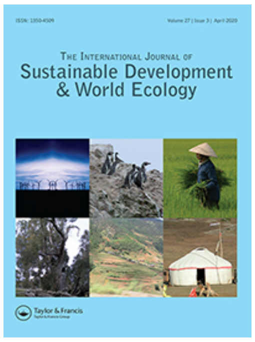

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Rethinking urban sustainability using fuzzy cognitive mapping and system dynamics

E. R. G. T. R. Assunção[a], F. A. F. Ferreira[b,c], I. Meidutė-Kavaliauskienė[d,e], C. Zopounidis[f,g], L. F. Pereira[a] and R. J. C. Correia[h]

[a]ISCTE Business School, University Institute of Lisbon, Lisbon, Portugal; [b]ISCTE Business School, BRU-IUL, University Institute of Lisbon, Lisbon, Portugal; [c]Fogelman College of Business and Economics, University of Memphis, Memphis, TN, USA; [d]Faculty of Business Management, Vilnius Gediminas Technical University, Vilnius, Lithuania; [e]Business Research Unit, University Institute of Lisbon, Lisboa, Portugal; [f]School of Production Engineering and Management, Technical University of Crete University Campus, Chania, Greece; [g]Audencia Business School, Institute of Finance, Nantes, France; [h]Faculty of Social Sciences, University of Madeira, Campus Universitário da Penteada, Funchal, Portugal

ABSTRACT

The extant literature reveals a growing need to rethink urban sustainability. Sustainable urban development is becoming more important to city strategic planning since sustainability is a critical aspect of environmental protection, social cohesion, and economic growth. However, decisions are currently not always taking into account the need to maintain sustainability because either decision makers do not fully understand the decision problems at hand or they do not focus on finding realistic, contextualized solutions. In addition, most existing models of urban sustainability assessment are static. Therefore, new urban sustainability assessment systems based on landsenses ecology are needed, which should combine natural elements, physical senses, and psychological perceptions, and assist decision makers develop successful management policies. Using fuzzy cognitive mapping and system dynamics, this study sought to develop a fresh, holistic perspective on urban sustainability. Based on the knowledge and experience of a panel of experts in urban development, some of the most significant determinants of urban sustainability were identified, namely: *sustainable construction*; *urban planning and/or design*; *health*; *economy*; *culture, citizenship, and education*; *environmental quality*; *public policies and governance*; and *mobility and/or accessibility*. The results obtained were validated both by the panel members and the director of the Department of Urban Planning of the Lisbon City Council, Portugal. The advantages and limitations of our approach are also discussed, as well as recommendations for future research.

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Fuzzy cognitive mapping; landsenses ecology; Problem-Structuring Methods (PSMs); strategic planning; sustainable urban development; System Dynamics (SD); urban sustainability

1. Introduction

Urban sustainability is essential to ensure the environment and general populace wellbeing are protected. The number of people living in cities has been increasing, and, if this trend continues without any compensatory actions being taken, cities will soon face serious economic, social, and environmental problems. For example, no more space will be left for schools, and hospitals will not be able to meet all residents' needs, which will be a difficult challenge in terms of urban resource management. The complexity of these decision problems makes urban sustainability one of the greatest challenges of this century (Faria et al. 2018; Pires et al. 2018; Martínez-Bravo et al. 2019). In this context, understanding the economic, social, and environmental factors that affect cities and their sustainable efficiency is crucial.

Beginning in the 1980s, environmental degradation and the unsustainability of the current levels of natural resource consumption pressured international policymakers into creating new, more sustainable policies and initiatives to manage the use of forests, water wastage, and ocean pollution. Experts further developed the concept of sustainability, which until then had been vague and unexplored.

Urban sustainability is a complex decision problem that encompasses many variables and depends mainly on decisions made by urban managers and often by the general populace, so discerning which path to choose and decisions to make can be difficult (Castanho et al. 2019; Miguel et al. 2019). Thus, an evaluation model is evidently needed that can analyze urban sustainability and help people understand this problem from a more holistic perspective. This should be based on the conceptualization of landsenses ecology, which *'studies land-use planning, construction, and management toward sustainable development, based on ecological principles and the analysis framework of natural elements, physical senses, psychological perceptions, socio-economic perspectives, process-risk, and associated aspects'* (Zhao et al. 2016, p. 293).

Landsenses ecology combines natural elements, physical senses, and psychological perceptions, and can help urban planners to integrate human sensitivity

CONTACT F. A. F. Ferreira fernando.alberto.ferreira@iscte.pt; fernando.ferreira@memphis.edu

into their urban policies (Zhao et al. 2016; Becker 2019). Indeed, because *'rational and scientific planning needs comprehensive analysis of urban ecosystems, including both natural and human factors* [. . .], *scholars of urban ecology have started to recognize the importance of explicitly linking human and ecological processes in studying the dynamics of urban ecosystems'* (Dong et al. 2016, p. 298). Urban managers could use this conceptualization to gain a fuller understanding of their cities' realities and to make strategic decisions.

Although various models have been developed to evaluate urban sustainability, these approaches present limitations regarding the areas of urban sustainability addressed, geographic scope covered, and analyses of cause-and-effect relationships between decision criteria. The available models, therefore, may sometimes be unsuitable in terms of supporting city strategic planning to strengthen urban sustainability.

In the present study, fuzzy cognitive mapping techniques were integrated with the system dynamics (SD) approach because these methods facilitate the combining of quantitative and qualitative elements. In addition, this integrated methodology can be used to develop comprehensive, transparent models to help stakeholders better understand complex decision problems. The complementary nature of these methodologies allows decision makers to carry out dynamic analyses of urban sustainability as these individuals need practical models that give them as much information as possible about the problem.

The remainder of this paper is organized as follows. The next section presents a literature review focused on urban sustainability and its importance to society at large. Section three provides the methodological background, including presenting fuzzy cognitive mapping and SD. Section four then describes the procedures followed to develop a structured understanding of urban sustainability, as well as discussing the results and limitations of the dynamic system constructed. The last section details the methodological framework's contributions, and lays out a roadmap for future research.

2. Related literature and research gap

Currently, 55% of the world's population lives in urbanized areas (*cf.* United Nations Department of Economic and Social Affairs Population Division (UNDESAPD 2018)), which are consequently the zones affected the most strongly by humans on an economic, social, and environmental level. This percentage is expected to rise by 2050 to about 70% of all people, with underdeveloped countries in Africa, Asia, and Latin America contributing the most to this increase (UN-Habitat 2015).

According to UN-Habitat (2015), urbanization attracts human and technological resources to cities, which facilitate more productivity, innovation, and economic and social development. However, city growth can also result in increased poverty, inequality, and environmental degradation (Ferreira et al. 2018; Marques et al. 2018; Oliveira et al. 2018). Urbanization is thus seen as a social and environmental problem (Bibri and Krogstie 2017), which makes this a source of concern, and the focus of many researchers seeking to find more sustainable solutions.

