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Enhancing urban resilience evaluation systems through automated rational and consistent decision-making simulations

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ABSTRACT

Urban resilience is an increasingly important topic because of the need to protect and optimize the value derived from the urban built environment with its constructed assets. But there is still no harmonized definition or a consensual set of descriptors for this multi-dimensional concept. This paper aims to address this knowledge gap by outlining an Urban Resilience Evaluation System (URES) with a breakdown structure of 16 indicators and 75 parameters grouped into five interrelated dimensions: environmental, economic, organizational, social, and technical. The resilience scoring of the constructed assets relies on a novel Multi-Criteria Decision Analysis (MCDA) approach adapted from the Analytic Hierarchy Process (AHP) method. This novel approach involves Automated Rational and Consistent Decision Making (ARCDM) to pre-conceptualize and simulate behavior scenarios of a virtual panel of experts with different perspectives. These behavior scenarios are organized into a pairwise multilayer decision-making matrix that overrides the need for surveys. The authors use a portfolio of buildings with seven different use types (residential, research facilities, schools, hospitals, industrial facilities, shopping centers, and hotels) to test the applicability of the proposed URES breakdown structure for buildings with different levels of importance. This allows the comparison and validation of various ranges of results expressing different perspectives.

The proposed methodology can be readily used by various stakeholders of the Architecture, Engineering, Construction, and Operation (AECO) sectors involved in the lifecycle management decisions and activities of constructed assets. It impacts feasibility studies, design, construction, operation and maintenance, rehabilitation, and disposal of constructed assets that comprise the built environment for cities and societies.

1. Introduction

Natural hazards disasters have caused the loss of more than two million people and over $3 trillion since 1980 (World Bank, 2021). The frequency and severity of natural disasters and their impacts have increased due to global warming, population growth, and extensive urbanization. The cost of the cities' vulnerability to natural disasters amounted to $150 billion in the last decade, and there are estimates that it can reach $314 billion per year by 2030 in case of insufficient investment in the enhancement of urban resilience (World Bank, 2021).

The urban built environment comprises multiple constructed assets with life cycles extending several decades or even centuries. The tangible and intangible value derived from these constructed assets, namely infrastructure and buildings that are critical for the functioning of society, is of great importance. Some reports claim that investing $1 in infrastructure implies $4 in return by enhancing more reliable infrastructures (Hallegatte, Rentschler & Rozenberg, 2019). Therefore, the interest in resilience of constructed assets is on the increase, namely regarding both man-made and natural disaster risks.

To this extent, the Architecture, Engineering, Construction and Operation (AECO) sector is looking at provisions such as sophisticated design approaches and higher construction quality control and more robust building policies. Including those provisions ensuring resilience to disruptions and their consequences, and the capacity to maintain the

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Abbreviations: AECO, Architecture, Engineering, Construction, and Operation; ARCDM, Automated Rational and Consistent Decision Making; MCDA, Multi-Criteria Decision Analysis; URES, Urban Resilience Evaluation System.

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operational performance during and after adverse events.

It is relevant to note that resilience can be defined differently depending on the term's context. Regarding the resilience of constructed assets, a possible definition discussed in this study, based on the combination of other proposals, is the intrinsic ability of constructed assets to absorb and adapt to the disruption and recover its functional performance (Hosseini, Barker & Ramirez-Marquez, 2016).

Additionally, urban resilience is an increasingly important topic, being on the agenda of the top management of public and private AECO organizations of different kinds because of the need to protect and optimize the value that is derived from the urban built environment with its constructed assets (Falcão Silva, J., de Almeida, Salvado & Rodrigues, 2020). But there is still no harmonized definition or an undisputed set of descriptors for this multi-dimensional concept. This paper aims to address this knowledge gap by discussing the existing literature and establishing a proposed Urban Resilience Evaluation System (URES) combined with simulations that enable an Automated Rational and Consistent Decision Making (ARCDM) approach to this multidisciplinary problem.

The originality and novelty of this paper are twofold. On the one hand, it presents a structured URES, which establishes a foundation for optimizing lifecycle asset management decisions related to investment planning and budget prioritization. On the other, it is introducing a novel simulation-based decision support tool to accelerate the structuring phase of complex multidisciplinary problems. These two mutually supportive main contributions (See Fig. 1) are combined in this paper in order to evaluate the impacts of various strategies for weighting decision-making criteria in urban resilience assessments.

This combination of URES with an ARCDM tool aims to solve the subjective bias of a wide range of influencers and decision-makers involved in enhancing urban resilience. Conventionally, this is tackled by panels of experts and with recourse to surveys that are resource-consuming and difficult to perform and often with important limitations when there is a need to recalibrate conventional MCDA models after successive repetitions of the processes. The ARCDM is a novel algorithmic stochastic approach based on MCDA and AHP that can contribute to solving this important limitation of conventional decision-making tools. This combined approach of both URES and ARCDM is applied to a portfolio of buildings with seven different use types (residential, research facilities, schools, hospitals, industrial facilities, shopping centers, and hotels) for testing and validating the proposed URES breakdown structure for buildings with different levels of importance and the range of results expressing different perspectives.

This paper consists of six sections in line with the research process presented in Fig. 1:(1) Introduction – the motivation and general context of the paper, formulating the core research issues being addressed, the research goals, and an overview of the methods used; (2) literature review – introduction of the conceptual background of the main topics addressed in the paper, with an emphasis on to interrelations between asset management, risk management and urban resilience with regards to the disruption of the constructed asset due to natural and man-made disasters, plus the theoretical framework of MCDA and AHP that form the basis for the novel ARCDM decision-making approach that is proposed in the paper; (3) URES – discussion and presentation of dimensions, indicators, and parameters of the proposed URES breakdown structure; (4) Automated Rational and Consistent Decision Making (ARCDM) – presentation of a novel automated decision making approach to create a consistence pairwise matrix and extract a weighting arrangement from various scenarios; (5) Case application, results and discussion – presentation and discussion of empirical evidence obtained through the combined application of URES and ARCDM to a portfolio of buildings an empirical case study; (6) Conclusions and future work – overall assessment of the results obtained from the ARCDM scenarios used in the application of URES, including a discussion on how different point of views can affect the final results and how this enables better decision-making for those involved in the lifecycle management and resilience enhancement of constructed assets.

2. Literature review

The literature review presented in this section covers the two main focal points of this research. It presents an overview of previous work done regarding urban resilience evaluation systems and identifies the existing gaps. It also covers the background knowledge of MCDA methods and approaches to accelerate the problem structuring phase and simulations to compare and validate multidisciplinary panels of experts with varying perspectives.

2.1. Urban resilience and disruption of constructed assets

The risks of natural disasters and man-made disasters have increased globally, causing damage and negatively affecting society and the economy. Therefore, predicting and preparing for disasters is essential to reduce the vulnerability and risk of these disruptions. The complex interdependence between aging construction assets and infrastructure, especially with rapid population growth, makes the situation more difficult for a resilient society facing disruptions from different causes (Cutter et al., 2013; ECCE, 2020; ISO/TC 59, 2021; ISO DGuide 73 2009; ISO/TC 262 N 685 2021; ISO/TR 22845 2020).

There is a growing interest in making constructed assets more resilient facing disruptions. In this context, several researchers have been using qualitative and quantitative approaches to define and model

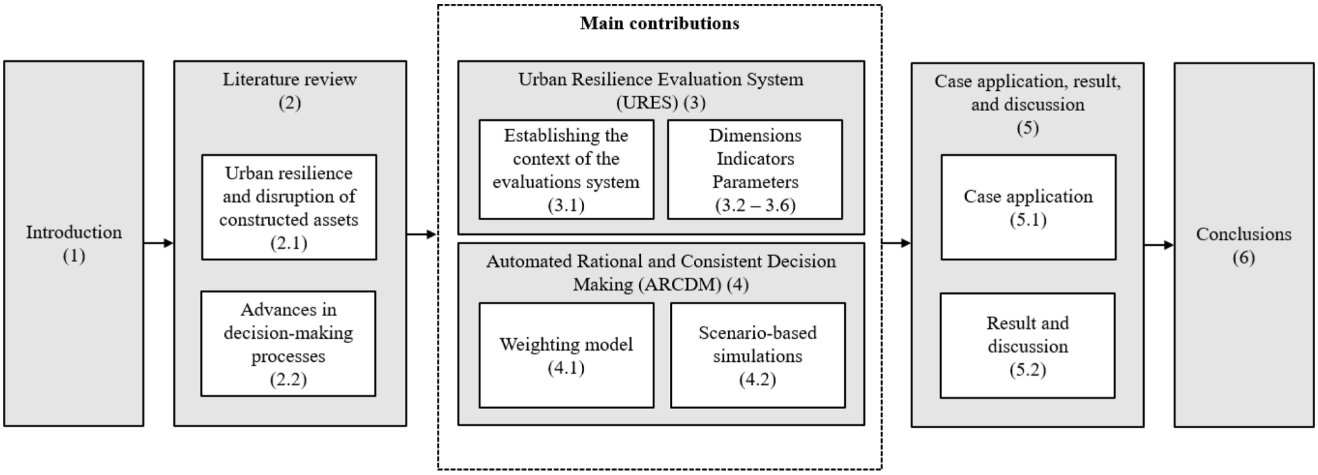


Fig. 1. Research process and main contributions.

urban resilience (Hosseini et al., 2016). Yang, Ng, Xu and Skitmore (2018, 2020) discusses a way to incorporate the concept of resilience in the equation of asset management decisions and investment planning. Several other authors have been looking into these types of decision-making problems under the umbrella of urban resilience (Newman, Beatley & Boyer, 2017; Ribeiro & Pena Jardim Gonçalves, 2019; Zhang & Li, 2018).

