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Improving the Resilience of Historic Areas Coping with Natural and Climate Change Hazards: Interventions Based on Multi-Criteria Methodology

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ABSTRACT

Cultural and Natural Heritage (CNH), a legacy bequeathed to present and future generations, casts light on the humanity of past generations. However, the increase and the intensity of natural and climate-change-related hazards threaten the conservation of such heritage. The aim of this research is to develop a multi-criteria prioritization methodology in support of intervention decisions, to enhance the resilience of CNH conservation through sustainable development. The application of two methods, the Integrated Value Model for Sustainability Assessment and the Analytical Hierarchy Process, ensures both the contribution of a wide panel of experts of heritage conservation and equitable indicator assessment measured on different scales. The prioritization methodology has been developed considering the most common hazards and specific disaster-risk scenarios. The three dimensions of sustainable development and both technical and cultural dimensions are also considered in the methodology. All dimensions and their indicators are weighted to produce a Prioritization Index to support decision-making.

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KEYWORDS
Adaptive solutions; heritage conservation; natural disaster risk; resilience enhancement; sustainable prioritization

1. Introduction

Cultural and Natural Heritage (CNH), a legacy bequeathed to present and future generations, casts light on the humanity of past generations. The United Nations Educational, Scientific and Cultural Organization (UNESCO) classifies heritage into either cultural or natural heritage. Cultural heritage reflects a broad range of values and includes artefacts, monuments, groups of buildings and sites, and museums. Natural heritage refers to natural features, geological and physiographical formations, and delineated areas that constitute the habitat of threatened species of animals and plants, and natural sites of value from the point of view of science, conservation, and natural beauty (UNESCO 1972, 2009). The conservation of CNH is a way of connecting the knowledge of past, present, and future generations and it throws light on our understanding of human and toponymic identities.

Over past decades, as a consequence of the effects of climate change, an increasing number of climate-change-related hazards (heat waves, floods, storms and wildfires) have impacted on CNH. The increased frequency and intensity of catastrophic events and existing geological hazards as earthquakes and subsidence is provoking CNH losses. The risks of each Historic Area (HA) are dependent on the nature of the hazard and the specific characteristics of the heritage, as well as the inherent vulnerability and geographical environment of the HA site (Forino, MacKee, and von Meding 2016; Mosoarca et al. 2017; Quesada-Ganuza et al. 2021).

The protection and conservation of the CNH constitute a significant contribution to sustainable development (UNESCO World Heritage Centre 2021). The United Nations established 17 Sustainable Development Goals (United Nations 2015) and heritage is explicitly referred to in Goal 11 "Sustainable Cities and Communities" under Target 11.4: "Strengthen efforts to protect and safeguard the world's cultural and natural heritage". Moreover, the need to cope with natural and climate-change related hazards is considered under Target 13.1 "Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries" of Goal 13 "Climate action". Financial support from the European Union to develop projects related to heritage-management to confront existing hazards (SHELTER.; HYPERION.; ARCH.; Pro-tecCH2save.; Climate Adapt) confirms the need for tools and solutions that enhance the resilience of cultural heritage throughout each disaster-risk management phase (Bonazza et al. 2021). These projects provide adaptation and retrofitting solutions to confront

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different threats, and they develop methodologies and tools to assess resilience, but without providing support for prioritizing the solutions.

This prioritization needs an objective and sustainable decision-making, given the diverse nature of the criteria used for identifying suitable solutions that improve the resilience of an historic area, together with the different expert profiles that take part in the decision-making process (Turk et al. 2019). Even if expressions of support for the need to consider heritage or historic value appear in many publications together with economic, technical, and environmental aspects (Nadkarni and Puthuvayi 2020; Turk et al. 2019), decisions are still taken nowadays in which solely economic or environmental aspects are considered without ensuring the conservation of historic value (Cucchiella et al. 2021; Gómez de Cózar et al. 2019).

