unique, so the experts observed that the results could have been more valuable if the methodologies had been applied to specific cities. These two specialists also noted that the cognitive-map contents rely significantly on the decision makers' professional experience. Both experts, nonetheless, concurred that DEMATEL is a valuable tool with which to analyze the clusters' importance and agreed with the results, although they voiced a slightly different opinion about the intra-cluster results. The interviewees found that the SCs chosen for each cluster were extremely specific but sometimes quite similar in meaning. The experts also suggested that the proposed model could be more easily applied if the methodologies and panel had focused on a single city. At this point, the interviewer reiterated that this study is process-oriented and constructivist in nature. In response, both specialists agreed that advantages could be gained from this methodological approach.

Following this, this approach can help professionals develop a clearer, more focused and transparent understanding of possible interventions by not only incorporating objective and subjective elements into the decision-making process but also enhancing learning through participation. As such, the analysis system created in the present study should be seen as a learning mechanism—and not as tool to prescribe optimal solutions.

5. CONCLUSION

5.1. Key Findings and Insights

Evaluating urban expansion effects on real estate ecosystems is extremely complex due to the large number of variables involved and the subjectivity inherent to this kind of analysis. The topic under study can be explored from multiple perspectives, making the search for a single answer to related questions almost impossible. The complexity of this decision problem requires an analysis model that can structure, evaluate, and generate solutions and recommendations so that decision makers know how and where to act in each area. The present study thus sought to create a multicriteria analysis model that supports decision-making processes by analyzing urban expansion impacts on these ecosystems.

The proposed model was developed using cognitive mapping, neutrosophic logic and DEMATEL to explore the cause-and-effect relationships between urban expansion determining factors. The combined methodologies produced a holistic and complete model that reflects experts' professional knowledge. This approach facilitated the incorporation of subjective, less easily quantified criteria because the results were based on the opinions of multiple specialists with different backgrounds. The use of cognitive mapping overcame some significant limitations of previous research, including a lack of data and dependency on quantifiable variables. DEMATEL, in turn, permitted quantitative evaluations of the cause-and-effect relationships between criteria, thereby revealing the level of importance of each factor within the model. Neutrosophic logic contributed the ability to deal with uncertainty to the model, which smoothed the decision-making process and made interpreting the results easier.

The model-building process was supported by experts who developed a more transparent model and then validated its findings. Based on these specialists' opinion, the results highlight five main areas of interest (*i.e.*, *Tourism* (C1); *Mobility* (C2); *Society* (C3); *Sustainability* (C4); and *Economy* (C5)). Within these topics, the participants were able to define the causality relationships between the identified determinants, which meant the five clusters and their SCs could be organized by order of importance. C3 is the most significant cluster and its most crucial criteria are: *employment*; *technologies rethought to adapt to the market's needs*; and *smart cities*. Next, the most influential C1 factors include: *heritage restoration*; *economic development*; and *difficult problems in projects generated by a failure to forecast future maintenance costs*. C5 presents two equally important determinants, namely: *economic development*; and *awareness of the need to implement balanced fiscal measures*. C2, in turn, contains the most significant factors of *chances to implement innovative ideas in urban areas*; o*pportunities to improve residents' quality of life by re-occupying city centers*; and *green-energy usage to reduce pollution*. Finally, the least important cluster is C4, whose dominant determinants are: *innovative construction practices*; *avoidance of scattered buildings*, and *structured growth*.

5.2. Research Innovation and Implications

One of most significant innovations of our research is the use of neutrosophic logic, which was only recently introduced in the literature. Thus, its application to real estate topics is still quite rare, especially in combination with other methodologies such as DEMATEL. The model developed thus offers promising positive findings regarding analyses of urban expansion impacts. Specifically, the present results highlight the enhanced ability of the selected methodologies to assess urbanization effects on real estate ecosystems. The incorporation of the decision makers' opinions and experiences, in particular, makes the analysis system more empirically robust, transparent, and realistic. Real estate stakeholders can benefit from the combined use of cognitive mapping, DEMATEL, and neutrosophic logic, which could significantly improve their strategic planning of appropriate initiatives.