Constructed assets can be directly impacted by climate change and extreme weather or seismic events, or various types of man-made disruptions such as those arising from wars (Tokgoz & Gheorghe, 2013) or other types of human-made disruptions (N. M. Almeida, Silva, Salvado, Rodrigues & Maletič, 2021; Dargin, Berk & Mostafavi, 2020; Komljenovic, 2020; Marasco et al., 2021; Rendon, Osman & Faust, 2021). The frequency and intensity of disruptions increase alongside the vulnerability and exposure of the constructed assets to these risks that can result in important social and economic losses (Cutter et al., 2013).

Cities and societies face several risks that require mitigation through appropriate action regarding the entire lifecycle of constructed assets and across generations. In this context, it is important to enable cities to respond rapidly to this challenge by Hernantes, Maraña, Gimenez, Sarriegi and Labaka, (2019); Jabareen, (2013); Ribeiro and Pena Jardim Gonçalves, (2019): i) absorbing the initial impact of casualties; ii) reducing the impacts of disasters; iii) adapting to newly formed changes; iv) improving the urban asset systems to enhance preparedness against future threats and increasing the adaption capacity.

Resilience enhancement of constructed assets has started to attract attention from the AECO professionals with regards to risk reduction and prioritizing budgeting (Phillips & Costa, 2007), especially in the case of constructed assets that are critical for the functioning of the society and for the national interests and that need to be preserved for future generations and to assure the achievement of the UN sustainable development. These are the cases of water, energy, transportation infrastructures, and commercial, residential, hospital, education, touristic, and office buildings.

Constructed assets are traditionally divided into three categories: infrastructure, buildings, and industrial facilities. Sustainability infrastructure implies achieving or retaining the best possible compromise among cost, performance, and risk over the life cycle of the constructed assets while preventing adverse long-term impacts resulting from unsound short-term decisions (PAS 55–1, 2008; PAS 55–2, 2008). Yates (2014) developed a guide for implementing sustainability practices in industrial facilities. This guidance includes two maturity models and a checklist for the sustainability evaluation of industrial construction projects. This work is implicitly interrelated with the concept of urban resilience.

Assets, both tangible and intangible, are items or things that provide value. As applied to constructed physical assets, asset management is a long-term optimized approach to convert organizational objectives into high-level, detailed, and long-term action plans (PAS 55–1, 2008; PAS 55–2, 2008). Asset management has emerged as a global trans-disciplinary management approach after the ISO 55,000 international series regulations of standards in 2014 (ISO 55000 2014; ISO 55002 2014). This management approach involves optimizing cost, risks, performance, resources, and benefits over the whole asset life and within any absolute constraints (Management, T. I. of A 2015; The Institute of Asset Management 2015). Urban resilience is a key aspect of sound asset management as it contributes considerably to recover the constructed assets' performance in case of disruptive events. Previous studies have explored the resilient enhancement of constructed assets as a branch of asset management (Almufti et al., 2013; Asadzadeh & Kötter, 2015; Atrachali, Ghafory-Ashtiany, Amini-Hosseini & Arian-Moghaddam, 2019; Burroughs, 2017; Engle, Bremond & Malone, 2013; Fortified, 2021; United States Resiliency Council, 2015; USGBC, 2018; Verrucci, Rossetto & Twigg, 2003). These studies helped to establish concepts, indicators, and metrics. However, the diversity of concepts is still quite prevalent, and the approaches and methods used to quantify resilience are not yet entirely consensual (Francis & Bekera, 2014)

Michele & Daniela (2011) emphasize that it is often the case that the information generated in asset management systems "is not efficiently used in decisional process" and that this "results in much waste in time and effort." Balinho and Picado-Santos (2020) also stress the importance of including risk-related information in decision support tools to attain sustainability and efficient investments in infrastructure asset systems.

Decision-making is a core issue of infrastructure asset management, especially with the growing complexity and diversity of constructed assets and the varying requirement profiles of their stakeholders. These requirements range from facility asset management needs for investment and life cycle costs optimization (Grussing, 2014) to infrastructure performance levels related to safety, serviceability, and capacity. In this context, this study proposes a model (ARCDM) that reduces the amount of time and effort for weighting the criteria in decision-making processes with several benefits compared to the current practice (see Section 4).

Urban resilience is strongly linked with policymaking and strategies. It is a multidisciplinary concept that includes physical, infrastructural, environmental, economic-social, political-regulatory, and organizational aspects (Adedeji, Proverbs, Xiao & Oladokun, 2018; Burroughs, 2017; Masood et al., 2016; Proverbs & Lamond, 2017; *Re* Cecconi et al., 2018; Reckien et al., 2017). Resilience management can involve complex cost-benefit analysis, and there are several attempts to make resilience evaluations more straightforward (N. M. Almeida et al., 2021; Burroughs, 2017; Francis & Bekera, n.d.; Wholey, 2015).

Resilience management is strongly interrelated with disaster risk management. "Risk is the effect of uncertainty on objectives" (ISO 31000, 2018; ISO/IEC 31010 2018). These objectives are context-dependent and can include financial, health, safety, and environmental issues. Researchers usually describe risk by reference to probable events and consequences or a combination of these. Studies describe it as a function of the consequences of an event and the associated probability of occurrence. Various authors have thoroughly explored the application of risk management concepts to the built environment (N. M. Almeida, Sousa, Dias & Branco, 2015a; Botequilha-Leitão & Díaz-Varela, 2020; Voghera & Giudice, 2020, N. Almeida, Sousa, Alves Dias & Branco, 2010). The interrelationship between diverse environmental and economic challenges within disaster and emergency management and risk mitigation, resilience, and disaster recovery has been explicitly identified by Miller (2015). Some authors (Mohebbi et al., 2020) have recently started looking at cyber-physical, social, and organizational interdependencies and their importance in promoting the resilience of various infrastructures.

Urban resilience management involves the consideration of ecological, organizational, social, and economic concerns, among others. It is thus a complex issue involving multiple domains. This complexity is usually modeled into a restricted number of dimensions to express resilience facing disruptions. These dimensions are then commonly broken into indicators. These indicators generally focus on specific areas of concern related to natural-induced or man-made disaster risks (Custer & Nishijima, 2015; ISO/TR 22845, 2020; Rezvani, 2010; Rose, 2007): climate, flood, earthquake, hurricane, fire, hazardous material spills, groundwater contamination, structure failures, explosions, etc. Several authors have proposed evaluation criteria for rating such indicators following existing standards, codes, technical documents, historical data, or best practices to preserve constructed assets from post-disasters disruptions(Almeida, Sousa, Alves Dias, & Branco, 2015a; Almeida, Sousa, Dias, & Branco, 2015b; Koks et al., 2019; Petchrompo & Parlikad, 2019; Sousa, Almeida, & Dias, 2014, 2015)

There is a new international standard being developed with guidelines for managing emerging risks and enhance resilience (ISO/CD 31,050, 2021). In this new standard, urban resilience's technical, social, and economic dimensions relate to the risk of emerging disruptions. For Ribeiro and Pena Jardim Gonçalves (2019), urban resilience covers social, economic, natural, human, technical, and physical dimensions. These authors define it as the capacity of absorbing first damage.

According to them, the four main pillars of resilience are identification, resistance, recovery, adaptation, and transformation to absorb the initial damage, reduce the impact, and adapt and transform for the future event.

According to Hernantes et al. (2019), the Resilience Maturity Model (RMM) is a tool for different authorities (local, regional, national, and international) that enables them to make decisions regarding resilience enhancement procedures. It provides five maturity levels (starting, moderate, advanced, robust, and vertebrate) to achieve excellence in urban resilience. Furthermore, it aims to enable cities to evaluate their current maturity level and recognize strategies that allow them to improve.

Schweikert, Chinowsky, Kwiatkowski and Espinet (2014) developed an Infrastructure Planning Support System (IPSS) to assess climate change, environmental, and social impacts for a longer-term approach to road infrastructure planning. It uses quantitative and qualitative analysis approaches such as estimated fiscal cost, GHG emissions, transportation cost and time savings, and social impacts of road construction.

Although the resilience field has been drawing much attention recently (Marana et al., 2019; Rasoulkhani, Mostafavi, Cole & Sharvelle, 2019; Yao & Wang, 2020), in many aspects, there is still a lack of wide-range consensus on how to evaluate resilience at the level of constructed assets (i.e., buildings and infrastructure). Concerning this, it is worth mentioning some efforts to incorporate resilience-related concerns in evaluation systems for the built environment, such as REDi, ARMS, RELi, and LiderA, to name but a few (Almufti et al., 2013; Atrachali et al., 2019; Burroughs, 2017; Pinheiro, 2011; RELi, 2018).