Urbanization is defined as *'the physical growth of urban areas due to the concentration of people and economic activity'* (Ochoa et al. 2018, p. 83). In other words, urbanization is the mobilization of people from rural to urban areas. Cities are thus highly developed zones with a high population density, which contributes positively to the development of economies and societies but negatively to environmental preservation (Mori and Christodoulou 2012).

Sustainability and sustainable development are distinct concepts (Axelsson et al. 2011; Fernandes et al. 2018). Sustainability is a goal to be achieved through natural capital management, while sustainable development is how this goal is reached. According to the Brundtland Commission (*cf.* World Commission on Environment and Development (WCED 1987, p. 54)), sustainable development can be understood as *'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'*. Thus, sustainable development is a process of change that seeks to meet human needs and aspirations through a harmonization of resource exploitation, directions taken by investors, economic development orientation, and social organization. According to various authors (e.g. WCED 1987; Hiremath et al. 2013; Ferrer et al. 2018; Olawumi and Chan 2018; Verma and Raghubanshi 2018; Yan et al. 2018), the three pillars of sustainable development are: (1) environmental protection; (2) economic development; and (3) social cohesion. A balance needs to be found to create a healthy, livable environment that provides quality of life and human wellbeing (Brito et al. 2019; Dobrovolskienė et al. 2019; Reis et al. 2019; Ferreira et al. 2020). This balance can be achieved through strategic planning of urban development, which generates systems to design, develop, implement, evaluate, and improve urban sustainability. Thus, sustainable development minimizes the use of and impacts on environmental resources and improves security, stability, and social justice (Zhao et al. 2016; Estêvão et al. 2019).

The evaluation of urban sustainability is not a new topic of research. In recent years, different tools have been developed for this purpose. Table 1 presents some examples of methods used to evaluate urban sustainability, which were developed by various entities in different countries.

The information provided in Table 1 highlights limitations that can be divided into four main categories. The first is that most evaluation tools in the literature

Table 1. Urban sustainability evaluation methods, contributions, and limitations.

AUTHOR/ENTITY	METHOD	CONTRIBUTION	LIMITATION
Hong Kong Special Administrative Region Government (HKSARG 2006)	Comprehensive Environmental Performance Assessment Scheme	• Holistic tool that evaluates various types of construction. • Guidelines that require urban sustainability to be oriented in terms of: (1) means to succeed; (2) means to improve; (3) benefits to industry; and (4) benefits to society. • Categorization of sustainability performance into eight groups: (1) indoor environmental quality; (2) building amenities; (3) resource use; (4) loadings; (5) site amenities; (6) neighborhood amenities; (7) site impacts; and (8) neighborhood impacts.	• Focuses only on assessing infrastructure sustainability. • Limited to one geographical area: Hong Kong. • Lacks an explanation of the selected indices.
United States Green Building Council (USGBC 2009)	Leadership in Energy and Environmental Design for Neighborhood Development	• Certification of projects that perform well in terms of smart growth, urbanism, and green building. • Five distinct categories applied: (1) smart location and linkage; (2) neighborhood pattern and design; (3) green infrastructure and buildings; (4) innovation and design process; and (5) regional priority credit. • Contributions to the development of other projects in various countries such as Malaysia, South Korea, China, and Canada.	• Contains prerequisites that limit the method to specific projects. • Focuses only on assessing infrastructure sustainability, specifically in entire neighborhoods, parts of neighborhoods, or various neighborhoods. • Lacks a justification of the selected indices.
Abu Dhabi Urban Planning Council (ADUPC 2010)	Pearl Community Rating System	• Culture assessed in addition to the three traditional dimensions of sustainability. • Seven categories recognized as fundamental for sustainable development: (1) integrated development process; (2) natural systems; (3) livable communities; (4) precious water; (5) resourceful energy; (6) stewardship of materials; and (7) innovative practices.	• Entails a complex evaluation process. • Limited to one geographical area: the United Arab Emirates. • Focuses only on assessing infrastructure sustainability. • Lacks a logical explanation of the selected indices.
Building Research Establishment (BRE Global 2011)	BRE Environment Assessment Methodology	• Environmental evaluation method of urban planning projects, buildings, and infrastructure. • Buildings classified into eight different categories: (1) climate and energy; (2) place shaping; (3) community; (4) ecology; (5) transport; (6) resources; (7) business; and (8) building.	• Entails a complex process of attributing weights that reduces the transparency of results. • Needs a stronger focus on other areas of sustainability beyond infrastructure. • Contains requirements that limit the method to specific projects. • Limited to one geographical area: the United Kingdom. • Lacks a justification of the selected indices.
Barbosa et al. (2013); Castanheira and Bragança (2014)	SBToolPT-UP	• Creation of organized, transparent, and objective indicators. • Twelve categories incorporated into the three dimensions of urban sustainability, with a fourth dimension added that contains two indices: sustainable buildings and information and communication technologies.	• Lacks an explanation of the selected indices. • Limited to one geographical area: Portugal. • Entails a complex, time-consuming method.
Institute for Building Environment and Energy Conservation (IBEC 2014)	Comprehensive Assessment System for Built Environment Efficiency	• Simple tool to evaluate the performance of environmentally-friendly buildings, which focuses on the introduction and implementation of methods to reduce carbon dioxide emissions in urban areas. • Categorization based on the three dimensions of urban sustainability: (1) resources; (2) nature; (3) artifact (i.e. building); (4) impartiality and/or fairness; (5) security and/or safety; (6) amenity; (7) traffic and/or urban structure; (8) growth potential; and (9) efficiency and/or rationality.	• Lacks a justification of the selected indexes. • Constitutes a methodology conditioned by Asian realities.

focus on only one area of sustainability, namely, physical infrastructure, even though other areas are also important to urban sustainability, such as transportation and waste management. The second category is that most new tools are limited to the authors' geographical area, so they do not provide a methodology that can be easily generalized. The third limitation is that sometimes the entities responsible for developing these methods only present the categories and indicators used in the analysis without providing a logical, rational basis for the researchers' choices. The last category is that previous studies have not conducted dynamic analyses with the selected variables.

Although statistical models are by far more popular in this type of research, these models impose rigorous distributional assumptions, require data with particular scaling properties, and have limited flexibility (*cf.* Yan et al. 2018; Brito et al. 2019). Correlations also do not necessarily imply cause-and-effect relationships, so, to model and analyze complex systems' behavior adequately, causal relationships need to be examined carefully. In addition, because ecological planning has become more and more people-oriented and considers the relationship between people and the environment (Dong et al. 2016), landsenses ecology requires the combination of innovative techniques of observation, simulation, statistics, and computer programing (*cf.* Ren et al. 2017). Therefore, according to Zhang et al. (2017), the major challenge of urban planners is to find approaches that can link human well-being to urban ecosystem. For example, information related to urban lifestyle preferences, social fairness, and satisfaction cannot be easily collected, meaning that human sensory information, which planners really need, should be part of the planning process (Dong et al. 2016). All these aspects provided the motivation to use fuzzy cognitive mapping and SD in the present study.

