Paper 42

Resilience rating system for buildings against natural hazards

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Abstract In recent decades, there has been an increase in the frequency and intensity of natural disasters. The worldwide growth of population, and consequently of infrastructure, increases the exposure to risks of this type. The expectation that the frequency of such disasters will increase amplifies the need to act today, to minimize the associated economic risks and costs in the future. The ability of buildings to maintain or restore their functionality after disruptive events, within a certain period, has increasingly attracted the attention of academics and professionals. This work intends to study and develop a method to measure the resilience of built assets. Therefore, a resilience classification system is proposed, which assesses resilience according to 5 dimensions (environmental, economic, organizational, social, and technical), which are subdivided into 16 indicators and 75 parameters. This proposal is based on various existent systems such as REDi or Building Scorecard, and its applicability is tested with 11 buildings with varied uses. The results are analysed via SPSS using a Pearson correlation coefficient matrix and clustering techniques. These empirical cases allowed improvements in the system initially proposed. The proposed resilience classification system allows classifying and comparing the performance of buildings, identifying their vulnerabilities, essential information to establish investment priorities. Multiple stakeholders are involved in the life cycle of buildings that may benefit from the developed proposal. The work carried out is in its early stages of development and includes the identification of improvements to be developed in future work.

1 Introduction

The risks induced by natural and man-made disasters are inherently present throughout the entire lifecycle of buildings and engineering works. The built environment is thus vulnerable to risks that are impossible to eliminate, and this prompts the need for managing the resilience of constructed assets.

The impact of climate change on society, the construction sector, and individuals is widely debated. Various studies show that the frequency and intensity of natural disasters are increasing and that this, combined with high vulnerability and exposure, is also leading to increased economic and social losses [1-2]. According to ISO/TR 22845 the frequency of these events is not expected to decrease, and this

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amplifies the need for action today to mitigate disaster risks in the future. For these reasons and given of achieving the sustainable development goals, increasing attention is being drawn to the resilience of buildings and civil engineering works.
Nowadays, the resilience of buildings is defined as “the ability to protect, maintain, or restore the functionality of, value of, and income generated by a building after a damaging event or circumstance within a prescribed time frame” [3]. The use of this concept is based on four pillars basic: i) resilience as trauma recovery and balance restoration; ii) resilience as synonymous with robustness; iii) resilience as the opposite of fragility; and iv) resilience as network architectures that can sustain the ability to adapt to future surprises as conditions evolve. For an infrastructure to have a high level of resilience it is necessary to be concerned with the four concepts, that is, pre-event drastic (preparation and mitigation) and post-event concerns (recovery and speed). It is worth noting the efforts currently involved in producing resilience-related international standards by both academics and various stakeholders such as construction project owners, managers, insurers, and municipalities. These standards are expected to enhance the understanding of resilience issues and allow comparison of pre and post-disaster measures of various infrastructures and building assets. In recent years, the development of building sustainability and resilience classification systems, such as ARMS [3], LiderA [4], REDI [5], RELi [6], Building Scorecard UN ARISE, [7], etc., has 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 quite consensual [8]. The recently published international standard ISO/TR 22845 somehow helps to fill this gap within the context of buildings and civil engineering works. It establishes some core concepts and countermeasures and covers natural risks (e.g. earthquakes and climatic effects) and risks induced by man (e.g. terrorism). However, it does not solve all the difficulties in establishing resilience dimensions and metrics.

The overall goal of the present article is to: i) harmonize resilience metrics for buildings; ii) identify building vulnerabilities; and iii) streamline communication between various stakeholders. The interconnection of the objectives defined above is expected to be achieved by creating a multidisciplinary resilience rating system for buildings against natural hazards, thoroughly detailed bellow. The proposal builds upon ISO/TR 22845, ISO 31000 and the Sendai Framework for Disaster Risk Reduction.

2 Resilience rating system

2.1 Design and development

This chapter proposes a resilience classification system, with standardized metrics and simplified classification to understand and assess the resilience of buildings regarding natural disasters. The system is developed based on a holistic, comprehensive and systematic approach, allowing its application to different types of buildings (school, industrial, commercial, residential, hotel, etc.), at any stage of its life cycle (project, construction, use, etc.). This tool simplifies the identification of the building's resilience and weaknesses, allowing easy communication and comparison, either over time concerning the same building or others. It is intended for everyone involved in the construction, maintenance and building management processes, such as designers, contractors, project managers, construction owners and even insurance companies and municipalities, whose need to determine the resilience of the building and the community is high.