REDi™ is a resilience-based rating system for earthquake and beyond-code design approach in the planning and assessment phase to achieve a higher performance design (Almufti et al., 2013).

Australian Resilience Measurement Scheme for buildings (ARMS) incorporates physical infrastructure, environmental, economic, social, political, regulatory, and organizational resilience as a holistic concept that employs resilience. This system evaluates different dimensions and sub-dimensions and rates the building's performance aspects (strengths and weaknesses) providing an overall assessment of its resilience (Burroughs, 2017).

RELi™ 2.0 Rating System is a holistic, resilience-based rating system for environmentally and socially resilient design and construction in integrative design processes, utilizing existing sustainable and regenerative guidelines for emergency preparedness, adaptation, and community vitality (USGBC, 2018).

LiderA supports the assessment and is a sustainability certification system oriented to the design, construction, and operation phases of all types of constructed assets in the built (LiderA, 2005).

The resilience assessment of buildings has become a reality at the international level. Great progress has been made in some countries such as Australia (ARMS, BRRT) and the United States of America (RELi, FORTIFIED, ANCR, BRLA), namely with regards to natural disaster deriving from climate and seismic risks. Table 1 shows some voluntary resilience rating systems in construction and civil engineering for these categories.

Table 1
Resilience measurements current systems.

Resilience Assessment Systems	Risks	
	Climate	Seismic
RELi (U.S. Green Building Council, 2018)	x	x
REDi (Almufti & Willford, 2013)		x
Building Scorecard (ARISE, 2020)	x	x
ARMS (Burroughs, 2017)	x	x
B-READY (DNV, 2021)	x	
FORTIFIED (Fortified, 2021)	x	
Building Resilience Index (IFC, 2020)	x	x
USRC Building Rating System (United States Resiliency Council, 2015)		x

Despite the important developments towards higher resilience of constructed assets, there is still a margin for improvement regarding decision-making processes, especially during and after the probable disruption. This paper aims to contribute to this field by proposing a structured URES (Section 3).

2.2. Advances in decision-making processes

Making a decision requires a detailed understanding of the problem, how the response is supposed to resolve the problem and the context in which the response will be implemented. Some techniques are largely used to make asset management and risk management-related decisions involving constructed assets. For example, there have been considerable interests in the use of multi-criteria decision-making techniques for infrastructure management (Taylan, Bafail, Abdulaal & Kabli, 2014). These approaches allow consideration of various stakeholders' interests into a decision-making criterion. Multi-criteria decision analysis (MCDA) is often used in the form of subjective judgment using a panel of experts in decision conferencing (Phillips & Costa, 2007) or combination with other techniques such as the Delphi method.

One of the first efforts to use alternative function-driven and data-driven approaches was the robust operational structure and a theoretical framework integrating with other related social science, economic, political science, and environmental management approaches (Buckle, Mars & Smale, 2000). Studies aimed to improve the resilience evaluation methods' by establishing criteria and scoring systems. These have inspired further research in an attempt to improve the performance of stochastic technique using a system approach to natural disaster resilience (Harrison & Williams, 2016) and a risk management approach (Mitchell & Harris, 2012).

Arif, Bayraktar and Chowdhury (2016) discussed a decision support framework for maintaining infrastructure assets using Markov decision process (MDP), Multiattribute utility theory (MAUT), and portfolio management method. These authors used their framework to measure infrastructure performance and provide performance curves, decision logic maps, and network-level maintenance investment plans for a set of bridges.

The authors believe that the body of knowledge in resilience-related decision-making can expand by incorporating a novel approach for automated decision-making. This novel approach is described in Section 5. It aims to enable facilitators of decision-making with an initial estimation of decision outcomes based on various scenarios, at an early stage of the decision-making process, when there is still limited access to experts or resources for surveys. This novel approach is also very convenient when there is a need to repeatedly monitor and analyze decision-making outputs or results towards the achievement of appropriate robustness levels.

Another study using the MCDA on the different fossil fuel reduction measures that apply to residential buildings is a case study of the relative use of integrated renewable energy sources. This study analyses the heat and electricity consumption of that building according to various criteria such as economic assessment, energy efficiency integration, CO2 emissions reduction, ease of raw material procurement, and the availability of governmental incentives. (Campisi, Gitto & Morea, 2018).

The best-worst method (BWM) is the MCDA approach choosing the best alternative based on the working criteria in function of the initial choices of the decision-maker. It runs a pairwise comparison based on these criteria, followed by a maximin method to weight other criteria in between. The same approach applies to the alternatives. The final score derives from aggregating the weights from different criteria and alternatives to reach the preferable alternative based on the final ranking, validated by checking the consistency ratio (Rezaei, 2015, 2016).

TOPSIS is another MCDA method using almost the same approach of ranking alternatives by giving weights to criteria calculating the geometric distance between each option and the best option/alternative besides normalizing each criterion score usually required in all MCDA approaches. Also, TOPSIS assumes that all criteria can increase and decrease monotonically as well as allow trade-off among the criteria which leads to dropping the weakest one and raising a superior one which leads to a more realistic modeling approach (C.-L. Hwang & Yoon, 1981; C. L. Hwang, Lai & Liu, 1993; Yoon, 2017).

The decision-making trial and evaluation laboratory (DEMATEL) is another MCDA approach based on AHP. It aims to create a network of relations among criteria. It solves complex relations through a visual structural model, which is known as a practical approach identifying cause and effect chain components of intricate systems (Si, You, Liu & Zhang, 2018). There are several variations of DEMATEL in various fields. These are (Si et al., 2018): i) classical DEMATEL; ii) fuzzy DEMATEL; iii) gray DEMATEL, iv) analytical network process- (ANP-) DEMATEL; and v) other DEMATEL.

All the methods as mentioned earlier can be combined with Fuzzy logic to achieve more realistic results in decision-making problems. Similarly, this study uses MCDA to weight the criteria combined with an enhanced AHP-based ARCDM approach. As compared to previous studies by the authors (Duarte, Almeida, Falcão & Rezvani, 2021), this novel approach facilitates the comparison of weaknesses and strengths of clusters of buildings for various resilience-related scenarios.

3. Urban resilience evaluation system (URES)

3.1. Establishing the context of the evaluations system

Following a broad management principle approach, such as that established by the international standard ISO 31,000 for risk management, the rating system proposed by the author includes conceptualization of the internal and external context of the intended application. Following this approach, the proposed URES is related to the objective, expected outcome, time, location, and specificities of its pilot-test case application. Therefore, the proposed URES is adjusted to the specificities of the asset portfolios in Portugal that are used as case studies. Indicators and parameters have been selected to comprehensively cover most of the potential disruptions that apply to similar asset portfolios. These indicators and parameters can be adapted and recalibrated to any other country or asset portfolio by assessing how other probable disruptions can affect the context of urban resilience.

The conceptual breakdown structure of the proposed URES has five dimensions, which, in their turn, are subdivided into several indicators and parameters. The URES proposed in this paper organizes these dimensions, indicators, and parameters and is grounded on existing literature and previous studies by the authors (Duarte et al., 2021). Namely, the proposed URES builds upon the existing body of knowledge in various fields, e.g., earthquake (Takewaki, 2013), flood (Najafi, Zhang & Martyn, 2021), and tsunami (Leong, 2016), namely concerning the project and budget prioritization and performance loss and post-disruption recovery (Marasco et al., 2021; Repetto et al., 2017; D. Y. Yang & Frangopol, 2018). For example, the URES considers that when an earthquake happens, there might be a considerable decrease in building performance (e.g., decreased structural safety). This condition might worsen if there is fire and road closure simultaneously. Furthermore, with regards to the post-disruption recovery phase (Karakoc, Barker, Zobel & Almoghathawi, 2020; Rašković et al., 2020; Reisi et al., 2020), the URES takes into account, for example, that the users of constructed assets may need to face lower serviceability (Koliou et al., 2020) due to higher demand (Mohebbi et al., 2020).

The proposed URES is structured into five dimensions covering specific characteristics such as environment (i.e., earthquake, tsunami and tidal effect, flood, and fire), economic (i.e., insurance, financial and strategic implications), organizational (i.e., internal and external), social (i.e., emergency infrastructures and social responsibility), and technical (i.e., conservation, accessibility, building seismic safety, building security against fire, building security against flooding, and tsunamis).

The dimensions in the URES generally relate to high-level concerns. The breakdown structure of URES includes the dimensions as mentioned above, 16 indicators, and 75 parameters, as listed in Appendix A. The components of the proposed URES can be continuously improved. For example, early warning and horizon scanning can be considered to cope with emerging risks, and issues such as cybersecurity can also be added to consider the complexities of the constructed assets in an industry 4.0 environment. The breakdown structure of URES is further explained in the entire owing Sections 3.2 to 3.6.