Given the above limitations, this research sought to develop a more complete, transparent, and holistic system analysis, incorporating the most important areas of urban sustainability. This was achieved by using a constructivist methodological approach, which, as previously mentioned, was based on the conceptualization of landsenses ecology, and integrated cognitive mapping techniques with the SD approach. Notably, the dual methodology used was not intended to be a substitute for statistical approaches. Managers and decision makers can apply this integrated approach to gain insights into key feedback loops in urban sustainability analysis, which might otherwise go undetected when statistical approaches are used alone.

3. Methodological background

3.1. Cognitive mapping and Fuzzy Cognitive Maps (FCMs)

New approaches to decision support were developed in the early 1970s because companies felt they needed to be better prepared to deal with their decision problems. Over time, sophisticated problem-structuring methods (PSMs) have emerged to help firms deal with their issues (Smith and Shaw 2018). According to Mingers and Rosenhead (2004), PSMs are decision-support methods that facilitate the representation and resolution – at least partially – of decision problems. These methods are context-specific (i.e. idiosyncratic).

One of the best-known PSMs is the strategic options development and analysis (SODA) method (Eden and Ackermann 2001), which is based on cognitive mapping techniques, and which considers the viewpoints of different decision makers (Guarnieri et al. 2016). In the present study, SODA enabled an expert panel to analyze and structure the problem of urban sustainability, covering economic, social, and environmental aspects.

According to Eden (1988), cognitive maps need to be an integral part of the first stage of decision-problem resolution so that the perspectives of all decision makers can be considered. Each decision maker has his or her own vision of the decision problem since each individual has different experiences, competences, and roles in the performance of their duties. When constructing cognitive maps, all the participating decision makers need to reflect and negotiate with each other to identify the key decision criteria and/or determinants that influence the decision problem in question. This process is necessary to understand the relationships between criteria and define the nature of the system in which the decision criteria are embedded (Eden 1988). According to Ferreira et al. (2012), these maps are useful because they: (1) promote discussion among decision makers; (2) reduce the number of relevant criteria omitted; and (3) improve participants' understanding of the cause-and-effect relationships between criteria.

Cognitive maps represent networks of ideas, in which individuals' opinions and beliefs (i.e. about decision criteria) are depicted as nodes. The nodes are connected by arrows whose direction shows the cause-and-effect relationship between the criteria involved. Relationships with a plus sign (+) represent a direct causal link, while cause-and-effect relationships with a minus sign (–) indicate negative influences between criteria (Ferreira et al. 2017; Ribeiro et al. 2017; Fonseca et al. 2018). Figure 1 presents an example of a cognitive map.

Compared to traditional cognitive maps, fuzzy cognitive maps (FCMs) are able to analyze cause-and-effect relationships between variables dynamically and quantitatively. That is, variables evolve over time through their interactions (Salmeron 2012). Fuzzy cognitive mapping was first introduced by Kosko (1986), who complemented traditional cognitive mapping with fuzzy logic. Since then, the method has been used to model and analyze multiple social, economic, and political problems (Carvalho 2013; Ribeiro et al. 2017). FCMs are considered *'a well-established artificial intelligence technique, incorporating ideas from artificial neural networks and fuzzy logic, which can be effectively applied in the domain of management science'* (Carlucci et al. 2013, p. 208). FCMs consist of the following elements (Kok 2009):

- Criteria $(C_1, C_2, C_3, \ldots, C_n)$, which are the concepts/decision criteria considered relevant to the decision problem;
- Vector$A = (a_1, a_2, a_3, \ldots, a_n)$, in which a_i represents the state of the criterion C_i, thereby reflecting the criterion's value, which can vary between 0 and 1;
- Arrows, which represent the criteria's causal relationships so that they are usually accompanied by w_{ij}, which in turn represents the weight that the criterion C_i has on criterion C_j;
- Adjacent matrix W, which contains all the weights of the connections between the criteria present in the system, with values that can range from −1 to 1.

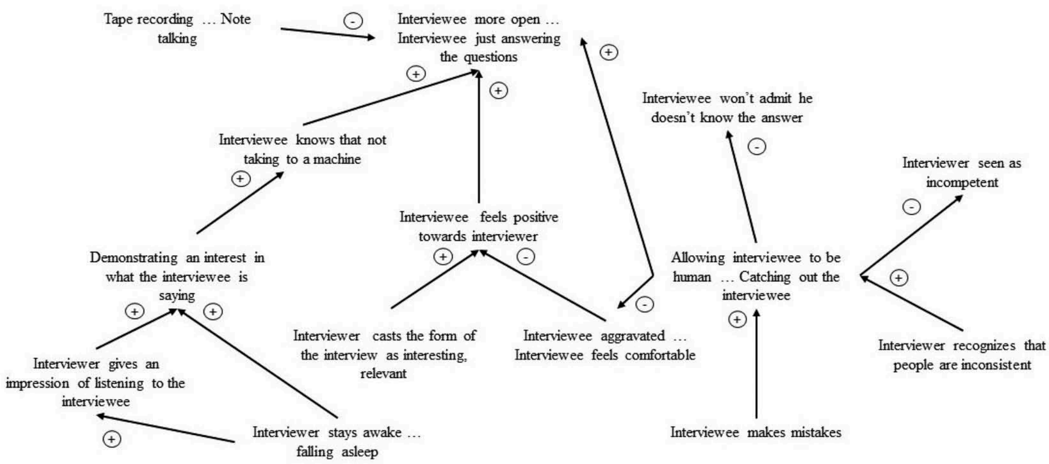

Figure 1. Example of a cognitive map (Partial view).
Source: Eden and Ackermann (1992, p. 311).

Ferreira (2016, p. 133) states that *'all the values in the map can be fuzzy'* because, as mentioned previously, a_i can vary between [0, 1]. That is, criterion C_i can contribute more (1) or less (0) intensely to the system, and w_{ij} is between [−1, 1] so criterion C_i's influence on C_j can be negative, neutral, or positive, and more or less significant. In addition to the map's graphical aspects, it involves a mathematical formula consisting of the vector A $1 \times n$ containing the values of n criteria, and the adjacent matrix W $n \times n$ comprising the weights w_{ij} of the links between n criteria. Equation (1) presents FCM mathematical operation, in which $A_i^{(t+1)}$ represents the activation level of the criterion C_i at time $t+1$. In addition, $A_i^{(t)}$ translates the level of activation of criterion C_i at time t, while $A_j^{(t)}$ represents the level of activation of criterion C_j at t. Finally, w_{ji} is the weight of the connection between C_j and C_i, and f is the activation function.

$$A_i^{(t+1)} = f\left(A_i^{(t)} + \sum_{\substack{j \neq i \\ j=1}}^{n} A_j^{(t)} \cdot w_{ji}\right) \tag{1}$$

To simplify Equation (1), Mazlack (2009) further posits that the new vector A_{new} results from the multiplication of the previous vector A_{old} by the weights of the matrix W, as shown in Equation (2).

$$A_{new} = f(A_{old} \cdot W) + A_{old} \tag{2}$$

The dynamic nature of this decision-support system facilitates the evaluation of a change in a criterion on the system, and a fuller understanding of criteria's impact on one another. In addition, 'what if' questions can be formulated in order to define the impact on the system if changes occur (e.g. add or remove criteria) (Carlucci et al. 2018).

