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Simulation-Based Automation for Consistent Asset Management Decisions: Pilot-test Application in Urban Resilience Assessments

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Abstract Decision-makers in public and private asset-intensive organizations strive to consistently deliver and maximize benefits in the face of competing investment alternatives. The intended aim of these decisions is to satisfy organizational objectives and stakeholders' needs and expectations. This paper proposes a decision-making support tool based on a novel multi-criteria decision analysis (MCDA) approach using Analytic Hierarchy Process (AHP). This support tool enables Automated Rational and Consistent Decision Making (ARCDM) by simulating scenarios and behaviors of a virtual Panel of Experts (PoE) with different perspectives. These scenarios are organized into a pairwise multi-layer decision-making matrix that supersedes the need for a PoE. The proposed decision-making support tool is tested in 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 to be weighted. A building portfolio with seven different types of use (hospitals, schools, industrial facilities, shopping centers, hotels, research facilities, and residential) is used as a testbed for applying the support tool. The successful application of the proposed ARCDM support tool on the URES breakdown structure shows that similar applications can be made in other asset management decision making contexts, such as feasibility studies, design, construction, operation and maintenance, rehabilitation, and disposal of constructed assets that comprise the built environment for cities and societies.

1 Introduction

Decision-making is a fundamental issue of infrastructure asset management, especially with the increasing diversity and complexity of this particular type of man-made assets, plus the requirements of the everchanging changing profile of their stakeholders. Those involved in the life-cycle management of constructed assets (e.g., infrastructure, buildings, and advanced facilities) are expected to promote the grasping of opportunities and an enhanced balancing of costs, risks, and performance throughout the life cycle of asset portfolios. This balancing is an iterative decision-making process [1] with the aim of optimizing life cycle costs [2] for a

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given required level of performance [3] and considering a level of risk that is deemed acceptable or tolerable [4].

There are various techniques to support asset management and risk management decisions. Decision-making as part of asset management requires a comprehensive understanding of the problem and how and where to apply adequate responses to those problems. This decision process is the case of multi-criteria decision analysis (MCDA), which is suitable for multi-dimensional infrastructure asset management problems [5]. Other examples of decision support frameworks are Markov decision process (MDP) that can be used, e.g., in the context of maintenance of infrastructure assets [6]. Multiattribute utility theory (MAUT) and portfolio management method are other examples [6].

This paper studies an Automated Rational and Consistent Decision Making (ARCDM) approach that simulates scenarios and behaviors of a virtual Panel of Experts (PoE) with different perspectives. Among the envisaged advantages of the proposed ARCDM model is that it decreases time and effort to weight the criteria in decision-making processes.

The paper is organized into five sections that follow the sequence of the research process. Section 2 discusses the research gap in the field of decision making and why the novel ARCDM approach can help fill this gap. Section 3 presents the case study that is used as a pilot-test application of the ARCDM decision-making approach. This case study is an evaluation system that includes decision-making problems to rate the resilience of the built environment. Section 4 includes a critical analysis of how the ARCDM algorithm works to reach rational and consistent decision-making using Python and its relevance for scenario-based analysis in the context of the application of an urban resilience evaluation system to 11 buildings of 7 different use types. Section 5 presents the conclusions, highlighting the main findings and future research opportunities.

2 Automated Rational and Consistent Decision Making (ARCDM) model

Multi-criteria decision analysis (MCDA) aims to weight the criteria to reduce inconsistency and avoid biased decision-making to reach more robust weighting among criteria to rank alternatives. MCDA is beneficial in the context of UR, in which various indicators are needed to be weighted and compare to each other, and reach the final raking of the constructed assets; by ranking their indicators to enable decision-makers to identify the real weaknesses of CAs and invest in improving them in terms of preparedness exposing to disruptions. In this context, Analytic Hierarchy Process (AHP) [7] is the most practical approach that allows pairwise comparison and can make consistency coding as part of the automation goal of this study. Moreover, AHP is the most known MCDA method among scholars, and it is more practical to use in the urban resilience context.