Hence, the decision-making process for heritage conservation is a multidisciplinary process. In a suitable multicriteria decision methodology, not only must the contributions of all experts be guaranteed, but the wide variety of indicators must also be compared on an equal footing. Multi-Criteria Decision-Making (MCDM) methods combine different criteria for determining an optimal solution. The procedure for the development of the methodology has five stages: (i) definition of the objectives; (ii) definition of the criteria to measure the objectives; (iii) specification of the alternatives; (iv) assessment of weights to the criteria; and (v) application of the appropriate mathematical algorithm for ranking alternatives (Haroun, Fouad Bakr, and El-Sayed Hasan 2019; Mosadeghi et al. 2015). Multi-criteria methodologies are widely used in the construction sector (Jato-Espino et al. 2014; Sánchez-Garrido, Navarro, and Yepes 2022). Fuzzy Analytical Hierarchy Process is also widely used for risk assessment (Díaz, Teixeira, and Guedes Soares 2022; Githinji et al. 2022; Marhavilas et al. 2020; Qin, Yan, and Pedrycz 2020; Yariyan et al. 2020). However, the complexity of its computational procedure (Díaz, Teixeira, and Guedes Soares 2022) means that decision-makers have in many cases opted for a more user-friendly methodology. On the contrary, the criteria are not hierarchized in Analytical Network Process (ANP), so the resolution with quite a high number of criteria is complicate (Kheybari, Mahdi Rezaie, and Farazmand 2020); PROMETHEE (Preference Ranking Organization Methods for Enrichment Evaluations) methods are not intuitive and their implementation takes too long (Navarro, Yepes, and Martí 2019); simple analyses of the alternatives are performed with SAW (Simple Additive Weighting) and COPRAS (Complex Proportional Assessment) and they are suitable when all indicators are quantitative (Sánchez-Garrido, Navarro, and Yepes 2022); Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Multi-criteria Optimization and Compromise Solution Vise Kriterijumska Optimizacijal Kompromisno Resenje (VIKOR, Slovene acronyms) are methods that rank the alternatives and the decision is made according to the distance between the alternative and the most ideal and the least ideal option (Kiani, Liang, and Gross 2018; Pinzon Amorocho and Hartmann 2022).

Unlike the previously mentioned MCDM methods, the model is first evaluated with the Integrated Value Model for Sustainability Assessment (MIVES, Spanish acronym) methodology, after which the different alternatives are generated. The fact that the methodology is developed without contemplating the possible alternatives avoids their influence in the evaluation and reduces the subjectivity of the results. This procedure makes it possible to evaluate each alternative objectively (Pardo-Bosch and Aguado 2015). Furthermore, the implementation of the value function enables an equitable evaluation of criteria of a different nature. MIVES has been widely used for the assessment of sustainability in different fields of the construction sector: structures (Cuadrado et al. 2015; Zubizarreta et al. 2019), industrial buildings (San-José Lombera and Garrucho Aprea 2010), rehabilitation and refurbishment (Habibi, Pons Valladares, and Peña 2020; Piñero et al. 2017), urban planning when coping with climate-change hazards (Gandini et al. 2020, 2021; Hosseini, Albert de la, and Oriol 2016), selection of public project investment (Pardo-Bosch and Aguado 2015, 2016; Pujadas et al. 2017), *etc*. Hence, MIVES appears to be a suitable method for promoting sustainable reconstruction; however, its adaptation is needed to include additional dimensions such as cultural, natural, even social value, aimed at the conservation of CNH.

1.1. Objective and methodological approach

The research presented here has been developed in the SHELTER project, through which it is intended to improve the resilience of historical areas at different scales considering a four-phase disaster-risk management plan (prevention, preparedness, response, and recovery and building back better). The contribution of this study towards achieving that goal is on the basis of the prioritization of potential solutions for their implementation. The work is divided into two main steps: (1) the development of the portfolio with the possible solutions according to disaster-risk phases, natural hazards to be confronted, and the intervention scales; and (2) the prioritization of those solutions.

A panel of experts defined the criteria and the indicators to be considered for prioritization and assessment of their relative weights. The participants were selected based on a purposeful sampling technique, in which each potential participant was assumed to possess ample knowledge of the problem under investigation, based on both personal and professional experience (Ritchie and Lewis 2003). Forty-one experts with over 10 years of expertise formed the panel of experts, working within the fields of architecture, engineering, environmental and heritage management in urban and regional construction, heritage conservation, history, local government, and scientific disciplines, for the protection of heritage in the face of natural and climate change-related hazards.