A deep approach at various levels is considered necessary, seeking to minimize interdependencies, and to achieve this, a three-level hierarchical structure was selected, consisting of dimensions, indicators and parameters. Each parameter is evaluated according to determined evaluation criteria. This work is recursive, with items and evaluation criteria calibrated and improved at each iteration.

The process is carried out with conceptual support from selected articles for this purpose. Their selection was based on the use of the keywords "resilience", "buildings", "natural hazard", "indicators", "seismic resilience", "climate hazard" on the ScienceDirect platform whose results there were about 700. They are segregated based on publications and subjects, leaving only 50 for the literature review. Concepts were subsequently extracted from 9 selected documents: Almufti & Willford (2013), Asadzadeh & Kötter (2016), Burroughs (2017), Engle et al. (2013), Atrachali & Ghafory-ashtiany, et al., (2019), UN ARISE (2020), USGBC (2018), Verrucci et al. (2003) and World Economic Forum (2021). Their choice considers: i) their relevance to natural hazards; ii) their relevance to the built environment; iii) the justification given for the importance of the defined parameters; iv) recent documents.

The definition of indicators and parameters aims at assessing resilience and facilitating communication and consultation procedures. The parameters subdivide indicators, and, in their turn, each set of indicators express in a more detailed manner each of the dimensions mentioned above. Their selection was substantiated through a literature review, bearing in mind that: (i) the selected parameters are possible to measure; (ii) information is available for their quantification and (iii) it is desirable to avoid overlaps or repetition of metrics. An initial list of more than 200 indicators was revised and reduced to 16 indicators, subdivided into 75 parameters that best fit the purpose of the intended rating system. The main drivers in the revision process were the elimination of repetitions of indicators and of those expressing a perspective at the level of urban and community concerns but that do not necessarily improve the resilience at the level of the constructed assets. Evaluation criteria were initially established based on thresholds for the different metrics.

The natural disasters covered by the proposed system correspond to disasters whose national exposure is high or medium, adapted from Union & Protection (2019): Earthquakes, floods (urban, river, sea), fires, tsunami.

2.2 Scoring

The proposed rating system builds upon existing resilience scoring systems [3], [5]–[7] and sustainability scoring systems, like LiderA (Portugal), Green Star (Australia), CASBEE (Japan), LEED (United States of America) and BREAM (United Kingdom) that are reasonably matured. A semi-quantitative scoring method is used.

This allows grading progressive levels of performance for each indicator assuring: (i) accessible language, both in terms and concepts, that allows understanding by individuals who work or are qualified in the area of management of facilities and related built assets, (ii) criteria applicable to buildings with different types of use and (iii) identification of the level of attention needed for the analyses of indicators and dimensions. Following [9], the adopted scale complies with recommendations of ISO 11863 for considering five different levels expressed in whole numbers of a digit on a scale of 1,3,5,7 and 9, where 1 corresponds to the worst performance and 9 to the best. This scale allows even levels to be used when the correct assessment is between two levels.

For reasons of simplicity, the weighting of each parameter in the pilot-test proposal is considered of equal importance. This allows the identification of the building's general performance and the performance of individual and unique aspects. For a clearer interpretation of the final score, the numeric scoring can be transposed into resilience classes from F to A ++ (Fig. 1), allowing differentiation of resilience levels to be easily understood and intuitive.

Class	Average score
A++	[8,9]
A+	[7,8[
A	[6,7[
B	[5,6[
C	[4,5[
D	[3,4[
E	[2,3[
F	[1,2[

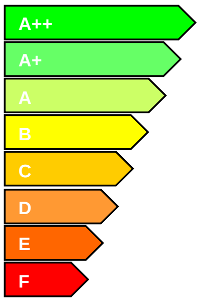


Fig. 1. Proposed rating scale

2.3 Dimensions

The output of the literature review was that the resilience of constructed assets in the face of natural risks could be structured into five dimensions: D1 – environmental; D2 – economic; D3 – organizational; D4 – social; D5 - technical. These dimensions are in line with: (i) the essential pillars for economic, social and environmentally sustainable development defined by the UN in EC0-92 Agenda XXI (United Nations Conference on Environment and Development); (ii) the four technical, organizational, social and economic dimensions defined by Bruneau et al. [10]; and (iii) the dimensions mentioned in various other selected documents (varying from 3 to 10 dimensions), taking into account that different terminologies were used to describe the same characteristic and the need to avoid overlapping concepts.