Carlucci et al. (2018) point out that the greatest challenge of this methodology is the recruitment of a group of experts – in this study, specialists in urban sustainability – able to meet for several hours in the same place in order to construct a collective FCM. However, the benefits obtained from applying this methodology appear to counterbalance the effort needed to overcome this challenge.

3.2. System dynamics

Forrester (1961) pioneered system dynamics (SD) research, using the first SD model to study persistent oscillations of production and sales in industrial supply chains. Despite the specificity of this initial study, the main objective of the cited author was to create a generalized model that could be used to analyze the dynamics of any system, and not necessarily only at the management level. Subsequent authors have utilized conceptual and software tools to develop, test, and improve these same models, as well as implementing recommendations based on SD (Sterman et al. 2015).

The SD approach is thus a modeling method that examines internal dynamic interactions, cause-and-effect relationships, and feedback among variables (Sedarati et al. 2018). The variables considered include stocks when systems have inflows and outflows that determine variable values, representing stocks graphically by rectangles. Another variable involved is information flows when these connect variables to each other, shown graphically by arrows (Pizzitutti et al. 2016; Castellacci 2018). In addition, Sterman (2001, 2002)) argues that feedback is the results of individuals' actions that are mirrored in the situations faced in the future. SD models are driven by these feedback mechanisms. Each mechanism represents the relationship between the system's variables, which can be a reinforcing feedback, in which the dynamics between the variables is supportive to all system components. Mechanisms can also be a balancing feedback, in which one variable attenuates the growth of another until the relationship reaches equilibrium again (Sterman 2002; Castellacci 2018).

The SD approach provides rules for decision making that can be included in systems with implementation delays and resource constraints. These restrictions mean that actions that occur in the systems do not change them immediately but can influence them to move in a particular direction. Decision-making rules are inserted into the model through flow equations that produce stock levels. These stock variations facilitate a fuller understanding of how decision-making rules guide the SD approach (Papachristos 2019).

On a mathematical level, SD models are represented by a set of nonlinear integral equations. Since obtaining mathematically analytical solutions for dynamic systems is difficult, SD uses computational simulations to analyze dynamic behaviors (Castellacci 2018). Richardson (2011, p. 241) provides a simple, succinct definition for SD: '[it] *is the use of informal maps and formal models with computer simulation to uncover and understand endogenous sources of system behaviour*'.

The integration of decision-support techniques, such as FCMs and SD, into practices can greatly enhance the accurate structuring of complex decision problems, thereby supporting decision making. In the present study, the decision problem was analyzing, understanding urban sustainability. By modeling diagrams and representing cause-and-effect relationships between decision criteria, better informed and more grounded decisions can be made based on a fuller understanding of the dynamics involved.

4. Implementation

According to Salmeron et al. (2019), constructing an FCM requires a group of experts with experience and knowledge in the specific area under study. To facilitate the representation of a group cognitive model, the present research was divided into three stages. These were to: (1) identify the variables, key decision criteria or determinants; (2) clarify the cause-and-effect relationships between decision criteria; and (3) estimate the intensities of these causal connections. To ensure the three stages could be completed, the methodological process was divided into various phases that differ essentially in their level of technology (Ackermann and Eden 2010). The process is depicted in Figure 2.

In the initial phase, the most important objectives were to determine which experts were most likely to participate in the panel, and how many would be needed. The goal was to ensure the panel could function well as a group of experts working together to explore an issue of common concern (Belton and Stewart 2002). The participants also had to be able to identify the problem components, and all the experts involved in the process had to share a broad understanding of this study topic (i.e. urban sustainability). In addition, the panel had to be heterogeneous in terms of gender, age, and professional experience. Notably, the mixed composition of the panel was not meant to achieve representativeness or the ability to form generalizations, but rather to maintain a strong focus on process. Bell and Morse (2013, p. 962) argue that, in this type of research, *'there is less emphasis on outputs per se and more focus on process'*. Dong et al. (2016, p. 301) also note that *'knowledge-based stakeholder participation in planning through deliberation and collaborative learning is one way forward for better strategic and comprehensive planning'*, which supports the conceptualization of landsenses ecology.

As for the number of panel members, the literature does not provide an absolute rule, but Eden and Ackermann (2001, p. 22) suggest that *'the consultant* [i.e. the researcher or facilitator] *will relate personally to a small number (say, three to ten persons)'* or *'small groups (ideally of 6–10 key individuals)'* (Eden and Ackermann 2004, p. 618). In the first group session, seven decision makers met with the facilitator, with the primary goal being the construction of a cognitive map. Before the first session began, the room layout was adjusted to enhance group dynamics, as shown in Figure 3.

The session began with a brief presentation of the methodology to provide the decision makers with necessary information, and give them a chance to ask questions. The following trigger question was then asked to stimulate a discussion among the panel member: *'Given your professional experience, what do you*

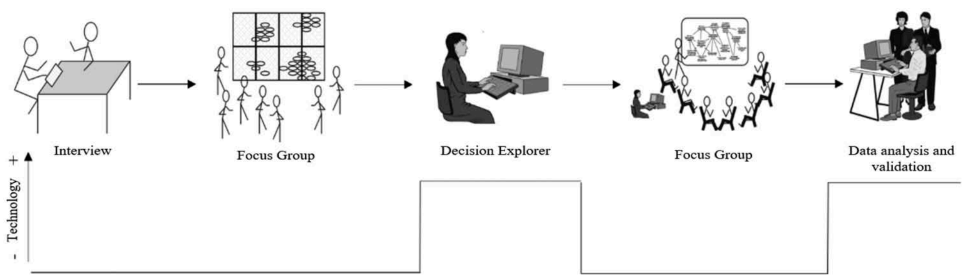

Figure 2. Methodological process and associated technology levels.
Source: Adapted from Ackermann and Eden (2010).

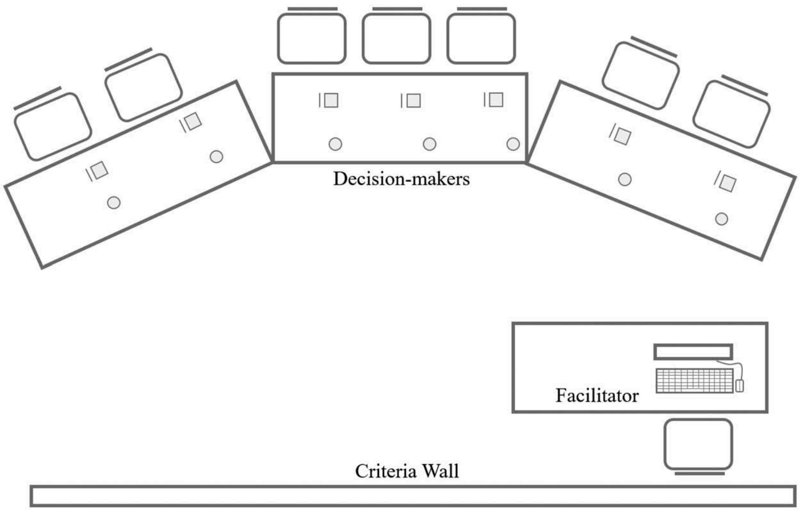

Figure 3. First session room layout.

think the main challenges of urban sustainability are?'. The answers were given using the 'post-its technique' (Ackermann and Eden 2010), based on the following rules. First, the panel members could only write one decision criteria, determinant of urban sustainability on each post-it note. Second, if they identified a determinant that has a negative impact on urban sustainability, they had to put a minus sign (–) in the upper right corner of the post-it note.