2. Description of the methodology

2.1. Portfolio creation

The first step was to develop a solution portfolio, in which the solutions responded to those hazards with the greatest potential impact on CNH, as geological and climate change-related hazards: heatwaves, flooding, earthquakes, subsidence, wildfires, and storms (Cacciotti et al. 2021; Calheiros, Pereira, and Nunes 2021; Maio, Miguel Ferreira, and Vicente 2018; McBean and Ajibade 2009; Quesada-Ganuza et al. 2021; Ravankhah et al. 2019). Figure 1 shows the template developed for the solution data sheet. The data sheet provided information related to: (i) the suitability of the solution depending on the hazard and disaster-risk management phase; (ii) technical, economic, cultural, and environmental information to be used for the development of MIVES; and (iii) additional information that can help end-users with decision-making, although that information was not considered in the prioritization methodology.

In total, 148 adaptive solutions (AS) were gathered in the portfolio. Two main phases were considered: a general and an emergency phase. In the former, all four phases of the disaster-risk management plan were considered (prevention, preparedness, response, and recovery, and building back better) and in the latter, only two of them (preparedness and response). Moreover, three different intervention scales were considered for the implementation of the solution: territorial scale, when the solution is implemented not only to protect the whole municipality, but also to protect other architectures/artefacts in the landscape; urban scale, when a protective solution is implemented at an urban scale; and asset scale, whenever protection of a particular asset is needed.

The information processed in MIVES is defined with indicators that characterize each proposed solution according to four criteria: Type of Solution, CNH Conservation, Technical parameters, and Circular Economy parameters. Type of adaptive solution criterion identified the invasiveness of the solution, which is any physical alteration to the original element and the technical requirements for installation with respect to skills and specialist equipment; Cultural/Natural Heritage Conservation criterion aims to identify solutions that helps in the conservation of protected individual assets, areas, and environments as well as the social function (Ornelas, Miranda Guedes, and Breda-Vázquez 2016), in other words, it is used to identify whether the solutions have an impact on both cultural value, and protected CNH, and whether it is reversible; the technical requirements criterion considers technical and economic aspects that somehow have an impact on resident lifestyles with implementation time, cost, effectiveness maintenance, and disruption of occupancy or use indicators; and the circular economy criterion is a means of identifying environmental aspects that contribute to the mitigation of climate-change effects such as CO_2 emissions, and if it is recyclable or reusable. The definition of the indicators for each criterion are summarized in Table 1.

It must be pointed out that some indicators were not considered in the emergency phase, such as: maintenance, disruption time, and CO_2 emissions. This decision was taken with the panel of experts, all of whom agreed that when facing an emergency phase these indicators should not be taken into consideration in the decision-making process.

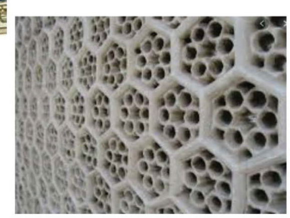
2.2. Introduction of MIVES prioritization methodology

Sustainable development was defined in the report of the World Commission on Environment and Development published in 1987 (United Nations 1987) as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. In 2015, United Nations member states adopted 17 goals to be achieved by 2030 that would ensure sustainable development. These goals were defined considering the three dimensions of sustainability development: economic, social, and environmental (United Nations 2015).

The contribution to sustainable development should be in all dimensions, which implies that factors of a diverse nature must be considered when analysing sustainability. The use of MIVES has yielded successful results when evaluating sustainability in the

Adaptive solution	Shading and sun screens in vernacular architecture		Prioritization Index	0.77	Shelter
DRM phase	☐ Emergency	☐ Prevention	☑ Preparedness	☐ Response	☑ Recovery & BBB
Hazard	☑ Heat waves	☐ Flooding	☐ Earthquakes	☐ Subsidence	☐ Wildfires ☐ Storm
Action Scale	Asset	Function (1)	Climate adaptation	Function (2)	
Type of AS	Soft	Vernacular		Technical requirement	Low
Impact on cultural value:	Yes			Reversibility	n/a
Impact on protected CNH	Yes	Identify impact on element:			
Building:	☐				
Façade:	☐ Material	☑ Components	☑ Carpentry	☑ Colour/finishing	
Roof:	☐ Material	☐ Volumetry	☐ Components		
Structure:	☐ Material	☐ Structural system			
Public zone:	☐ Pavement/ material	☐ Natural species	☐ Path/ Gradient	☐ Park / natural environment	

		Pictures
Implementation time	Medium time	
Cost	Medium	
Effectiveness	Permanent solution	
Maintenance	Medium	
Disruption of occupance/use [days]	Low	
Impact radius	Building	
Recyclable	Partly	
Reusable	Partly	
CO_2 emissions	Low	



Description

Different materials are used in vernacular architecture such as shading, combined with ornamental motifs. Some example are:

The Venetian Blind: Using the venetian blind, the sun's rays can be deflected or shut out without obstructing the flow of air. The blinds consist of thin bands of reflectant materials that can be titled, so that light can enter at various angles or can be shut out completely. Structures such as pergolas and loggias that provide shade in open areas such as quadrnagles, patios, and gardens. Seemingly ornamental, they block sunlight at different times of day, yet remain open to outdoor airflows.