The authors suggest that the body of knowledge for decision-making can be enriched by integrating automated decision-making approaches. The authors suggest that this type of approach can be suitable in the context of initial assessments of different scenarios at an early stage of problem structuring without panels of experts or resource-consuming surveys. The authors envisage that this approach can also be beneficial when there is a need to make iterative analyses to achieve proper levels of robustness. The hypothesis to be tested is that this suggested approach is suitable for multi-criteria decision analysis problems.

The proposed Automated Rational and Consistent Decision Making (ARCDM) approach simulates scenarios and behaviors of a virtual Panel of Experts (PoE) with different perspectives. Among the envisaged advantages of the proposed ARCDM model is that it decreases time and effort spend on weighting the criteria in decision-making processes.

ARCDM consists of a weighting model that is based on the Analytic hierarchy process (AHP) and is established using Python [8] and additional packages such as Pandas [9] and Numpy [10]. In this model, a breakdown structure of evaluation metrics defines the AHP model's criteria, where the alternatives will be scored and compared.

ARCDM model can be defined as a weighting system to define the scenarios and as a tool for testing the problem structuring method without using resources in surveys involving a panel of experts. It can work weighting the criteria of asset management to facilitate the decision-making process and reduce the amount of time that needs to spend on the decision-making process to validate where and how to allocate the budget. Urban resilience as a part of asset management also requires increasing the recovery capacity and speed of the constructed assets based on various indicators and parameters. These indicators need to be weighted where ARCDM can assist in weighting them in a small amount of time.

The weighting method is based on an improved AHP approach that considers various stakeholders with various perspectives towards the asset management domain. ARCDM integrates scenario-based simulations and sensitivity analysis to increase decision-making stability by considering consistency in the decision model.

When the weighting varies for different metrics, it can be described as scenarios to indicate different points of view. The proposed ARCDM model has the internal normalization parameter that will combine various points of view when set more than the number one to create a combined multidisciplinary point of view. That is to say, by iterating two times rather than one time, it will combine different groups of metrics as a combined weighting or even more than one scenario. In this context, the variety of weighting and where the dominant is located defines the scenario-based simulation.

Scenarios are defined based on AHP using only metrics to weight and then to be used for weighting alternatives and verify the application and the case studies. Scenarios can be defined using a traditional methodology like a panel of experts pairwise comparison matrixes. This paper aims to establish an alternative with low resource consumptions that relies on a mechanism to get an automated rational and consistent decision making (ARCDM) conveying diverse points of view from multiple experts. When obtained results are a rational decision, and there is one dimension that is always overweighted, that means it is biased in that decision, which is the case of a real panel of experts. This biased output is considered a scenario-based simulation in this article.

This study established and verified the ARCDM algorithm considering consistency index and ratios that have been tested by the following class attribute in python to access each class attribute by other callings:

```
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 initially creates an identity matrix that is going to be filled by random numbers among AHP options ((1/9), (1/8), …, 1, …, 8, 9) [7]. Then there will be a consistency check for each iteration to reach an acceptable consistency ratio. This algorithm enables to development of different scenarios devoid of time and resources with the capacity of iterating by the different levels of the normalization process to get desired results. In this study, we consider normalization iteration equal to one to have a more biased ARCDM that increases the variability of the study. The following python class demonstrate the random choice among defined AHP scores and check the consistency ratio for the rational and consistence decision-making process:

```
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)
    MAT = np.identity(n)
    for i in range(len(MAT)):
        for j in range(len(MAT)):
            if i < j:
                MAT [i][j] = rd.choice(options)
    return MAT