In the second phase of the first session, the experts organized the post-it notes by areas of interest (i.e. clusters). This phase of the organizing process led to the identification of eight clusters. These were numbered and labeled as: (1) *Sustainable Construction*; (2) *Urban Planning and/or Design*; (3) *Health*; (4) *Economy*; (5) *Culture, Education, and Citizenship*; (6) *Environmental Quality*; (7) *Mobility and/or Accessibility*; and (8) *Public Policies and Governance*. Notably, the decision makers consider the determinant of accomplishing sustainable development goals to be fundamental. Given that this criterion is quite broad and that it encompasses all aspects of urban sustainability, the suggestion was made that the determinant should appear immediately below urban sustainability (i.e. as a fundamental objective to be fulfilled). In this way, all identified clusters were linked to this one criterion, which is then connected to urban sustainability.

In the third phase of this session, the panel was asked to create a hierarchy of urban sustainability criteria within each identified cluster, that is, to organize the criteria on post-it notes within each cluster from top to bottom from the most important to the least important. This was a quite important part of the process since the decision makers had more contact with each determinant, fomenting their involvement and engagement in the structuring of the cognitive map.

The results of the first session (i.e. determinants of urban sustainability, clusters of criteria, and determinant hierarchies) were used to generate the cognitive map that served as the basis for the development of an FCM in the second work session. The group cognitive map was created using the *Decision Explorer* software (www.baxia.com). Figure 4 contains the final version of the cognitive map, which contains 137 determinants of urban sustainability, and which was validated by the decision makers after they collectively analyzed and discussed the map (size restrictions prevent the presentation of a clearer version of the group cognitive map developed in this study, but an editable version can be obtained from the corresponding author upon request).

In the second group session, two decision makers who had participated in the first session could not be present. However, this type of situation is mentioned in the literature (*cf*. Azevedo and Ferreira 2019), and previous studies have found that absent panel members do not negatively affect the methodological process. In the second session, the decision makers attributed intensities to the cause-and-effect relationships identified among the urban sustainability determinants. The panel was told that, at this stage of the process, they would need to assign values between −1 and 1 to all causal links (i.e. to all the arrows) included in the group cognitive map. In addition, if necessary, the experts could eliminate decision criteria or add new ones, which demonstrates the openness to adjustments/improvements of the methodology used. The process of assigning intensities was the last phase in the construction of an FCM on urban sustainability.

4.1. Rethinking urban sustainability

Urban sustainability needs to be rethought. Currently, decisions are still being made in urban planning and development that damage the environment. A practical example of this is the climate change observed in recent years, which has given rise to

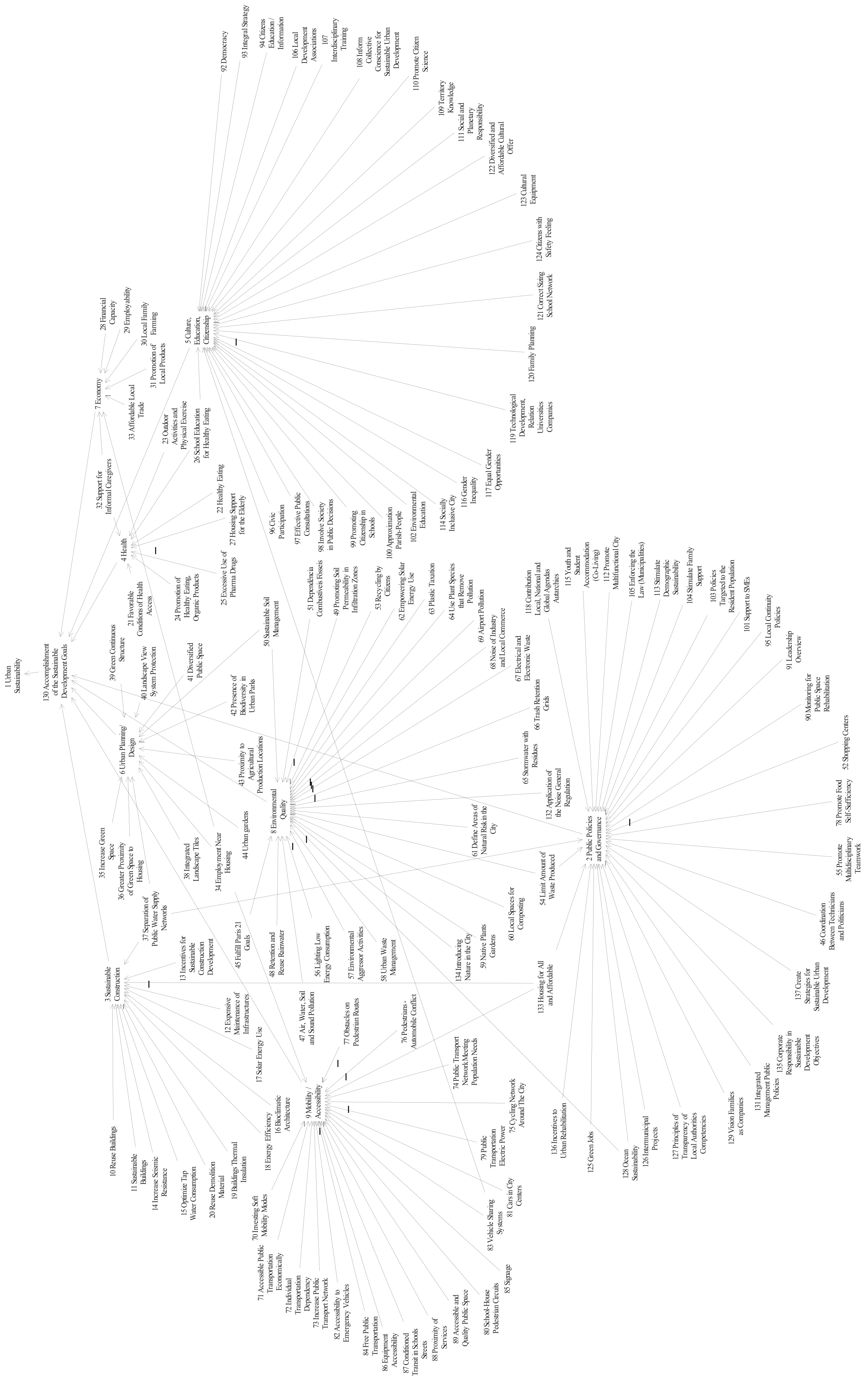

Figure 4. Group cognitive map.

melting glaciers, uncontrollable fires, and severe storms. Another consequence is reduced air, soil, and water quality. However, depending on the professionals involved in planning processes, perspectives related to urban sustainability have also changed.