Table 1 demonstrated the selected dimensions and indicators after the reduction was made.

In total, there are 5 dimensions, 16 indicators and 75 parameters in the system. The following sections provide descriptions of the rating system's contents for each of these dimensions.

Table 1 System's dimensions and indicators

ID	Dimension	ID	Indicator
D1	Environment	I1	Earthquake
		I2	Tsunami and tidal effect
		I3	Flood
		I4	Fire
D2	Economic	I5	Insurance
		I6	Financial and strategic implications
D3	Organizational	I7	Internal Organization
		I8	External Organization
D4	Social	I9	Emergency infrastructures
		I10	Social responsibility
D5	Technical	I11	Conservation
		I12	Accessibility
		I13	Building seismic safety
		I14	Building security against fire
		I15	Building security against flooding
		I16	Building security against tsunamis

2.3.1 Environment

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).

This dimension seeks to foster a broad understanding of environmental issues, focusing on the vulnerability of the area to natural disasters of the upper and middle categories. The parameters were calibrated for the case of Portugal, providing an overview of potential threats as well as the determination of the intrinsic characteristics of the study area, such as altitude, distance to sea and river, slope, etc., since it can increase the risk propensity. The assessment related to natural disasters must be carried out for the present and future, considering that climate change modifies the frequency and intensity of disasters.

2.3.2. Economic

The Economic dimension includes two indicators (I5 – Insurance; I6 - Financial and strategic implications) and 3 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 greatly affect the quality of the building, especially during and after suffering the impacts of a natural disaster [11]. Studies show that good economic management and consistent financial availability improves the response to imposed natural disasters, and the recovery period is reduced. This dimension is related to the owner's monetary capacity in the face of imposed disturbances, including expenses on repairs, losses of assets and monetary losses from temporarily closed activities.

2.3.3 Organizational

The Organizational dimension includes two indicators (I7 - Internal organization; I8 - External organization) and 10 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 capacity in emergency situations, that is, decision making by the owner regarding the identification, monitoring, and risk management. This dimension focuses on the pre-disaster, promoting preventive actions that reduce the impacts of natural disasters, guaranteeing a good performance of the building, minimizing the harmful consequences, and creating the least inconvenience for the users [12]. Topics outside of the owner’s reach were also considered, like compliance with the existing regulatory scenario and the use of other standards of resilience. These indicators ensure construction safety and contribute to the preparation of buildings in the face of existing obstacles, helping to identify and prioritize problems.

2.3.4 Social

The Social dimension includes two indicators (I9 - Emergency infrastructures; I10 - Social responsibility) and 7 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 seeks to relate the building to society and the surrounding community, which are intrinsically related to each other, especially in times of stress whose individual response is difficult to identify and parameterize, but important to consider. Studies in resilient communities show that attentive and sensitive cities to individuals are better prepared for disasters, reducing its consequences [1], the same can be said for buildings. For this reason, factors like the building's social vulnerability, which corresponds to the number of elderly people, children, were considered. Additionally, it is intended to emphasize the role of citizens in response to disasters and the building's proximity to community infrastructures like fire stations, police stations, hospitals, etc.

2.3.5 Technical

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 signalling; 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 characteristics of the building are crucial to guarantee resistance to natural disasters and to minimize the damage caused by them [12]. This dimension derives from technical approaches and relates to the engineering component, which includes structural, security and the assessment of the building's physical vulnerabilities in the face of the natural disasters identified above. The building's redundancy and robustness strategies are included in this dimension, such as improvements beyond the building code or installing protection systems against natural disasters [11]. Intrinsic characteristics of the building like age, number of floors, irregularities, quality of construction, current condition, and state of conservation are considered in this dimension. Characteristics of the surrounding must also be analysed especially because of their impact on post-disaster recoveries [12] like the building accessibility that depends on multiple aspects like the existence of alternative routes, building density and street features.

3 Case Analysis of the system's implementation

The choice of buildings used as case studies was made to test the feasibility of the proposed rating system in different situations. The sample of buildings covers new and old buildings, with or without rehabilitation interventions, higher and lower vulnerability to natural disasters, etc. Bellow are presented the results for 11 buildings: 2 residential buildings (C1 – single-family and C2 - multifamily), 2 schools (C3 – school 1 and C4 – school 2), 1 administrative building (C5 - research campus), 1 hospital (C6), 1 industrial building (C7 - carpentry factory), 2 commercial buildings (C8 – commercial building 1 and C9 - commercial building 2) and 2 hotels (C10 – hotel 1 and C11 – hotel 2). According to Portuguese regulations, this sample covers 7 out of 12 building use types. All the selected buildings are in the metropolitan area of Lisbon due to their ease of travel.