Vernacular example: The Mashrabiya, a cantilevered enclosed space on building façade with latticework openings on its external walls. Small water jars were often stored there, as airflows through the opennings cooled the water, due to the evaporation effect. The Mashrabiya whith its distinctive latticework arranged at specific regular intervals, often in decorative and intricatae geometric patterns, is synonymous with an oriel window projecting outwards from the façade of a building.

Material

Available in many materials and many vernacular styles

Other aspects:

Positive aspects:	Negative aspects:
An embedded and ornamental solution	Often not removable or operable

References

Fathy, 1986, Natural Energy and Vernacular Architecture Principles and Examples with Reference to Hot Arid Climates

Cr.1: Type of solution. Cr.2: CNH conservation. Cr.3: Technical requirements. Cr.4: Circular economy.

Figure 1. Solution data-sheet example. Indicators within the same criterion are identified with the same colour.

construction sector in different fields. MIVES uses a multi-attribute-utility theory and a multi-criteria decision-making method, including value function definitions, and the assignation of weights by means of the Analytic Hierarchy Process (AHP) (Saaty 2008; Saaty and Vargas 2012). This methodology provides a Prioritization Index (PI) for each solution in a ranking that facilitates the decision-making process.

Table 1. Definition of each indicator.

Cr. 1 TYPE OF SOLUTION
Ind. 1.1 Type of Adaptive Solution
The invasiveness of the solution is rated on a scale from soft, for minimally invasive solutions, to hard, for invasive solutions. Additionally, the type of solution is identified, *i.e*., whether it is an architectural or an engineering solution, a Nature-Based Solution (NBS), a technology or a tool, a vernacular architecture, or a circular economy solution.
Ind. 1.2 Technical requirement
Skill levels and resources needed for the design and installation stage are rated on a scale from low, for solutions that do not need high skill or special resources, to high for solutions that need high skill or special resources.
Cr. 2 CNH CONSERVATION
Ind. 2.1 Impact on cultural value
Whether the solution has an impact on or limits the use of CNH. For instance, the intervention limits the current use of the CNH, because the dimensional characteristics change. Usually, this use can be related to the organization of traditional events, or the storage of cultural or protected elements when, during or after the intervention, the CNH cannot hold the event or store the cultural or protected elements.
Ind. 2.2 Reversibility
Cultural heritage interventions should be reversible and minimally invasive, *i.e*., if a solution is removed in the future, there is no alteration of the original element. However, considering that elements may have different listings or degrees of protection, some more invasive solutions might be applied, *e.g*., steel tie rods for arches which are widely used in earthquake prone areas. This indicator implies no alteration to the original condition, if the solution is removed.
Ind. 2.3 Impact on protected CNH
Whether there is some type of physical impact to any element of the historic protected asset. While impact on cultural value refers to the use of the space and indicates if any activity developed in the CNH should be moved to another location, this indicator informs of the direct physical impact on the CNH. If an impact is identified, the affected heritage is selected. The template shows a classification that identifies those elements commonly protected in heritage legislation.
Cr. 3 TECHNICAL REQUIREMENTS
Ind. 3.1 Implementation time
The time needed for implementing the solution, considering installation and operating times. Short and long-time spans are rated on the scale.
Ind. 3.2 Cost
The cost of the product and its installation. Low to high-cost interventions are rated on the scale.
Ind. 3.3 Effectiveness
A rating of building performance and improvements.
Ind. 3.4 Maintenance
Maintenance needs are rated on the scale: no maintenance to high maintenance, i.e., frequent and with high costs.
Ind. 3.5 Disruption of occupancy/use
The duration of any disruption to the use of the heritage. Disruption is rated on the scale from low-to-high.
Cr. 4 CIRCULAR ECONOMY
Ind. 4.1 Recyclable
The recyclable capacity of the solution and its components. The scale values are: yes, if the complete solution is recyclable; partly, if only one part of it is recyclable; none, if the solution is not recyclable.
Ind. 4.2 Reusable
Whether the solution can be used in another intervention, *i.e*., whether it can be used more than once. The scale values defined are: yes, if the complete solution is reusable; partly, if only one part of it is reusable; no, if the solution is not reusable.
Ind. 4.3 CO_2 emissions
The level of CO_2 emissions considering the full life cycle of the solution are rated on a scale from low-to-high emissions.