Kaur and Garg (2019, p. 147) emphasize that *'this incomprehensive* [sic] *understanding of urban sustainability results in* [a] *lack of integrated solutions and coordinated actions which are required* [… when] *addressing such a complex issue, necessitating a holistic understanding of sustainability in the context of urban areas'*. The cited authors also point to the excessive importance given to economic and demographic aspects in urban planning. Previous research has shown that this approach results in the depletion of non-renewable natural resources and excessive production of waste, thereby producing more pollution. Zheng and Yu (2017) and Kaur and Garg (2019) also report that socio-cultural and environmental aspects have been ignored, and the consequences have been noticeable around the planet. As a way to rethink urban sustainability, an FCM was created in the present study to develop a better understanding of this theme, and the ways this complex system behaves within different scenarios. Figure 5 shows the stock-and-flow diagram that resulted from the FCM generated with *Vensim Personal Learning Edition software* (www.vensim.com).

Although the values that are the basis of this FCM are not visible in Figure 5, they were included both in the modeling process and the stock-and-flow diagram presented. Notably, the values attributed by decision makers to the cause-and-effect relationships were quite high. The experts agreed that, if these are key decision criteria in urban sustainability, then their impact has to be significant. The values vary for positive causal relationships between 0.3 and 1, with an average value of 0.79. For the negative causal links, the values vary between −1 and −0.4, with an average value of −0.88.

After the relationship values were entered into the computer program, equations were created that facilitated the calculation of the aggregate values of clusters and urban sustainability overall. Equation (3) is related to urban sustainability, and Equation (4) to the Health cluster, which serves as an example since all the equations formulated followed the same logic. These represent the sum of all cause-and-effect relationships between the criteria and their respective cluster. The overall value of urban sustainability is equal to the value of the accomplishment of sustainable development goals determinant, which comprises the aggregation of the values of all clusters.

$$\text{Urban Sustainability} = \text{INTEG}\,(\text{Accomplishment of Sustainable Development Goals}) \quad (3)$$

$$\begin{aligned}\text{Health} = \text{INTEG}\,[\text{In}\,(&\text{Housing Support for the Elderly} + \text{Support for Informal Caregivers} + \text{Outdoor Activities}\\ &\text{and Physical Exercise} + \text{Favorable Conditions of Healthcare Access}\\ &+ \text{School Education about Healthy Eating} + \text{Healthy Eating} + \text{Promotion}\\ &\text{of Healthy Eating and Organic Products} + \text{Excessive Use of Pharmaceutical Drugs})]\end{aligned} \quad (4)$$

The analysis of results was divided into two phases: (1) inter-cluster; and (2) intra-cluster. In the inter-cluster analysis, the impacts that different changes in clusters have on urban sustainability were examined. In the intra-cluster analysis, the impacts of changes in criteria within their respective clusters were studied. Since the decision-support system has values quite close to 1 (i.e. the maximum possible value that could be assigned) (*cf.* Yaman and Polat 2009; Lee et al. 2013), most scenarios performed for positive relationships included variations in intensities at −0.1, −0.25, and −0.5. For negative connections, the variations were positive changes at the same values. Twelve determinants were selected for analysis. One criterion was chosen from each cluster with the smallest dimensions (i.e. *Sustainable Construction*, *Urban Planning and/or Design*, *Health*, and *Economy*), and two from the larger clusters (i.e. *Culture, Education and Citizenship*, *Environmental Quality*, *PublicPolicies*and *Governance*, and *Mobility and/or Accessibility*).

The SD approach was applied to examine the inter-relationships between urban sustainability determinants and simulate changes in the criteria to understand what impact the variations would have on urban sustainability. Thus, the first time the software was used was to understand how urban sustainability would behave. Figure 6 reveals that urban sustainability tends to increase over time if the determinants are based on the assumption that sustainability will grow over time.

To understand how the simulations performed in a realistic context, 9 scenarios were created to support the inter- and intra-cluster analyses conducted. The first 8 scenarios included 4 optimistic scenarios (i.e. scenarios 3, 5, 6, and 8) and four pessimistic scenarios (i.e. scenarios 1, 2, 4, and 7). This meant that, in the optimistic scenarios, the values of the cause-and-effect relationships were increased by 0.1, 0.25 and 0.5, and, in the pessimistic scenarios, the values were decreased based on the same proportions. Table 2 combines all the information about these simulations, the 6 simulations (i.e. 3 inter-cluster and 3 intra-cluster) in each 8 scenarios. For example, in the first scenario, a decrease in the investment in sustainable buildings determinant negatively affects urban sustainability and the city