5.3. Limitations

All studies present limitations, and this research is no exception to the rule. The online group sessions were associated with problems that included connectivity issues and difficulty accessing the necessary digital tools. The sessions also were tiring for the participants due to the meetings' length. In addition, the panel members' answers and opinions influenced the results, so other experts with different backgrounds could have generated different results. The study was presented to external specialists who confirmed that the findings are context dependent. Because the decision-maker panel brought to the group work different realities from within Portugal, these participants' findings cannot be generalized to other settings. However, this issue was openly acknowledged from the beginning due to the constructivist and process-oriented nature of the methodologies used. Despite these limitations, the results are promising and provide a better understanding of urban expansion effects on real estate ecosystems.

5.4. Future Research

Future research can explore the advantages of conducting similar analyses, including applying different MCDA methods and carrying out comparative studies. The methodological approach used in this research could also be expanded to other contexts. Another interesting option would be to improve the proposed model or adapt it further for use in online platforms to enable decision makers to evaluate urban expansion impacts in quicker and more transparent and intuitive ways. Any appropriate adjustments made to the present model will comprise a step forward in the search for better decision-support systems to be used in analyses of urbanization effects on real estate ecosystems.

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HIGHLIGHTS

- This study provides a holistic analysis of urban expansion, fostering its nuanced real-world understanding.
- The process-oriented approach followed overcomes limitations inherent in purely statistical methods.
- Cognitive mapping enhances the understanding of urban-expansion effects.
- Integration of cognitive mapping, neutrosophic logic, and DEMATEL forms a unique analytical approach to urban expansion.

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Professor Rajan Batta
Editor-in-Chief of *Socio-Economic Planning Sciences*

Dear Editor:

The contents of the revised version of our manuscript have not been previously published; they are not and will not be copyrighted, submitted or published elsewhere, while acceptance by *Socio-Economic Planning Sciences* is under consideration.

Sincerely yours,

Fernando Ferreira
ISCTE Business School, University Institute of Lisbon, Portugal.
Fogelman College of Business and Economics, University of Memphis, USA.

Inês C. Correia received the M.Sc. degree in business administration from the University Institute of Lisbon (ISCTE-IUL), Lisbon, Portugal, in 2022. She is currently working with private sector, where he provides consultancy and advisory services to help national and international companies and organizations implement solutions for risk management and thrive in the varied environments in which they do business. Her research interests include strategy, urban planning, and decision support systems (DSS).

Fernando A.F. Ferreira received the Ph.D. degree in quantitative methods applied to economics and management from the University of Algarve, Faro, Portugal, in 2008. He is currently Full Professor of Strategy and Decision Analysis at the ISCTE Business School of the University Institute of Lisbon, Portugal, and Adjunct Research Professor at the Fogelman College of Business and Economics of the University of Memphis, Memphis TN, USA. Some of his articles are published in premier journals such as *Annals of Operations Research*, *European Journal of Operational Research*, *Journal of Business Research*, *Journal of Cleaner Production*, *Journal of the Operational Research Society*, *IEEE Transactions on Engineering Management*, *Management Decision*, *R&D Management*, and *Technological Forecasting & Social Change*. He has delivered keynote and invited speeches at conferences across the world (*e.g.*, Mexico, Spain, Hungary, Albania, Japan, South Korea). His research interests include MCDA, fuzzy logics and integrated systems for performance measurement. He was recently ranked among the top 2% best scientists in business & economics in the world by Stanford University, USA.

Constantin Zopounidis received the Ph.D. degree in Management Science from the University of Paris Dauphine, France in 1986. He is currently Professor of Financial Engineering and Operations Research at the Technical University of Crete, Greece, Distinguished Research Professor at Audencia Business School, Nantes, France, Senior Academician of the Royal Academy of Economics and Financial Sciences of Spain, and President of the Financial Engineering and Banking Society (FEBS). He has edited and authored 115 books in international publishers and more than 500 research papers in scientific journals, edited volumes, conference proceedings and encyclopedias, in the areas of finance, accounting, operations research, and management science. In recognition of his research work, he has received several awards from international research societies such as the International Society on Multiple Criteria Decision Making, the Decision Sciences Institute, the MOISIL International Foundation, ESCP Europe, and the Hellenic Operational Research Society.

Neuza C.M.Q.F. Ferreira is a Ph.D. candidate in management at the University of Beira Interior, Portugal. She received the M.Sc. degree in communication, culture and information technology from the University Institute of Lisbon, Portugal, in 2010. Some of her articles are published in premier journals such as *Annals of Operations Research*, *Journal of Cleaner Production*, and *IEEE Transactions on Engineering Management*. Her research interests include strategy, urban planning, and decision support systems (DSS).