3.2. Environment dimension

The Environment dimension includes four indicators (I1 – Earthquake; I2 - Tsunami and tidal effect; I3 – Fire; I4 - Flood) and 25 parameters (P1 - Seismic zoning type 1 EC8; P2 - Seismic zoning type 2 EC8; P3 - Seismic vulnerability of the PDM soils; P4 - Slope of the terrain; P5 - Type of soil EC8; P6 - Distance to cliffs; P7 - Altitude of the terrain; P8 - Distance to the coast; P9 - Distance to the river; P10 - Natural barriers in the surroundings; P11 - Man-made barriers in the surroundings; P12 - Movable objects; P13 - Rows built between the coast and the building; P14 - Susceptibility to the direct tidal effect PDM; P15 - Relative location; P16 - Distance to the river; P17 - Natural barriers in the surroundings; P18 - Man-made barriers in the surroundings; P19 - Vulnerability to floods PDM; P20 - Distance to vegetation; P21 - Density of vegetation; P22 - State of maintenance of vegetation; P23 - Type of vegetation; P24 - Adjacent buildings; P25 - Proximity to the industrial zone).

Its consideration aims to promote a broad understanding of environmental issues, focusing on the area's vulnerability to moderate and high natural disaster risk levels. The parameters are calibrated for the situation in Portugal, providing an overview of potential threats and the determination of the inherent characteristics of the study area, such as altitude, distance to the sea and rivers, slope, etc. Considering that climate change will change the frequency and intensity of disasters, current and future assessments related to natural disasters are in order.

3.3. Economic dimension

The Economic dimension includes two indicators (I5 – Insurance; I6 - Financial and strategic implications) and three parameters (P26 - Insurance against natural disasters; P27 - Financial plan; P28 - Economic assessment of downtime).

The economic aspects are crucial to make a building resilient and can significantly affect the quality of the building, especially during and after suffering the impacts of a natural disaster (Cerè, Rezgui & Zhao, 2019). This dimension is related to the owner's financial capacity to face the imposed interference, including maintenance costs, asset losses, and monetary losses due to the temporary closure of activities. Research shows that sound economic management and continued financial availability can improve response to natural disasters and shorten recovery.

3.4. Organizational dimension

The Organizational dimension includes two indicators (I7 - Internal organization; I8 - External organization) and ten parameters (P29 - Business continuity plan; P30 - Risk management analysis; P31 - Post-disaster recovery plan; P32 - Routine; P33 - Plans and post-disaster exercises; P34 - Learning and updating; P35 - Destructive event data; P36 - Responsible; P37 - Compliance with the existing regulatory scenario; P38 - External standards for resilient construction).

The organizational capacity of buildings is related to the management ability in emergencies, that is, the owner's decision-making on identifying, monitoring, and managing risks. This dimension focuses on pre-disaster, promoting preventive measures to reduce the impact of natural disasters, ensuring buildings' good performance, minimizing harmful consequences, and minimizing inconvenience to users (Atrachali et al., 2019). It also considers issues outside the owner's scope, such as compliance with existing regulatory schemes and the use of other resilience standards. These indicators ensure construction safety and help prepare the building to deal with existing obstacles, helping to identify and prioritize problems.

3.5. Social dimension

The Social dimension includes two indicators (I9 - Emergency infrastructures; I10 - Social responsibility) and seven parameters (P39 - Access to police stations; P40 - Access to fire stations; P41 - Access to emergency infrastructure; P42 - Access to hospitals and health centers; P43 - Occupants; P44 - Disclosure; P45 - Social vulnerability).

The social dimension tries to connect the building with the surrounding society and essentially interconnected communities, especially in times of disaster. In addition, it aims to emphasize the role of citizens in disaster response and the proximity of buildings to community infrastructure (such as fire stations, police stations, hospitals, etc.). It isn't easy to identify and parameterize their responses, but it is imperative to consider this. Research on resilient communities shows that attentive and sensitive cities can better respond to disasters and reduce the consequences of disruptions (World Economic Forum, 2021). Therefore, factors such as the social vulnerability of the building are considered concerning the number of elderly and children.

3.6. Technical dimension

The Technical dimension includes 6 indicators (I11 – Conservation; I12 - Accessibility: I13 - Building seismic safety; I14 - Building security against fire; I15 - Building security against floods; I16 - Building security against tsunamis) and 19 parameters (P46 - Year of construction; P47 - Structural system; P48 - Conservation status; P49 - Density of buildings; P50 - Alternative routes; P51 - Street characteristics; P52 - Plan irregularity; P53 - Height irregularity; P54 - Interaction with adjacent buildings; P55 - Slope difference; P56 - Expansion joint; P57 - Clearance between overlapping spans; P58 - Gas installations; P59 - Control and smoke evacuation systems; P60 - Intrinsic fighting means; P61 - Electrical installations; P62 - Fire compartment; P63 - Security team; P64 - Outdoor fire hydrants; P65 - Emergency lighting and signaling; P66 - Fire extinguishers; P67 - Fire detection and alarm; P68 - Escape routes; P69 - Barriers; P70 – Flood pumping systems; P71 - Exposure of the walls; P72 - Number of floors (flooding); P73 - Number of floors (tsunami); P74 - Orientation; P75 - Ground floor hydrodynamics).

This dimension focuses on all the technical and physical characteristics of both the building and its surroundings. The physical properties of buildings are essential to ensure protection from natural disasters and minimize their damage (Atrachali et al., 2019). This dimension derives from technical methods related to engineering components, including assessing buildings' structures, safety, and physical vulnerability to deal with the aforementioned natural disasters. This dimension includes building redundancy and robustness strategies, such as improvements beyond building codes or setting up protection systems against natural disasters. (Cerè et al., 2019). In this dimension, the inherent characteristics of the building are considered, such as age, number of floors, irregularities, construction quality, current status, and protection status. It is also necessary to analyze the characteristics of the surrounding environment, especially for its impact on post-disaster recovery (Atrachali, Ghafory-ashtiany & Amini-hosseini, 2019). For example, the accessibility of buildings depends on multiple aspects, such as the existence of alternative routes, the density of buildings, and the characteristics of streets.

4. Automated rational and consistent decision making (ARCDM) model

Resilience-related decision-making as applied to constructed assets is a complex multidisciplinary problem. This study contributes to a novel automated decision-making approach that minimizes the number of resources and effort needed to establish the weighting of decision criteria. This optimization one achieves by introducing scenarios-based Automated Rational and Consistent Decision-Making (ARCDM) simulations.

The authors propose this novel ARCDM model for establishing and testing the weighting for various criteria during the problem structuring phase. Decision-makers can then take the final decision with information on the scenarios generated with the ARCDM model.

The ARCDM working on five different main steps accelerate the problem structuring phase and achieves a self-explanatory solution that optimizes the cost and time of the decision-making process by: i) auto refilling of the pairwise comparison matrix (upper diagonal area randomly and refill the lower diagonal automatically by dividend); ii) checking the consistency ratio to be within the acceptable range 0.00 to 0.10 and append those into multi-dimensional matrix known as list using NumPy library and convert the multi-unit information into a unique data frame using Pandas library; iii) segregating each scenario based on scenario dimension weight over 0.4 and create an internal scenario mean data frame as a scenario output; iv) comparing the result of each scenario and how it can affect the final decision (decision-maker/facilitator interpretation), and v) introduce the best solution based on the accord/meeting most of the scenarios converting into a final raking.

The ARCDM code can provide multiple results in a random condition, which the Monte Carlo simulation fits the decision matrix provided in the AHP model. The extracted results will be among numerous randomly generated results that need to be evaluated rationally enough to be included in the result table.

After this step, the discussion lies in grouping the result and interpreting them as various scenarios; likewise, an expert in a specific field of study weighted the criteria multipliers shown in Fig. 2. By this weighting, factors extracted from simulation buildings can be scored and analyzed to identify the weakest aspects (parameters) that need improvement to make it more resilient against various disasters.

4.1. Weighting model

The proposed ARCDM weighting model conceptually derives from the Analytic Hierarchy Process (AHP). It is developed using python (van Rossum & Drake, 2009) and additional packages such as NumPy (Harris et al., 2020) and Pandas (McKinney, 2010). There is a possibility to combine the proposed approach with Fuzzy AHP (F-AHP), which can be counted as an additional scope for future studies. For the purpose of this

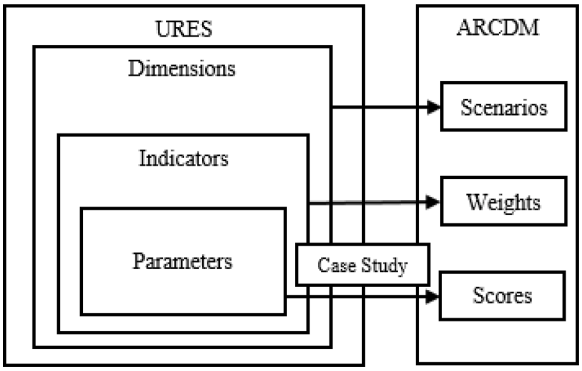


Fig. 2. - URES+ARCDM functionality chart.

study, AHP meets the ARCDM design requirement and fulfills the model's needs in combination with the available URES dimensions and indicators.