The schematics of the workflow process is shown in Figure 2 and is described below:

(1) Definition of the requirements tree. The information for sustainable assessment is organized into a hierarchical structure: the information flows from general aspects (requirements) to specific aspects (criteria and indicators) (Aguado, Manga, and Ormazabal 2006).

(2) Value function definition. The value of indicators can be either qualitative or quantitative. The value function turns these values into a standard value between 1 and 0, depending on the satisfaction level, to enable an equitable evaluation of all indicators. The ratings can yield different value function curves on the graph (concave, convex, "S" shaped, and straight lines).

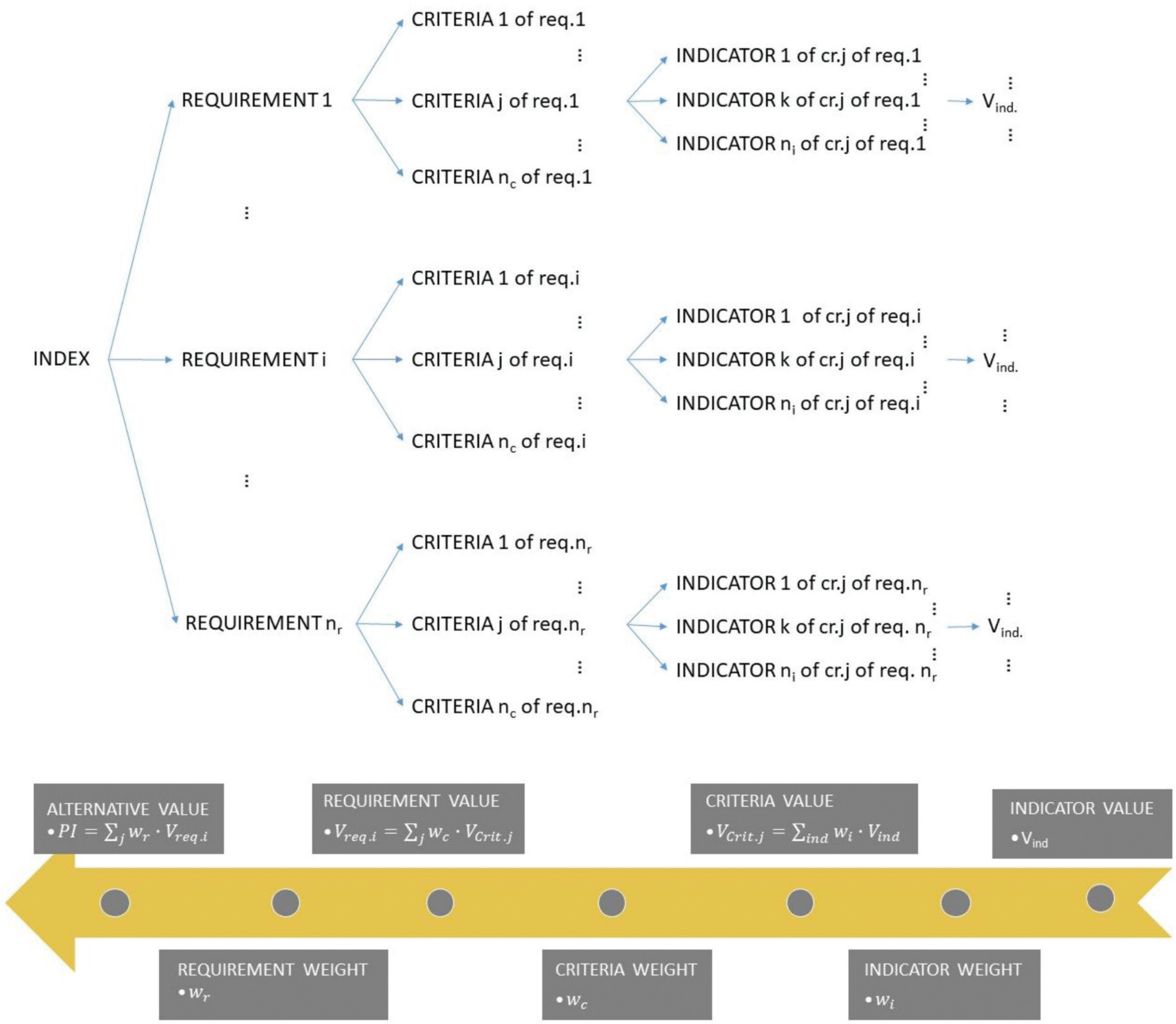


Figure 2. Requirement tree and MIVES workflow.