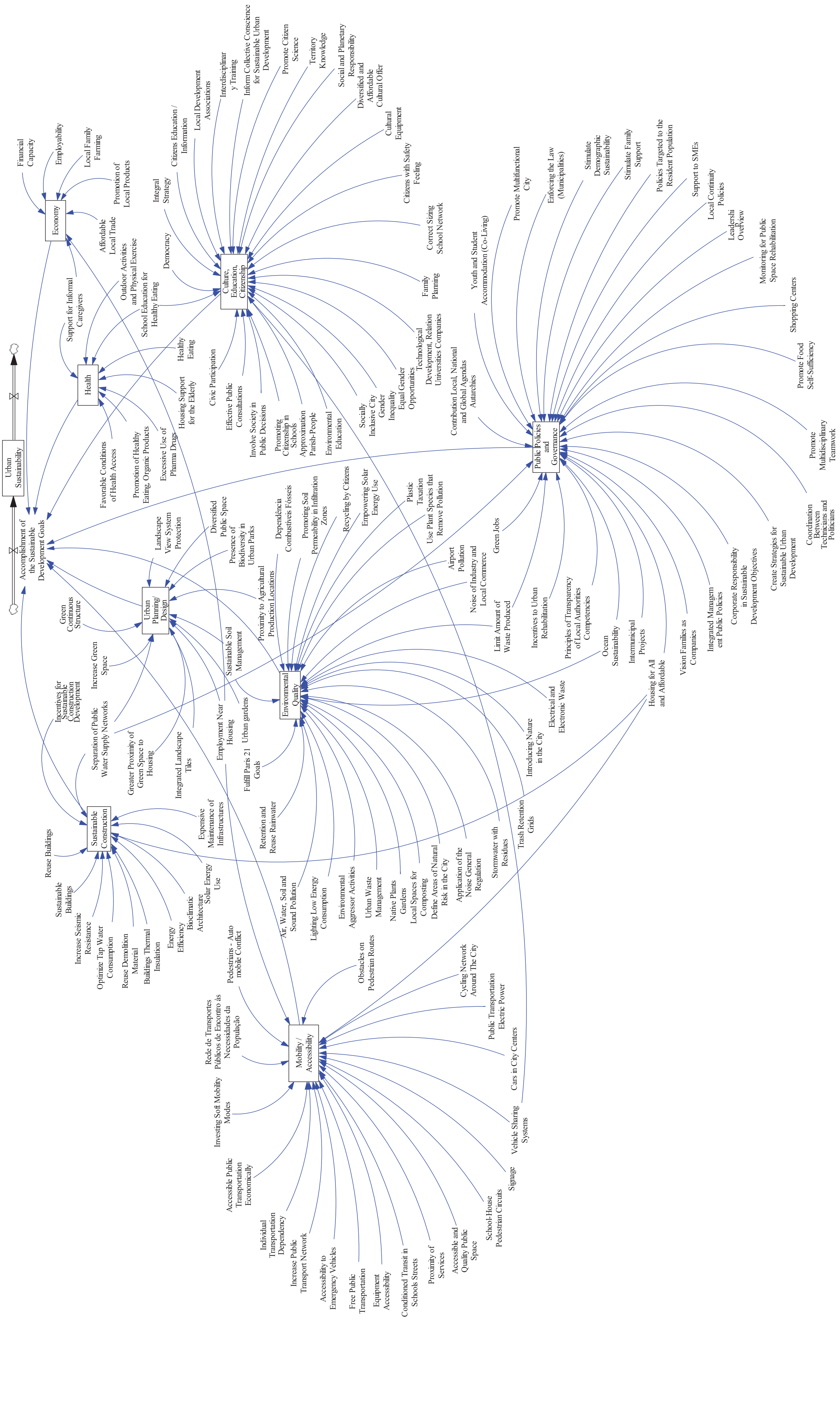

Figure 5. Urban sustainability stock-and-flow diagram.

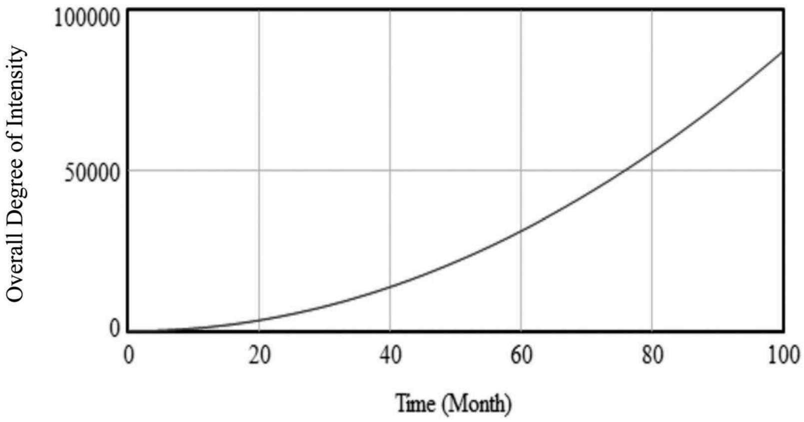

Figure 6. Temporal evolution graph of urban sustainability.

Table 2. Inter-cluster simulation runs for 12 selected determinants.

				INTER-CLUSTER			INTRA-CLUSTER		
SCENARIO/CLUSTER	CRITERION	INITIAL VALUE	Δ	S 1	S 2	S 3	S 1	S 2	S 3
1. Sustainable Construction	Sustainable Buildings	0.8	(–)	–51	–128	–259	–1.025	–2.584	–5.237
2. Urban Planning and/or Design	Diversified Public Spaces	0.6	(–)	–59	–148	–300	–1.183	–2.985	–6.062
3. Health	Excessive Use of Pharmaceutical Drugs	–1	(+)	+152	+372	+719	+3.077	+7.522	+14.518
4. Economy	Employability	0.9	(–)	–102	–259	–533	–2.061	–5.236	–10.763
5. Culture, Education, and Citizenship	Equal Gender Opportunities	0.5	(+)	+53	+131	+259	+1.07	+2.653	+5.237
	Promotion of Citizen Science	0.4							
6. Environmental Quality	Dependence on Fossil Fuels	–1	(+)	+114	+280	+544	+2.299	+5.651	+11
	Air, Water, Soil, and Sound Pollution	–1							
7. Public Policies and Governance	Stimulate Demographic Sustainability	0.95	(–)	–48	–121	–246	–0.973	–2.443	–4.963
	Promote Food Self-Sufficiency	0.5							
8. Mobility and/or Accessibility	Pedestrian-Automobile Conflict	–0.8	(+)	+94	+232	+454	+1.904	+4.695	+9.18
	Individual Transportation Dependency	–1							
9. Urban Sustainability	–	–		+154	+360	+639	–	–	–

sustainable construction determinant. In addition, the sixth scenario provides concrete evidence that, when cities increase their investment in reducing dependence on fossil fuels and air, water, soil and noise pollution, cities' environmental quality will improve along with their urban sustainability.

To complement these analyses, a final scenario was performed. This ninth scenario gathered all the changes made in the previous scenarios (i.e. the 8 scenarios analyzed: 4 pessimistic and 4 optimistic). In the first simulation, the 12 determinants selected were changed by + or – 0.1, in the second simulation by + or – 0.25, and in the third simulation by + or – 0.5. The ninth scenario was thus more realistic since, in urban management, complex decisions are made based on multiple-variable interactions. In all three simulations, urban sustainability increased, as can be seen in Table 2 and Figure 7.

Given the above results, a holistic understanding of what different investments can be made in different

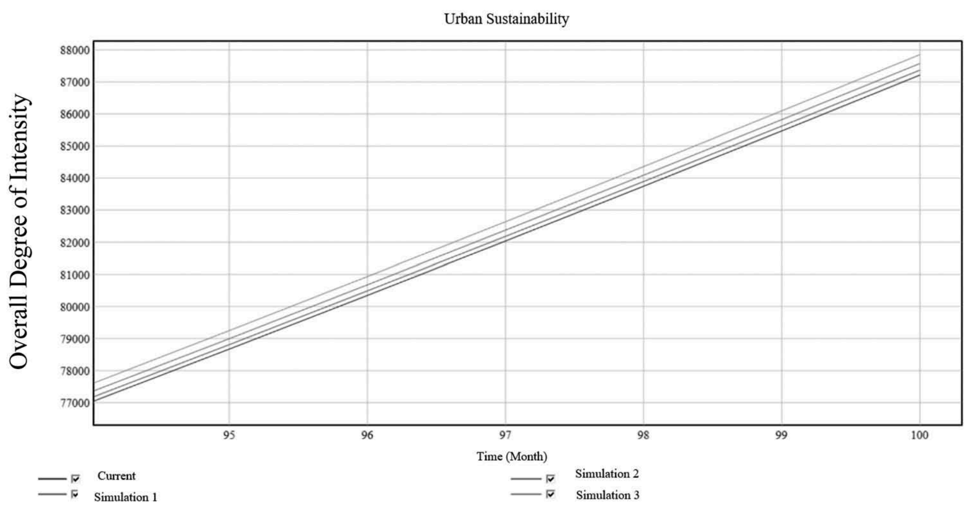

Figure 7. Temporal evolution of urban sustainability simulations.

areas, and of their impact on city sustainability, is provided, while taking into account that the main goal will always be to achieve more urban sustainability. An analysis of the nine scenarios supported the conclusion that smaller clusters have a greater influence on urban sustainability because they contain fewer determinants and a change in one of them triggers a more significant effect. In addition, the results also revealed that the optimistic scenarios in which the values of negative relationships were increased were also the ones that had the most positive impact on urban sustainability. All the determinants that already influence urban sustainability more or less positively are, therefore, not a problem because their presence is already making a contribution. However, the determinants that have a negative influence are significant issues that are often quite serious, and urban decision makers should pay more attention to these criteria. They need to be the focal point for managers' efforts to improve urban sustainability, thereby providing residents with a fairer, cleaner, and more pleasant world in which to live.