In this ARCDM model, descriptors define the criteria in which the options or alternatives can be scored and compared. These descriptors can be standardized and weighted through objective and subjective analysis. Although descriptors could be defined via previous studies, the model does not solve problems related to inconsistencies in the multiple options that can be followed to establish these descriptors (see discussion in the background knowledge section) or those arising from insufficient information to define these descriptors properly.

For each scenario, six matrices have been calculated in the loop. Five of these are calculated at the indicator level of the breakdown structure of URES, obtaining each internal dimension ranking weight. The one in the top-level to create whole scenario weight to rank the alternatives and correlate dimensions into one unified result and work as a multi-layer decision solution in this study.

The proposed ARCDM model uses the URES described in Section 4 and an empirical case study described in Section 5 as a baseline. Improvements are possible in future studies alongside the refinement of URES and further applications of it. To this extend, e.g., for URES code D1-I12-P49 "Technical"- "Accessibility"- "Building Density" there are three criteria: i) ">100 buildings within 0.5 km radius"; ii) "50–100 buildings within 0.5 km radius"; and iii) " <50 buildings within 0.5 km radius". The first one has the lowest score, and the third one has the highest score as the latter increases the global ability of the constructed assets to return to their expected performance more rapidly (Fernandez, 2015; INE, 2012).

The proposed weighting model can be applied for various types of constructed assets and in different contexts if the parameters of the URES are accurately calibrated for the specific context of each country or region and considering the applicable codes or standards. Many of the proposed URES parameters can easily be adjustable and determined for different countries or regions.

At the level of the third layer of the URES, 75 items need to be scored and weighted. The scoring of each 75 parameters follows the recommendations established in ISO 11,863, i.e., a rating scale of the odd number between one and nine. The soring of one point means lower resilience of the constructed assets, and nine points the highest. The weighting procedure follows an enhanced MCDA-type approach that considers the complexity of various stakeholders with different perspectives regarding urban resilience. This enhanced approach combines scenario-based simulations with pairwise comparison, sensitivity analysis, and group evaluation. In addition, each scenario increases the decision-making reliability by adding consistency in the URES dimensions, indicators, and parameters, which require weights to be comparable.

4.2. Scenario-based simulations

Scenarios are defined as the AHP over the indicators and dimension of URES as criteria to weight them and be the basis of decision for the options or alternatives, which are the case studies. Scenarios can be built following a traditional approach involving pairwise comparison matrixes and resource-intensive surveys with a panel of experts. This paper proposes a low resource alternative that relies on a mechanism to get an Automated Rational and Consistent Decision Making (ARCDM) matrix expressing different viewpoints from multiple experts. Real experts are not required in this model, while the simulated experts conceptualize within the context of various scenarios. This study developed and tested an algorithm to incorporate ARCDMs in the AHP. The consistency index and ratio check the reliability of the comparisons and validate by the following class attribute in python. The reason for using class is to access each attribute through other calls:

The ARCDM algorithm creates a random matrix for the AHP decision model to generate a consistent matrix under a 10% consistency ratio. These matrices are to be used in later steps to be normalized and create scenarios. This method is applicable to the multi-layer decision problem. The model has a minimum of two levels and all the scenario-based layers should present equivalences to the structure of other levels. This assures a sufficient contribution of each element in the final result because all layers are distributed equally in their scenarios.

To model considers the effect of risk on system stability and does not run with a large number of executions to reach the central limit theorem, due to seeing this uncertainty that enable to reach the results more closely of subjective judgments. Normalization can be done both in code and in the spreadsheet. In this study, the extracted sums of the decision weight results present a variation of +/- 5% which normalized before making the final outputs.

A scenario means the highest level of the decision matrix that creates a favorable context in which the critical points of the result can be found as local and universal maximums and minimums. Indicators and parameter maximums and minimums help make more reliable decisions when the parent node, i.e. the dimension or scenario, is the minimum or maximum. For example, in the context of urban resilience, if a parameter has a weakness, if the parent node has a high or low weight, the decision maker can reach a final decision step that leads to an alert or warning to allocate a budget for that element to become more robust.

Python code classes help use less memory and save vital information within the object. The code presented below together with comments are self-explanatory.

Creating the analytical hierarchy processors as a class: class AHP: def _init_(self, name, matrix, weightx=1.1): self.name = name self.matrix = matrix self.children = [] self.parent = None self.weightx = weightx

RI = [0.01, 0.01, 0.58, 0.90, 1.12, 1.24, 1.32, 1.41, 1.45, 1.49,

1.51, 1.48, 1.56, 1.57, 1.59] self.*n* = int(len(matrix)) self.*A* = np.reshape(matrix, (self.n, self.n)) for a in range(len(self.A)): for b in range (len(self.A)): if *a* > b*:* self.A[*a*][b] = 1./self.A[*b*][a] self.alpha = self.A.sum(axis=1) self.Column_sum = self.A.sum(axis=0) self.A_norm = self.A/self.Column_sum self.weight = np.round(np.average(self.A_norm, axis=1), 3) self.Weigted_*A* = self.A*self.weight self.Priority = np.average(self.Weigted_A, axis=1) self.Lmda_Max = np.average(self.Weigted_A.sum(axis=1)/self.weight) self.CI = (self.Lmda_Max-self.n)/(self.n-1) self.CR = self.CI/RI[*self.n*-1]

The ARCDM defines as an identity matrix that is filled by random choice among our assumptions ((1/9), (1/8), (1/7), (1/6), (1/5), (1/4), (1/3), (1/2), 1, 2, 3, 4, 5, 6, 7, 8, 9) (Saaty, 1984) based on the AHP ranking criteria. This algorithm enables drawing various scenarios without spending time or extensive resources to fill matrixes with information from an expert panel with the capacity to iterate through the normalization process to get average results. In this study, the authors consider normalization iteration equal to one to have a more biased ARCDM that increases the variability of the study. The following python functions illustrate the random choice among available options and check the consistency ratio for the rational decision-making process:

AHP decision matrix creator def mc(n): options = ((1/9), (1/8), (1/7), (1/6), (1/5), (1/4),

(1/3), (1/2), 1, 2, 3, 4, 5, 6, 7, 8, 9)

A = np.identity(n) for a in range(len(A)): for b in range(len(A)): if *a* < b*:*

A[*a*][b] = rd.choice(options) return A

Consistence matrix creator def cmc(n):

A = mc(n) while AHP("A", A).CR > 0.1:

A = mc(n) return A

Case studies for scoring the resilience of the buildings: i16.csv is the initial score of the buildings' indicators. df = pd.read_csv('i16.csv', index_col=0) i16 = df.to_numpy()

D = []

Taking the initial data frame as a CSV file containing 5 dimensions, 16 indicators and 11 building final scores to be normalize and further analyses in spread sheet. Save a CSV file as below:

D1,D2,D3,D4,D5,i1,i2,i3,i4,i5,i6,i7,i8,i9,i10,i11,i12,i13,i14,i15, i16,B1,B2,B3,B4,B5,B6,B7,B8,B9,B10,B11 dfm = pd.read_csv ('Dwiwb11s.csv')

The result.csv can be normalized in a spreadsheet. After having the normalized results, the outputs can be sorted and filtered based on the context of the problem for a proper interpretation. In the area of urban resilience, parameters that significantly reduce the building performance in case of disruption are to be identified. This identification can be based on the lowest scored parameter of the weakest building or using the score after clustering the buildings based on the use-type and then finding the lowest parameters. By identifying the lowest parameters, the urban management entities can decide where to invest public and private budgets based on a solid result.

ARCDM accepts the decision only when the consistency ratio is less than ten percent and returns the priority matrix by having the decision dimension and number of iterations for normalization. This scenario generator can be used in various problems by applying criteria and alternatives in more than one level of decision layer complexity. In this part of the code, a while loop is used, which demonstrates till the consistency ratio (CR) is above 0.1, it cannot return any result and capture it into the favorable decision-matrix variable.

The multilayer approach enables the model to have fair weighting by each defined criteria and allows them to affect the result. Through the stochastic process by running the model in a loop, the stability of the result is established.

5. Case application, result, and discussion

5.1. Case application

The authors used a portfolio of 11 buildings (B1 to B11) in Portugal representing seven different use types (residential, research facilities, schools, hospitals, industrial facilities, shopping centers, and hotels) was used to test the applicability of the proposed URES breakdown structure in combination with the ARCDM weighting model.

The buildings for the case study were chosen to test the feasibility of the proposed rating system in different situations. The building samples cover new and old buildings, whether rehabilitation interventions, with higher and lower vulnerability to natural disasters, etc. a sample of the results for 11 buildings are shown in Table 2: 2 residential buildings (B1 – single-family and B2 - multifamily), 2 schools (B3 – school 1, and B4 – school 2), 1 administrative building (B5 - research campus), 1 hospital (B6), 1 industrial building (B7 - carpentry factory), 2 commercial buildings (B8 – commercial building 1, and B9 - commercial building 2) and 2 hotels (B10 – hotel 1, and B11 – hotel 2). According to Portuguese regulations (Diário daRepública, 2015), the sample covers 7 out of 12 building use types.