def cmc(n):
    MAT = mc(n)
    while AHP("MAT ", MAT).CR > 0.1:
        MAT = mc(n)
    return MAT
```

ARCDM takes the decision only when the consistency ratio is less than ten percent and returns the priority weighting vector. This scenario generator can be used in different problems by applying various criteria and options in multi-layer decision-level complexity. The while loop with the comparison of more than 0.1 indicates that as far as the consistency ratio is higher than the proposed threshold, there is a need to take a new decision with the “def mc(n):”. Hence, the result came out at once the consistency reach less than 10 percent based on Saaty discussion on AHP[7].

3. Pilot-test case study: evaluation of urban resilience

Several authors have been studying decision-making problems related to urban resilience [11]–[13]. The authors use urban resilience as a pilot-case application of the proposed ARCDM approach.

Disaster risks, both from natural and man-made sources, are increasing globally and lead to disruptive events with adverse effects on society and the economy. Forecasting disruptions and awareness are thus critical to decrease the exposure of constructed assets to these disruptions in the combination of the interdependency of aging infrastructures, particularly with high population growth, create a harder situation for resilient societies facing disruptions of different sources.

Constructed assets are prone to disruptions both natural and man-made, such as those wars [14] or various forms of man-made disruptions [15]–[19]. The vulnerability and exposure of the CAs to these risks increase the frequency and intensity of disruptions that cause social and economic losses [20]. These disruptions literature have been reviewed qualitatively and quantitatively [21]. Another approach has been developed to integrate the resilience concept in asset management decisions and planning [22], [23].

Cities and societies are exposed to several risks that require mitigation through suitable actions throughout the entire life-cycle of Constructed Assets (CAs) that comprise the built environment. Resilience-related actions enable cities to respond properly to these challenges by [13], [24], [25]: i) absorbing disruption; ii) decreasing the impacts of disruption; iii) adapting to changes; iv) improving urban preparedness against future risks. To this extent, these four are the recovery steps or urban resilience, which are indeed achievable through proper decision-making procedures.

Urban resilience has started to draw attention from the Architecture, Engineering, Construction and Operation (AECO) professionals considering decreasing risks and budgeting prioritization [26] regarding constructed assets that are in an important place for the social functioning and need to be preserved for future generations and achieving the UN sustainable development goals. This is the case of transportation infrastructures, hospitals, energy, water, education, commercial, touristic, offices, and residential buildings.

Urban resilience is a multidisciplinary concept that includes economic-social, environmental, infrastructural, physical, organizational, and political-regulatory aspects [27]–[32]. Resilience management can comprise complex cost-benefit analysis, and various contributions have been made to make resilience assessments more practical [19], [29], [33], [34].

However, these systems often involve multiple dimensions and a wide range of indicators with different levels of importance. Appropriate decision-making support tools are needed to facilitate the weighting and prioritization processes involved in these decisions.

Urban Sustainability indicates reaching the best possible cooperation among cost, performance, and risk over the life-cycle even though avoiding adverse long-term impacts causing by fallacious short-term decisions [35], [36]. In urban resilience and constructed asset context, asset management is a long-term enhanced methodology to adapt the organizational objectives to detailed, high-level, and long-standing action plans [35], [36]. Asset management has materialized as a global multidisciplinary management approach once the ISO 55000 international series of standards in 2014 has been published [37] to optimize cost, performance, risks, resources, and benefits over the asset life-cycle [38]. Urban resilience is a fundamental aspect of sound asset management as it contributes significantly to optimize the recovery of the constructed assets' performance facing disruptions.

Various studies inspired the scoring system to enhance the performance by implementing stochastic techniques to natural disaster resilience [39] and a risk management approach [40].