Table 2, indicates in a summarized way, the numerical score and corresponding resilience class for the five dimensions of each case study, derived from the arithmetic mean of the 75 parameters. In short, the hospital building obtained the best rating compared to the other case studies, A+. In the class below, A, there are both commercial buildings and school building 1. In class B, there are the hotels and school building 2. In class C there is multifamily residential building, industrial building and administrative building. The lowest class in this study proved to be D for the residential single-family building.

Table 2. Resilience rating of the case studies

Case studies	Dimensions					Total	
	D1	D2	D3	D4	D5		
C1	6,32	1,00	1,00	7,00	4,18	3,90	D
C2	5,95	2,00	3,75	6,00	6,72	4,89	C
C3	7,97	4,50	4,13	7,00	7,06	6,13	A
C4	7,31	4,00	2,88	6,33	5,64	5,23	B
C5	7,23	1,50	2,50	6,00	5,07	4,46	C
C6	6,73	8,00	7,00	7,67	8,72	7,62	A+
C7	6,11	2,00	2,00	6,42	6,89	4,68	C
C8	8,13	7,00	5,63	7,08	6,91	6,95	A
C9	5,81	7,00	5,63	6,33	7,13	6,38	A
C10	6,63	4,00	4,38	6,17	6,82	5,60	B
C11	5,27	4,00	4,38	5,42	7,44	5,30	B

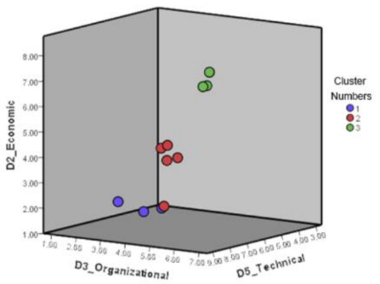
After a first pilot-test application, the classification system was revised and purged from parameters that showed low applicability. An exhaustive analysis of the output results was made with the statistical software SPSS, performing a Pearson correlation analysis and Cluster analysis. The Pearson correlation matrix was made for every system's layer (dimensions, indicators and parameters), and in **Erro! Autorreferência de marcador inválida.** it's possible to see the results for dimensions, which demonstrate a high correlation between D3 - Organizational and D2 - Economic, D2 - Economic and D5 - Technical, and D3 - Organizational and D5 - Technical, moderate correlation between D4 - Social and D1 - Environment, D4 - Social and D2 - Economic and D4 - Social and D3 - Organizational. The remaining showed no significant correlation. The dimensions with high correlation thus need revision in the future to ensure that each dimension has unique and distinctive items, avoiding repeated classifications or unnecessary criteria.

Table 3. Heat map of Pearson's correlation coefficients for dimensions

Pearson correlation	D1	D2	D3	D4	D5
D1		0,23	0,10	0,54	-0,11
D2			**0,93**	0,47	**0,73**
D3				0,31	**0,84**
D4					0,17
D5					

The clustering studies help us identify buildings with the same characteristics based on the clustered data, which is particularly helpful when comparing dimension's results (Fig. 2). Different clustering methods known as hierarchical (agglomerative) and non-hierarchical (K-mean) approaches were used for every system's layer. Results show that the k-means clustering approach narrowed down the outputs and provided the best results. The first cluster includes the residential single family building, administrative building and the industrial building, the second cluster includes the hotels, schools and the residential multi-family building and the third one includes the commercial buildings and the hospital.

Fig. 2. K-mean (**non-hierarchical**) clustering allocation 3D representation of economic, organizational, and technical dimensions



The final scores, shown in Table 2, demonstrate that buildings with a high number of public users, such as hospital and commercial buildings, have higher levels of resilience, followed by hotels and school buildings and, finally, industrial, or residential buildings. In Fig. 3 it's possible to observe the score for each dimension from the first cluster, where the economic and organizational dimension show low scores. This information is in line with expectations, as buildings with no commercial activity or small activity typically have less financial capacity and less administrative resources [13]. The tchnical dimension shows high variance, thanks to different conservation states and other intrinsic building's characteristics, fluctuating from class D to A, where social and environment dimensions show low variance, fluctuating from A to A+. The residential single-family building (C1) proved to be the worst classified on almost all indicators.