6. Result and discussion

The results were obtained after running the model for 50 ARCDMs to get each case study score based on the weighting procedure and prioritize the lowest resilience score that is the most vulnerable one compared to the others. To this extend, the outputs are organized for the different points of view. For example, the output resulting from the environmental point of view is shown in Table 2. In this case, the dimension "Environment" is always weighted above 40 percent of the total combined weighting of all dimensions.

Table 2
Output results from the environmental point of view (weight higher than 40 percent in "Environment").

#	Point of view	D1	D2	D3	D4	D5
22	Environment	0.622	0.038	0.26	0.058	0.047
26	Environment	0.62	0.013	0.136	0.143	0.132
32	Environment	0.582	0.142	0.168	0.085	0.032
47	Environment	0.569	0.086	0.031	0.2	0.138
14	Environment	0.545	0.04	0.125	0.244	0.027
36	Environment	0.505	0.019	0.183	0.037	0.251
1	Environment	0.485	0.112	0.041	0.03	0.371
27	Environment	0.445	0.071	0.047	0.357	0.076
4	Environment	0.431	0.186	0.081	0.273	0.028
2	Environment	0.423	0.027	0.14	0.206	0.195

The output of all the 50 runs of the stochastic ARCDM model, for all dimensions and indicators, organized in terms of the five dimensions (D1-D5) of the URES, is shown in Appendix B. The output of 50 ARCDM runs for each building (B1-B11) of the portfolio is shown in Appendix C. These outputs show that in the different points of view in the stochastic approach, there are various scores with high variation for each case study. The statistical analysis of the result is shown in Table 3. To this extent, it is apparent that there is significant variation among the min and max of each building's results, and the standard deviations of buildings are not the same and vary from 0.6 to 1.28. If the same statistical analysis repeats for each dimension point of view, the resilience score will not be equal. It will affect the priority of the building for budget allocation when a CA has a low resilience score. However, one should consider the type and functionality of those CAs. For example, the resilience of hospitals should be higher than residential. And CAs should compare based on the priority of service for society.

To this extent, based on the observed variation, categorized points of view need to be present for each resilience score. They represent the final score of each case study by prioritizing them as shown in Table 4. For all scenarios, B1 scores the lowest, due to being a residential building, followed by B7 in the scenario of "Environment", but by B5 in the other scenarios. Another example would be having B4 in high priority in the "Technical" scenario while scoring low in the "Environment" aspect. These outputs demonstrate that the strategic national or regional priorities and the organization management point of view can significantly affect the resilience ranking of constructed assets. On the other hand, a higher score means more resilient buildings. B6 and B8 can be chosen as the most resilient alternatives.

Fig. 3 shows a bar chart illustration for five categorized scenarios. Buildings B6, B8, B9 show better resilience score stability among various scenarios, while there is higher uncertainty in the cases of B1, B2, B3, B4, B5, and B7. The outputs for the remaining buildings are located between these two extreme cases.

Based on the results, it is deduced that the scenario emphasizing the Environment aspect increases the resilience score of the building due to the localization of the CAs. On the other hand, the scenarios based on Economic and Organizational dimensions give lower scores. It appears that scenarios on Social and Technical aspects have present certain limitations for describing and scoring the CA's resilience. Sometimes, they are less scored than Environment, Economic, and Organizational aspects and more in other cases. Therefore, the final resilience score should combine the ARCDM based on the organizational needs and their prospects toward urban resilience.

In this study, the authors present a scenario-based decision analysis at the dimension (first) level of the conceptual breakdown structure or decision hierarchy of URES. Future studies can include similarly detailed analyses at different levels (e.g., indicators and parameters). The stochastic approach enables the model to have flexibility in analyzing different scenarios at different decision-making procedures. Also, the consideration of lifecycle cost and budget analysis and uncertainties can help further improve the model's practical utility and robustness.

7. Conclusions

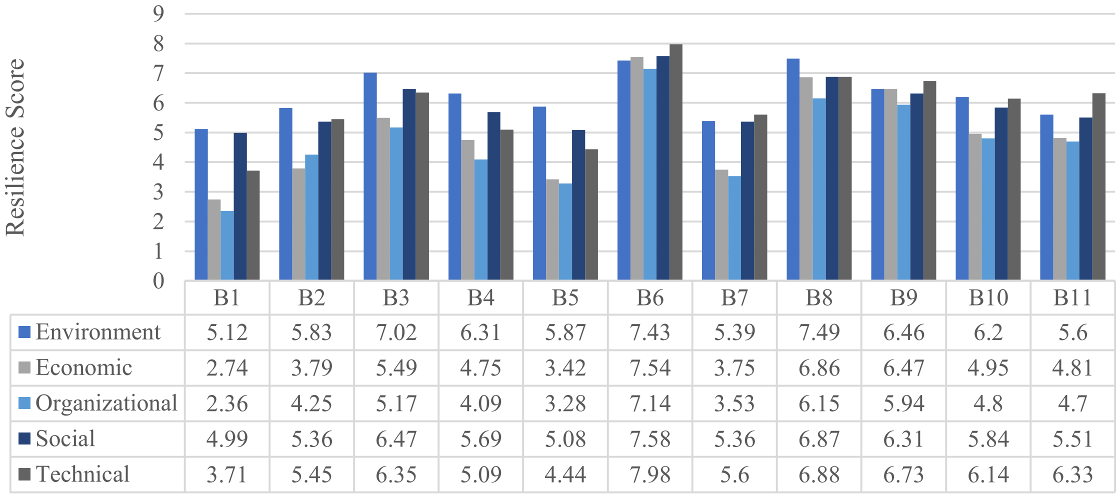
The current body of knowledge in resilience-related decision-making for constructed assets has gaps that need being addresses. The authors propose to contribute to filling this gap by proposing a novel approach for automated decision-making. This paper discusses this novel approach and its advantages, to wit, how it enables decision-making

Table 3
The Statistical analysis of the 50 ARCDM.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
mean	3.87	4.92	6.11	5.23	4.46	7.52	4.72	6.86	6.37	5.57	5.34
std	1.28	1.07	0.87	0.95	1.18	0.60	1.10	0.79	0.70	0.79	0.87
min	1.83	2.61	4.31	3.48	2.54	6.21	2.61	5.21	4.98	3.85	3.59
max	6.40	6.98	7.77	7.29	6.67	8.63	6.81	8.29	7.59	7.36	6.99

Table 4
Priority ordered based on each scenario average (lower score means less resilient).

Environment		Economic		Organizational		Social		Technical	
B1	5.12	B1	2.74	B1	2.36	B1	4.99	B1	3.71
B7	5.39	B5	3.42	B5	3.28	B5	5.08	B5	4.44
B11	5.6	B7	3.75	B7	3.53	B7	5.36	B4	5.09
B2	5.83	B2	3.79	B4	4.09	B2	5.36	B2	5.45
B5	5.87	B4	4.75	B2	4.25	B11	5.51	B7	5.6
B10	6.2	B11	4.81	B11	4.7	B4	5.69	B10	6.14
B4	6.31	B10	4.95	B10	4.8	B10	5.84	B11	6.33
B9	6.46	B3	5.49	B3	5.17	B9	6.31	B3	6.35
B3	7.02	B9	6.47	B9	5.94	B3	6.47	B9	6.73
B6	7.43	B8	6.86	B8	6.15	B8	6.87	B8	6.88
B8	7.49	B6	7.54	B6	7.14	B6	7.58	B6	7.98



	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
■ Environment	5.12	5.83	7.02	6.31	5.87	7.43	5.39	7.49	6.46	6.2	5.6
■ Economic	2.74	3.79	5.49	4.75	3.42	7.54	3.75	6.86	6.47	4.95	4.81
■ Organizational	2.36	4.25	5.17	4.09	3.28	7.14	3.53	6.15	5.94	4.8	4.7
■ Social	4.99	5.36	6.47	5.69	5.08	7.58	5.36	6.87	6.31	5.84	5.51
■ Technical	3.71	5.45	6.35	5.09	4.44	7.98	5.6	6.88	6.73	6.14	6.33

Fig. 3. Bar chart illustration of the average results for five categorized scenarios.

with scenario-based estimations when there is a shortage of experts or resources to perform the surveys at the initial phase. This novel approach can also be very useful when one must repeatedly monitor and analyze if appropriate levels of robustness are being achieved.

This paper presents and discusses empirical evidence obtained through the combined application of an Urban Resilience Evaluation System (URES) with Automated Rational and Consistent Decision Making (ARCDM) to an empirical case study of 11 buildings in Portugal. This combined application demonstrated that scenario analysis is vital for simulating virtual subjective judgment and enhancing the resilience of constructed assets.

In this study, the URES is proved to be suitable for different types of buildings, not only in Portugal, but also in other countries and, with adaptations, also to other types of constructed assets (transportation, water, energy infrastructure, etc., industry installation). One should carefully consider adjusting and refining the indicators and parameters in each of the five dimensions of the URES (environment, economic, organizational, social, technical), namely, to comply with the standards or codes that are applicable in each specific context, country or region. It is worth mentioning that this refinement has not been fully achieved in this research and that should thus be counted as future research.