The pilot-case study used in testing the ARCDM approach is an Urban Resilience Evaluation System (URES) that covers various natural and man-made disasters given preserving constructed assets (CAs) and increasing their life cycles and the value generated from there. URES involves five dimensions (Environment, Economic, Organizational, Social, and Technical), 16 indicators, and 75 parameters that have been detailed elsewhere [41]. The original URES relies on scorings and weightings based on surveys to capture various perspectives, but there is a need to deal with the inevitably involved bias. This study seeks to reduce that bias by using algorithms enabling rational and consistent decisions without the involvement of a panel of experts. The hypothesis is that this approach enables an optimized formulation and structuring of the problem and less uncertainty in achieving the intended outcomes, e.g., budget prioritization to renew CAs given lower disruption recovery rates or operational efficiency.

4 Result and discussion

The pilot-test case study used a portfolio of 11 buildings in Portugal, representing seven different use types (hospitals, schools, industrial facilities, research facilities, shopping centers, hotels, and residential buildings) that have been studied, testing the applicability of the proposed ARCDM scenario-based weighting system. By running the model for 50 scenarios and obtaining the output, getting each case study score based on the weighting procedure and sorting based on the lowest resilience score is the most vulnerable one compared to the others. In this context, the outputs are organized for the different points of view in which the output from the environment scenario is shown in Table 1. In this case, the dimension "Environment" is weighted more than 40 percent of the total weighting of all dimensions, which is equal to one. The output of all the 50 various scenarios of the stochastic ARCDM model, for all indicators and dimensions, consisting of five dimensions (D1-D5) for each building portfolio (B1-B11).

Table 1. Output of results for the environmental point of view

#	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 weight of each dimension has been distributed and averaged within each group to understand how they are distributed to get the score for each scenario (Fig. 1). The cumulative weight of each scenario needs to be equal to one or 100%, however, in which the ARCDM is working based on AHP pairwise comparison scoring and ranking system, this unit cumulative may slightly be more than or less than one which is quite normal, and it can normalize based on the application needs.

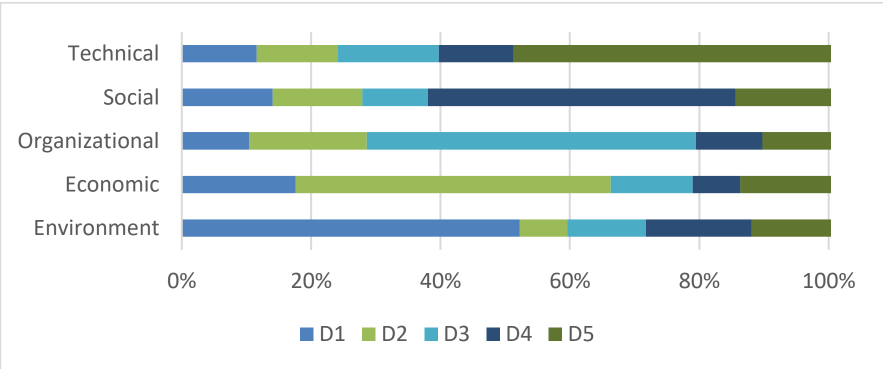


Fig. 1 Weight distribution of dimensions on various scenario base

The outputs show that in the different scenarios in the stochastic approach, we reach various scores with high variation for each case study, and the result is shown in Table 2. To this extent, it can be seen that there is substantial variation between the min and max of each pilot case result, and the standard deviations of constructed assets are varied from 0.6 to 1.28. If the same statistical analysis is done for each dimension point of view, the resilience score will not equal. That is to say, and it will affect the priority of the building for budget allocation when a CA has a low resilience score. Nevertheless, the building functionality should be considered; for example, the resilience of hospitals should be higher than shopping mall in which resilience score should compare based on the priority of service for society; this discussion is another subject that is out of the scope of this article and will be considered in future studies.

Table 2. 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

To this extend, 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 shown in

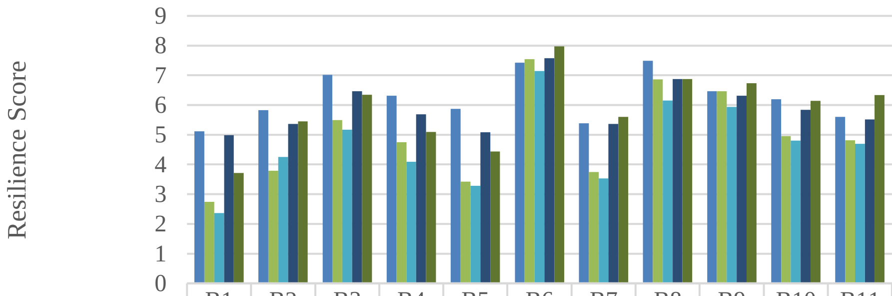
Table 3. That is to mean, i.e., in all scenarios, B1 is the lowest because of being a residential building, then B7 follows in the next scenario of "Environment" and followed by B5 in the other scenarios.

Another example would be having B4 in high priority in the "Technical" scenario while it is located in low priority in the "Environment" aspect. These outputs demonstrate that based on national priority and the organization management point of view, it can significantly affect the ranking of the different constructed assets.

This followed by the bar chart illustration of the five categorized scenarios average in Fig. 2 to be explained as none ordered based on the buildings' scores; i.e., in the B6, B8, B9, there is resilience score stability among various scenarios while this is uncertainty in case B1, B2, B3, B4, B5, and B7, and the remaining are in located between these two. To this extend, the dimension as discussed in previous sections are the criteria to create a weighting reference and compare when we get a biased result; and interestingly there is biased weighting in all outputs, which leads to group them and rank the building based on them in different scenarios.