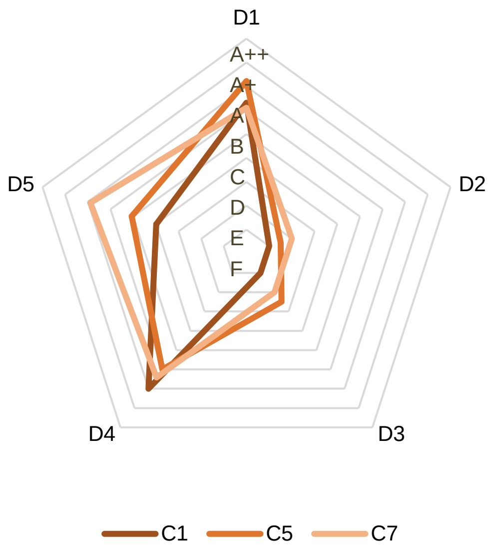


Fig. 3. Dimension's score for the first cluster

4 Conclusion

This paper contributes with a discussion about ways of measuring the resilience of constructed assets, namely based on a resilience rating system comprised of 3 layers, 5 dimensions, 16 indicators and 75 parameters. The proposed rating system covers not only the intrinsic building's qualities but also its interdependencies with the community, surroundings, and users in a post-disaster context. Eleven buildings are used as empirical case applications to test and calibrate the proposed system. The results were analysed with statistical techniques such as Pearson correlation coefficient and clustering via SPSS.

The final case studies scores demonstrate that the system represents the building's resilience adequately, presenting values that are in line with expectations. Buildings open to the public, with intensive use and managed by large organizations, with greater administrative and financial capacity, present better scores, especially in the economic, organizational and social dimensions, demonstrating greater concern with the safety of users and the quality of the building. This is the case for commercial and hospital buildings (cluster 3). This was followed by hotels, schools and residential multifamily buildings (cluster 2) and, finally, buildings with fewer users and low or no economic activity, such as residential single-family building, industrial and administrative buildings (cluster 1). This last cluster is portrayed by the reduced concern with the economic and organizational theme.

It is concluded that the developed system is well dimensioned, since the results obtained allow the differentiation of groups with different degrees of importance. According to Almeida [9], each group is formed by constructions with similar technical risks and has a degree of relative importance. The application of the system allowed the differentiation of three clusters that are aligned with different groups of importance. The third cluster consists of buildings of high importance, essential for support in a catastrophe situation, vital for society and with high risks to human lives, economic and social issues in case of failure. The second cluster is made up of buildings with a beneficial influence on society and occupied by many people and the first cluster is made up of buildings with normal risk in terms of loss of life, economic or social issues in case of failure.

Although the system presents satisfactory results, limitations were identified. Pearson's analysis allowed us to identify that the economic and organizational dimensions are highly correlated. In addition, a discrepancy was observed between the average scores of both dimensions compared to the others. These factors reveal that the dimensions are not completely uniform with each other, so the economic and organizational dimension should be reviewed in future studies. Indicators with reduced variance and high correlation between them should be revised in the future to ensure a uniform distribution score across the given scale and low proximity. Another limitation of the present study is the geographical limitation of the case studies carried out in the metropolitan area of Lisbon, which inhibited the proper analysis of 5 parameters, these being P1, P2, P20, P25 and P50

The proposed resilience rating system allows different stakeholders to efficiently identify which aspects should be improved and therefore establish investment priorities for enhancing the resilience of buildings. This information can be useful for all the stakeholders involved, i.e., owner, manager, insurers, and municipalities, enabling a better perception of the important contribution of constructed asset to resilient communities. This methodology hopes to facilitate the operation, maintenance and construction phases of built assets, seeking to standardize recurring concerns. The main goal was attained, that is, to help translate natural hazards imposed on buildings to measurable resilient strategies and determine their classification that allows comparison both over concerning the same building, as with other buildings previously evaluated.

Since the proposed system is in its initial stage of development, further work is needed to improve it. It is considered necessary to define thresholds corresponding to the minimum requirements for each group of degree of importance [9]. Different groups have different associated risks and different expected consequences, so the system should take this factor into account when determining the level of resilience. Finally, it is suggested to broaden the scope of the multidisciplinary rating system with regards to other types of disaster risks, like the man-induced risks. It should be noted that the developed items have an associated level of uncertainty, some being more developed than others. Thus, the system must be developed over time, improving items with a low level of development and or applicability such as the addition of new items emerging from future research opportunities.

Future work will determine the weight of each system’s layer using the analytic hierarchy process (AHP) [14], which in this paper is considered equal for reasons of simplicity.

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