URES, in its current state of development, covers the building's intrinsic qualities and interdependencies with the surroundings, community, and users in a post-disaster context. The results prove that URES is well designed and is sensitive to building groups with different levels of importance.

According to Almeida (2011), each building group consists of constructions with similar technical risks and levels of relative importance. The lowest URES scores were achieved for residential buildings, namely in the economic, organizational, and technical dimensions. However, these buildings scored significantly higher in their intrinsic aspects, such as environmental and social aspects. Another compelling conclusion for facility managers and decision-makers derives from the insights extracted by comparing results for different scenarios. Whereas some buildings show a consistent resilience score under all pre-established scenarios, others show significant variation when the weightings for the different scenarios also vary.

Because the proposed resilience assessment system can effectively identify areas for improvement by various stakeholders, it can prioritize investments to enhance the resilience of buildings and communities.

This information can be helpful to all stakeholders involved: owners, engineering and architecture professionals, managers, insurance companies, municipalities, and others. This methodology is pivotal to enable optimum construction asset operation, maintenance, and investment decisions.

Further work by the authors is underway to extend the applicability of the proposed approach to different scenarios and geographic areas and for varying economic and organizational contexts. It is also relevant for future work to establish different thresholds corresponding to the minimum requirements of each building's importance group (N. Almeida, 2011). This stems from the fact that each buildings group (e.g., residential buildings and hospitals) has different risks and functional performance expectations. The authors also propose that the URES requires further studies regarding a proper balance of all of the natural and man-made hazards established in ISO/TR 22,845.

The study presented in this paper includes a stochastic scenario simulation in the problem structuring phase of a decision-making problem in the context of urban resilience. These simulations allow for a sensitivity analysis without an actual panel of experts but with a broader view of the problem and various outcomes for multi-dimensional complexities, while arguably with insights that cannot be achieved due to the inherent bias of a real panel of experts in the same context. The simulation of a stochastic analysis ensures that the result is robust by testing the consistency ratio for each simulated decision matrix. Results outside of the acceptable range are automatically not appended in Data Frame storing the output data.

On the other hand, the sensitivity analysis performed to assess different initial conditions (scenarios) by changing the criteria's weights provided valuable insights into the model reliability and the soundness of the most likely decisions to be taken. Applying uncertainty to the criteria within global (ordinal and cardinal) weighting decreases the failure probability of making a biased decision, which is considered various simulated scenarios in this study.

Results show that buildings with resilience scores higher than 6.2/9.0 have more consistent output in the face of different scenarios. It seems that when the resilience score is lower than 6.2/9.0, there are more dispersed results by the higher standard deviation (above 0.79). It is the authors' view that those buildings with lower resilience can increase their score by prioritizing investments leading to higher scores in parameters related to economic and organizational indicators, such as insurance against natural disasters, financial plan, economic assessment of downtime, business continuity plan, risk management analysis, disaster recovery plan, routine, post-disaster plans and exercises, learning and updating, destructive event data, responsible, compliance with the existing regulatory scenario, and external standards of resilient construction. The combined URES+ARCDM approach enables the identification of concrete measures that can enhance the overall urban resilience by precisely detecting the weakest point of a given constructed asset compared to other similar assets under given scenarios.

The ARCDM model achieved high reliability, and the model can generate consistent results for varying conditions based on various scenarios and AHP. ARCDM can provide an overview of the scoring and weighting system to allow facility managers to see their problem holistically and approach the solution more realistically.

Furthermore, ARCDM has a more comprehensive application beyond urban resilience, and it can apply to any field of study that requires weighting among various criteria. Additionally, the case study has been done to illustrate the integrated application of both approaches.

The integration of the URES+ARCDM approach has already reached a level of maturity that allows being integrated into a web-based application. Such a platform can add scalability to the proposed solution and accelerate the continuous improvements and adaptation that might be mandatory in different countries and for different types of constructed assets.

Declaration of Competing Interest

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

Appendix A. Urban Resilience Evaluation System (URES)

ID	Dimension	ID	Indicator	ID	Parameters
D1	Environment	I1	Earthquake	P1	Seismic_Zoning_Type_1_Ec8
				P2	Seismic_Zoning_Type_2_Ec8
				P3	Seismic_Vulnerability_Of_Soils_Pdm
				P4	Slope_Of_The_Terrain
				P5	Soil_Type_Ec8
				P6	Distance_To_Cliffs
		I2	Tsunami_and_tidal_effect	P7	Terrain_Altitude
				P8	Distance_To_The_Sea
				P9	Distance_To_The_River
				P10	Natural_Barriers_In_The_Environment
				P11	Manmade_Barriers_In_The_Surroundings
				P12	Movable_Objects
				P13	Building_Rows_Between_The_Coast_And_The_Building
				P14	Susceptibility_To_The_Effect_Of_Direct_Tide_Pdm
		I3	Flood	P15	Relative_Location
				P16	Distance_To_The_River
				P17	Natural_Barriers_In_The_Environment
				P18	Manmade_Barriers_In_The_Surroundings
				P19	Flood_Vulnerability_Pdm
		I4	Fire	P20	Distance_To_Vegetation
				P21	Vegetation_Density
				P22	Vegetation_Maintenance_Status
				P23	Type_Of_Vegetation
				P24	Adjacent_Buildings
				P25	Proximity_To_Industrial_Zone
D2	Economic	I5	Insurance	P26	Insurance_Against_Natural_Disasters
		I6	Financial_and_strategic_implications	P27	Financial_Plan
				P28	Economic_Assessment_Of_Downtime
D3	Organizational	I7	Internal_Organization	P29	Business_Continuity_Plan

(*continued on next page*)

(*continued*)

ID	Dimension	ID	Indicator	ID	Parameters
				P30	Risk_Management_Analysis
				P31	Disaster_Recovery_Plan
				P32	Routine
				P33	Post_Disaster_Plans_And_Exercises
				P34	Learning_And_Updating
				P35	Destructive_Event_Data
				P36	Responsible
		I8	External_Organization	P37	Compliance_With_The_Existing_Regulatory_Scenario
				P38	External_Standards_Of_Resilient_Construction
D4	Social	I9	Emergency_infrastructures	P39	Access_To_Police_Stations
				P40	Access_To_Fire_Stations
				P41	Access_To_Emergency_Infrastructure
				P42	Access_To_Hospitals_And_Health_Centers
		I10	Social_responsability	P43	Occupants
				P44	Disclosure
				P45	Social_Vulnerability
D5	Technical	I11	Conservation	P46	Year_Of_Construction
				P47	Structural_System
				P48	Conservation_Status
		I12	Accessibility	P49	Building_Density
				P50	Alternative_Routes
				P51	Street_Features
		I13	Building_seismic_safety	P52	Irregularity_In_The_Plant
				P53	Height_Irregularity
				P54	Interaction_With_Adjacent_Buildings
				P55	Uneven_Slabs
				P56	Expansion_Joints
		I14	Building_security_against_fire	P57	Spacing_Between_Spans
				P58	Gas_Installations
				P59	Smoke_Evacuation_And_Control_Systems
				P60	Intrinsic_Means_Of_Combat
				P61	Electrical_Installations
				P62	Fire_Compartmentation
				P63	Security_Team
				P64	Outdoor_Fire_Hydrants
				P65	Emergency_Signage_And_Lighting
				P66	Fire_Extinguishers
				P67	Fire_Detection_And_Alarm
				P68	Escape_Paths
		I15	Building_security_against_flooding	P69	Barriers
				P70	Flood_Pumping_Systems
				P71	Exposure_Of_The_Walls
				P72	Number_Of_Floors_Flood
		I16	Building_security_against_tsunamis	P73	Number_Of_Floors_Tsunami
				P74	Orientation
				P75	Ground_Floor_Hydrodynamics

Appendix B. Output of 50 ARCDM runs organized in terms of dimensions

#	Point of view	D1	D2	D3	D4	D5
22	Environment	0.622	0.038	0.26	0.058	0.047
26	Environment	0.62	0.013	0.136	0.143	0.132
32	Environment	0.582	0.142	0.168	0.085	0.032
47	Environment	0.569	0.086	0.031	0.2	0.138
14	Environment	0.545	0.04	0.125	0.244	0.027
36	Environment	0.505	0.019	0.183	0.037	0.251
1	Environment	0.485	0.112	0.041	0.03	0.371
27	Environment	0.445	0.071	0.047	0.357	0.076
4	Environment	0.431	0.186	0.081	0.273	0.028
2	Environment	0.423	0.027	0.14	0.206	0.195
19	Economic	0.391	0.402	0.073	0.045	0.113
37	Economic	0.351	0.409	0.142	0.037	0.038
8	Economic	0.302	0.494	0.052	0.129	0.031
46	Economic	0.258	0.412	0.017	0.094	0.225
42	Economic	0.242	0.543	0.15	0.042	0.024
11	Economic	0.157	0.632	0.064	0.042	0.164
45	Economic	0.085	0.487	0.273	0.025	0.111
28	Economic	0.041	0.382	0.023	0.179	0.362
34	Economic	0.041	0.374	0.238	0.044	0.307
5	Economic	0.039	0.651	0.094	0.109	0.153
48	Economic	0.029	0.57	0.269	0.065	0.076
23	Organizational	0.21	0.298	0.387	0.071	0.019