Table 3. 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. 2 Five categorized scenarios comparison chart

Based on the obtained results, the Environment aspect increases the resilience score of the building due to just considering the locality of the CAs and is not considering the ongoing capability of the other dimensions. On the other hand, the scenarios based on Economic and Organizational dimensions give lower scores. At the same time, there are other scenarios based on Technical and Social aspects that need to be considered in the scoring system. Based on Technical and Social aspects and their limitations, they are not describing the CAs resilience score in the same manner in wherein same cases; the resilience score is less than scenarios based on Organizational, Environment, and Economic aspects and, in other cases, is more. Therefore, the final resilience score should be a combination of the ARCDM based on the organizational needs and their prospects toward urban resilience.

In this study, the scenario analysis was performed at level zero (dimensions) of the decision hierarchy, in which future study can be performed in other levels (indicators and parameters). The stochastic approach enables the model to have flexibility in various scenarios at different decision-making procedures. Also, cost and budget analysis in the different life-cycle can help further the model's preciseness and add the uncertainty in the initial assumptions to make the model more robust.

5 Conclusions

The decision-making processes in asset management are known to be multi-dimensional and complex. This study aims to contribute with a novel automated decision-analysis method to minimizes the amount of effort and resources needed to develop the weightings of decision criteria and scoring the alternatives in such processes. This optimization is achieved by introducing scenarios-based automated rational and consistent decision-making simulations (ARCDM).

ARCDM uses AHP to perform decision making as a non-expert based for the development phase of the problem structuring. ARCDM can generate scenario-based decision-making based on AHP in multi-layer/level problems to weight each of the metrics involved.

Urban Resilience Evaluation System (URES) criteria in our decision model are the dimensions and indicators and the parameters not involved in weighting in ARCDM for simplicity's sake accelerate the result achievement and decrease the computational load. This method will help the facilitator to develop a more mature model for the weighting system.

The current body of knowledge in urban resilience decision-making has gaps and can be extended by integrating the novel ARCDM approach for automated decision-making. This article discusses this novel approach and its advantages, such as scenario-based decision-making simulation when there is limited access to a panel of experts at the initial phase of the problem structuring. This novel ARCDM approach is beneficial once there is a need to constantly analyze to achieve appropriate levels of robustness.

This paper presents and discusses Automated Rational and Consistent decision-making (ARCDM) to an empirical case studies of 11 buildings in Portugal to test the model's validity. This model demonstrated that scenario analysis is crucial for simulating stochastic subjective judgment and enhancing the resilience of constructed assets.

Sensitivity analysis needs to perform to assess the different point of view approaches (addressed as the scenario in this article) by modifying the criteria's weights, and how this can improve the model reliability and the final decision to be taken, as well as the uncertainty of the criteria within global (ordinal and cardinal) to decrease the probability of failure.

The ARCDM model reached a high level of consistency, and the model generates reliable results for different definable conditions based on the required various scenarios in the problem structuring phase. Another characteristic of this model is considering uncertainty in stochastic analysis that takes all of the indicators and parameters based on their probability distribution and inversed cumulative probability methodology. The ARCDM can give insight toward the weighting and scoring to enable the manager to see their problem more comprehensively and approach the solution more practically.

Furthermore, this study has characteristic limitations, which need to recognize more indicators and parameters to describe them in different standard systems to be calibrated, which could be count as a future study.

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