4.2. Consolidation, discussion, limitations, and recommendations

To consolidate the decision-support system developed, a final session was held with the director of the Department of Urban Planning of the Lisbon City Council to present the model and elicit the feedback of this expert. The consolidation session had an extremely important function in the present study because this interview provided a fresh point of view, namely, that of a specialist in urban sustainability who had not participated in the group sessions. This expert could thus be considered neutral about the proposed methodology.

The final session was divided into four parts. The first was a presentation of the topic and methodologies used (i.e. FCMs and SD), while the second part involved presenting the results and getting feedback from the specialist. The third part was the interviewee's analysis of the advantages and limitations of the study. The session ended with this expert's opinion on the model's potential practical applications. After hearing the explanation of the techniques used, the specialist had the opportunity to examine the stock-and-flow diagram and watch how SD works after a simulation was input into the *Vensim* program. The interviewee's first impression left him pleased with the developed model, and he remarked that, *'in terms of conceptual arrangement, it seems to be interesting'* (in his words). When asked about the methodology's main limitations, he stressed that *'the issue of establishing weights is always the most difficult part of doing this type of work'* since *'it is very subjective'*, becoming many times a *'point of controversy'* (also in his words). He pointed out that the weights are so subjective that this raises concerns about how the model depends heavily on the experts' points of view. Nonetheless, this director clearly said that *'it is always good to have systems that give us guidelines and do not allow us to forget some factor'* (again, in his own words). The interviewee highlighted the important contribution of the use of cognitive mapping techniques in this research context. That is, because the model encompasses different views about the problem, the decision-support system allows varied areas of urban sustainability to be represented, reducing the possibility that the system is missing any criteria. When asked about the model's practical applications, the director asserted that it is a methodology that could work as a way to assess urban sustainability mainly *'because it is a method open to changes, which makes it more robust'* (in his words). This point is interesting in that it reinforces the importance given to constructivist models in the more recent literature. In addition, the proposed methodology complements quantitative analyses and reduces the subjectivity associated with evaluations in this context, which makes this approach completer and more reliable.

The consolidation session, in general, confirmed that the results of this study are satisfactory. Thus, the two sessions with the expert panel, the application of the integrated methodology (i.e. FCMs and SD), and the final session facilitated the gathering of important information on urban sustainability. This process produced a complete, realistic, and dynamic decision-support framework that can help urban managers make better decisions. However, although this research used an empirically robust methodology in terms of structuring decision problems, the approach has its limitations. First, it integrates subjective factors since it depends on the decision problem context and the experts' contributions, making the results idiosyncratic. Second, the process relied heavily on the experts' availability and participation in 2 sessions, for a total of 8 hours. Since the methodology used depends heavily on a specific context, changes in any variable (e.g. decision criteria, weights, decision makers, or facilitators) could change the decision-support system produced. Therefore, the decision-maker panel must be composed of a heterogeneous group so that different areas and perspectives of urban sustainability are incorporated and the proposed system is valid. In addition, particular care is needed when adapting this approach to fit different contexts. Because it assumes an idiosyncratic stance, the results represent a specific reality, reinforcing the point that appropriate adaptations need to be made. However, because the methodology is based on a continuous learning logic, the system can be easily updated and adapted.

The greatest challenge of this study was to obtain a panel of specialists willing to meet as a group in 2 sessions for a full 8 hours. Despite the difficulty of finding people able to make this commitment, 7 decision makers were present in the first session and 5 in the second, which allowed the research to complete the entire proposed process. The sessions were demanding for the experts, as they needed to focus on delivering the requested outputs and negotiating among themselves, but these decision makers expressed satisfaction with the end result.

In conclusion, the urban sustainability decision problem was structured based on an FCM and analyses of different scenarios using the SD approach. The results contribute to the literature by proposing a broad set of determinants whose intensities can be examined and altered according to the intended objectives. Although this combination of methodologies allowed for changes in the decision-support system at any time, the results should not be extrapolated without making the necessary adaptations.

5. Conclusion

Urban sustainability has increasingly become a topic of importance to city management (Faria et al. 2018). Urban decision makers are a large group of professionals, each with his or her own perspective on urban sustainability, which makes their decision-making processes even more difficult. While this debate continues, the associated problems increase, and some of them could become irreversible. Urban sustainability is a complex decision problem, so problem-structuring tools are needed to assist experts make decisions that lead to success. Based on the conceptualization of landsenses ecology, these tools should allow city managers to understand urban sustainability better by identifying the main determinants that influence sustainability, and enabling analyses of scenarios within the decision-support system.

The results and discussion presented in this study show that FCMs and SD are two quite complete and complementary methodologies that can identify the relevant variables in complex systems. In addition, the proposed methodology creates hypothetical scenarios that offer a better understanding of systems and the ways they react to changes in variables (Gray et al. 2013; Oriola 2014). In practical terms, these methodologies facilitate the structuring of the decision problem in question (i.e. urban sustainability), encourage communication about the topic among specialists, and provide tools for dynamic analysis, which can be useful to decision makers.

As previously mentioned, the proposed model is not without limitations. These include the difficulty of finding specialists in urban sustainability to create a panel and meet in two consecutive sessions, as well as the idiosyncrasy of results since they integrate subjective factors that depend on the specific context and specialists' contributions. Nonetheless, this study's findings provide added value in terms of urban sustainability by offering city decision makers a fuller understanding of the relevant issues. The results confirm the usefulness of the dynamic, adjustable tool developed, which can be adapted to fit any reality, with the necessary changes.

Future research could thus examine other contexts and create different decision-maker panels, including experts from various regions. Scholars may also want to use the proposed methodologies in other countries and/or contexts and compare the results. Since the approach applied in the present study does not focus on finding optimal solutions, the decision-support system created can also be modelled using other equations. Further complementary research will be vital to ensuring the continuous expansion of experts' understanding of urban sustainability.

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ORCID

F. A. F. Ferreira http://orcid.org/0000-0001-5208-9084
I. Meidutė-Kavaliauskienė http://orcid.org/0000-0003-0435-7632

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