(*continued on next page*)

(*continued*)

#	Point of view	D1	D2	D3	D4	D5
16	Organizational	0.176	0.304	0.431	0.061	0.016
50	Organizational	0.157	0.289	0.402	0.049	0.058
13	Organizational	0.13	0.024	0.548	0.032	0.32
41	Organizational	0.098	0.11	0.664	0.109	0.028
40	Organizational	0.078	0.03	0.502	0.104	0.313
12	Organizational	0.037	0.184	0.516	0.236	0.028
20	Organizational	0.031	0.273	0.43	0.058	0.218
43	Organizational	0.02	0.125	0.697	0.207	0.033
7	Social	0.33	0.121	0.014	0.413	0.14
3	Social	0.29	0.034	0.098	0.379	0.2
24	Social	0.249	0.089	0.026	0.578	0.05
10	Social	0.211	0.136	0.015	0.594	0.085
49	Social	0.171	0.042	0.157	0.603	0.033
15	Social	0.12	0.324	0.076	0.474	0.013
35	Social	0.101	0.275	0.015	0.456	0.171
44	Social	0.085	0.288	0.023	0.466	0.126
9	Social	0.067	0.017	0.21	0.364	0.327
29	Social	0.061	0.196	0.346	0.38	0.027
33	Social	0.061	0.02	0.052	0.56	0.337
6	Social	0.044	0.022	0.114	0.403	0.417
18	Social	0.034	0.239	0.175	0.51	0.051
25	Technical	0.252	0.04	0.063	0.046	0.657
21	Technical	0.195	0.022	0.258	0.064	0.457
31	Technical	0.176	0.057	0.294	0.091	0.387
30	Technical	0.074	0.252	0.02	0.237	0.424
39	Technical	0.051	0.266	0.018	0.218	0.416
38	Technical	0.035	0.167	0.155	0.048	0.65
17	Technical	0.026	0.079	0.282	0.102	0.533

Appendix C. Output of 50 ARCDM runs for each building (B1-B11) of the portfolio

#	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
1	4.9335	5.9946	6.854	6.2594	5.7989	7.7736	5.6585	7.1604	6.738	6.4111	6.4525
2	4.808	5.1933	6.2926	5.6762	5.1388	6.7732	5.3276	6.6879	5.9823	6.0471	6.2067
3	5.1041	5.4617	6.5785	5.7786	5.2828	7.7308	5.8205	7.1556	6.5888	6.3066	6.0529
4	5.5151	5.7744	7.2253	6.6416	6.0408	7.7038	5.1859	7.8465	6.3843	5.7042	4.2409
5	2.093	2.6131	4.8277	3.9925	2.8892	7.7596	2.7961	6.336	6.2991	5.4047	5.3764
6	4.6602	5.0059	5.8869	5.1604	4.4647	7.6653	6.1339	6.2426	6.285	6.0695	6.6352
7	6.0267	6.5173	7.4353	6.7728	6.3583	7.7116	5.605	7.4587	6.4592	6.2356	5.6187
8	3.1985	4.1286	5.7352	5.2259	3.3871	7.5005	4.1359	7.5062	7.1179	4.8446	4.5151
9	5.0738	6.4392	7.0168	6.233	5.759	8.1342	5.7661	7.0553	6.4451	5.9617	5.8949
10	6.4039	6.9816	7.7705	7.2863	6.668	8.4264	5.9372	8.1391	7.2874	6.2088	5.3279
11	2.4422	3.141	5.3406	4.5096	3.5152	7.8065	3.2217	6.455	6.3143	5.6843	5.6947
12	2.2869	3.4284	4.5161	3.6535	2.6277	7.3731	3.201	6.5977	6.5047	4.8824	4.8235
13	2.8356	5.8499	6.2523	4.6203	4.2814	7.3441	4.7992	5.809	5.7434	5.4284	5.4527
14	5.8634	5.1155	7.3874	6.7635	6.5061	7.5252	5.5668	8.2925	5.5118	5.6451	4.4363
15	5.0723	5.0427	6.447	6.0056	5.3583	7.7596	4.3108	7.1966	6.1395	5.3113	4.5832
16	2.2561	3.876	5.2823	4.2805	3.1257	6.642	3.5357	6.0953	5.3225	3.899	3.5914
17	3.637	5.8636	6.3582	5.2862	4.5595	7.7601	6.0479	5.8512	6.014	5.5273	6.36
18	4.7332	5.0597	6.1279	5.5952	5.0147	7.9378	4.2384	7.1017	6.5272	5.5723	5.0124
19	3.4961	4.7514	6.0685	5.4811	3.8798	7.6877	4.4183	7.7796	7.3787	5.2976	4.9767
20	2.0955	4.0463	5.0961	4.2829	2.876	8.4191	3.3838	7.5935	7.4768	5.2087	5.2042
21	4.0091	6.3324	6.8755	5.3606	5.0223	7.3767	6.1078	6.4099	6.0898	5.9802	6.3319
22	4.3423	6.2136	7.0304	5.9324	5.6483	7.2161	5.1097	7.0692	6.6519	6.4766	5.9446
23	2.6066	4.1164	5.2135	4.1848	3.6913	6.2314	3.1503	5.259	4.9802	4.6568	4.5111
24	4.8376	4.3647	5.9951	4.939	4.4486	6.8867	5.5799	6.4542	6.0171	6.2342	5.8084
25	4.2808	6.3742	7.7059	5.9564	5.6551	8.6281	6.8052	8.209	7.5387	7.3551	6.9863
26	5.649	5.9865	7.3025	6.667	6.4836	6.8151	5.6959	7.3583	5.8504	6.0396	5.2496
27	5.53	6.3141	7.3822	6.4556	6.0186	7.9232	5.8531	7.7711	7.1238	6.8139	6.031
28	3.2709	4.4304	5.9991	4.8631	4.3134	7.604	4.3356	6.5239	6.1915	5.7503	5.5079
29	4.1264	5.5563	6.2427	5.4555	4.7826	7.3195	4.2623	6.4397	5.8626	4.6923	4.123
30	3.6569	4.8264	6.341	5.5063	4.3981	8.1665	5.7616	7.4628	7.2056	5.7861	5.8681
31	3.6972	5.1342	5.8108	4.8772	4.2912	7.9007	5.1404	7.0869	7.0536	6.1518	6.5313
32	4.6637	5.635	6.573	6.0803	5.3689	7.0866	4.7189	7.4741	6.8281	6.0215	5.7724
33	4.947	5.5626	6.7289	5.1758	4.6278	7.5508	6.7455	6.566	6.4099	6.7387	6.807
34	2.5505	4.179	5.2525	4.7176	3.1919	8.42	4.2002	7.5168	7.5946	4.9548	5.2298
35	4.1517	4.0868	5.6955	4.9756	3.9833	7.2981	5.241	6.5326	6.3561	5.6251	5.6738
36	4.4942	5.8069	6.7061	6.0177	5.5499	7.4772	5.193	7.2513	6.6549	6.3767	6.2089
37	3.069	3.247	5.5973	4.6535	3.9667	6.8457	3.5888	6.4643	5.1388	5.0126	4.4768
38	3.3827	5.1333	5.6011	4.3065	3.4113	8.6068	4.1771	7.0122	6.9655	6.1067	5.8995
39	3.3368	4.4817	5.7821	4.3487	3.7136	7.4098	5.1416	6.1511	6.2231	6.0957	6.3392
40	2.568	5.1453	5.6855	4.1144	3.7591	6.7675	4.245	5.2938	5.1953	4.9969	4.8315

(*continued on next page*)

(*continued*)

#	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
41	2.2204	4.4308	5.0143	3.8981	3.3142	6.5549	3.2454	5.4875	5.3326	4.3517	4.3229
42	2.7593	3.6437	5.774	5.1971	3.3655	7.4903	3.8282	7.4895	6.2666	4.0358	3.597
43	2.149	3.1106	4.3095	3.4775	2.7185	8.3824	2.6131	7.4232	7.3492	5.8373	5.8196
44	5.2452	5.5966	6.594	6.0898	5.4136	7.9197	4.6113	7.2036	6.3991	5.3882	4.5348
45	1.8258	3.2354	4.8397	3.6103	2.8275	6.5652	2.7603	5.2139	5.0513	4.6927	4.5985
46	3.6042	4.6301	5.8727	5.5354	3.7994	7.5349	4.7799	7.2404	7.0001	4.9199	5.1129
47	5.3912	6.2601	7.4448	6.5999	6.1541	7.9787	5.5555	7.9674	6.8801	6.4856	5.4764
48	1.8329	3.7169	5.0798	4.5135	2.5377	7.6777	3.1932	6.8967	6.7922	3.8506	3.806
49	4.5283	4.041	5.5787	4.4641	3.9383	6.2091	5.4906	5.7665	5.2737	5.5882	5.5082
50	2.191	4.2519	5.1997	4.2569	3.1195	6.5777	3.5809	5.7746	5.5342	3.9622	3.7262

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