(3) Relative weight. The relative importance of indicators, criteria, and requirements is defined by AHP.
(4) Assessment of different alternatives. The alternatives are defined according to the characteristics of the requirement tree and then evaluated with the methodology.

3. Results of MIVES methodology

In this section, the results of the steps defined in the previous section are summarized.

3.1. Definition of the requirement tree

The information is organized into a hierarchical structure. In this case, there are two levels of information. Sustainability and resilience assessment criteria appear in the top section. Once the criteria are defined, suitable indicators are summarized at the next level to evaluate each criterion. Table 2 summarizes the criteria and indicators utilized for the requirements tree and the value range used for each indicator (where N/A is not applicable).

As shown in Table 2, resilience and sustainable enhancements are evaluated through 13 indicators grouped into four criteria. With the aim of promoting efficient conservation, not only are aspects directly related to the alteration of the protected heritage considered in the selection of the criteria, but so too are other relevant aspects such as cultural and technical aspects and the three dimensions of sustainability (social, economic, environmental) (Eken, Taşcı, and Gustafsson 2019; Elabd, Mansour, and Khodier 2021; Ornelas, Miranda Guedes, and Breda-Vázquez 2016; Pickard 2002).

Table 2. List of criteria and indicators used in the requirements tree for MIVES methodology.

Cr. 1 TYPE OF SOLUTION	
Ind. 1.1 Type of Adaptive Solution	Soft
	Hard
	N/A
Ind. 1.2 Technical requirements	High
	Medium-high
	Medium
	Medium-low
	Low
Cr. 2 CNH CONSERVATION	
Ind. 2.1 Impact on cultural value	Yes
	No
Ind. 2.2 Reversibility	Yes
	No
	N/A
Ind. 2.3 Impact on protected CNH	Yes
	No
Cr. 3 TECHNICAL REQUIREMENTS	
Ind. 3.1 Implementation time	Short time
	Short-medium time
	Medium time
	Medium-long time
	Long time
Ind. 3.2 Cost	Low
	Medium-low
	Medium
	Medium-high
	High
Ind. 3.3 Effectiveness	Temporal solution
	Permanent solution
	N/A
Ind. 3.4 Maintenance	None
	Low
	Medium-low
	Medium
	Medium-high
	High
	N/A
Ind. 3.5 Disruption of occupancy/use	Low
	Medium-low
	Medium
	Medium-high
	High
Cr. 4 CIRCULAR ECONOMY	
Ind. 4.1 Recyclable	Yes
	Partly
	No
	N/A
Ind. 4.2 Reusable	Yes
	Partly
	No
	N/A
Ind. 4.3 CO_2 emissions	Low
	Medium-low
	Medium
	Medium-high
	High
	N/A

3.2. Assignation of a value function to each indicator

The solutions are characterized according to the indicators and the qualitative values that are assigned in each case, as defined in Table 2. In this step, the qualitative value is converted into a quantitative value through a value function (V_{ind}). Eq. (1) and Eq. (2) were used for the definition of the value function; it is a dimensionless standardization mechanism with which dimensional variables are compared through individual values that vary between 0 and 1 (Alarcon et al. 2011; Piñero et al. 2017).

$$V_{ind} = B \cdot \left[1 - e^{-k_i\left(\frac{|x - x_{min}|}{C_i}\right)^{P_i}}\right] \quad (1)$$

$$B = \frac{1}{1 - e^{-k_i\left(\frac{|x_{max} - x_{min}|}{C_i}\right)^{P_i}}} \quad (2)$$

Where:

x_{min}: point of minimum satisfaction (defining an x-axis value for a minimum value of V_{ind})

x_{max}: point of maximum satisfaction ((defining an x-axis value for a maximum value of V_{ind})

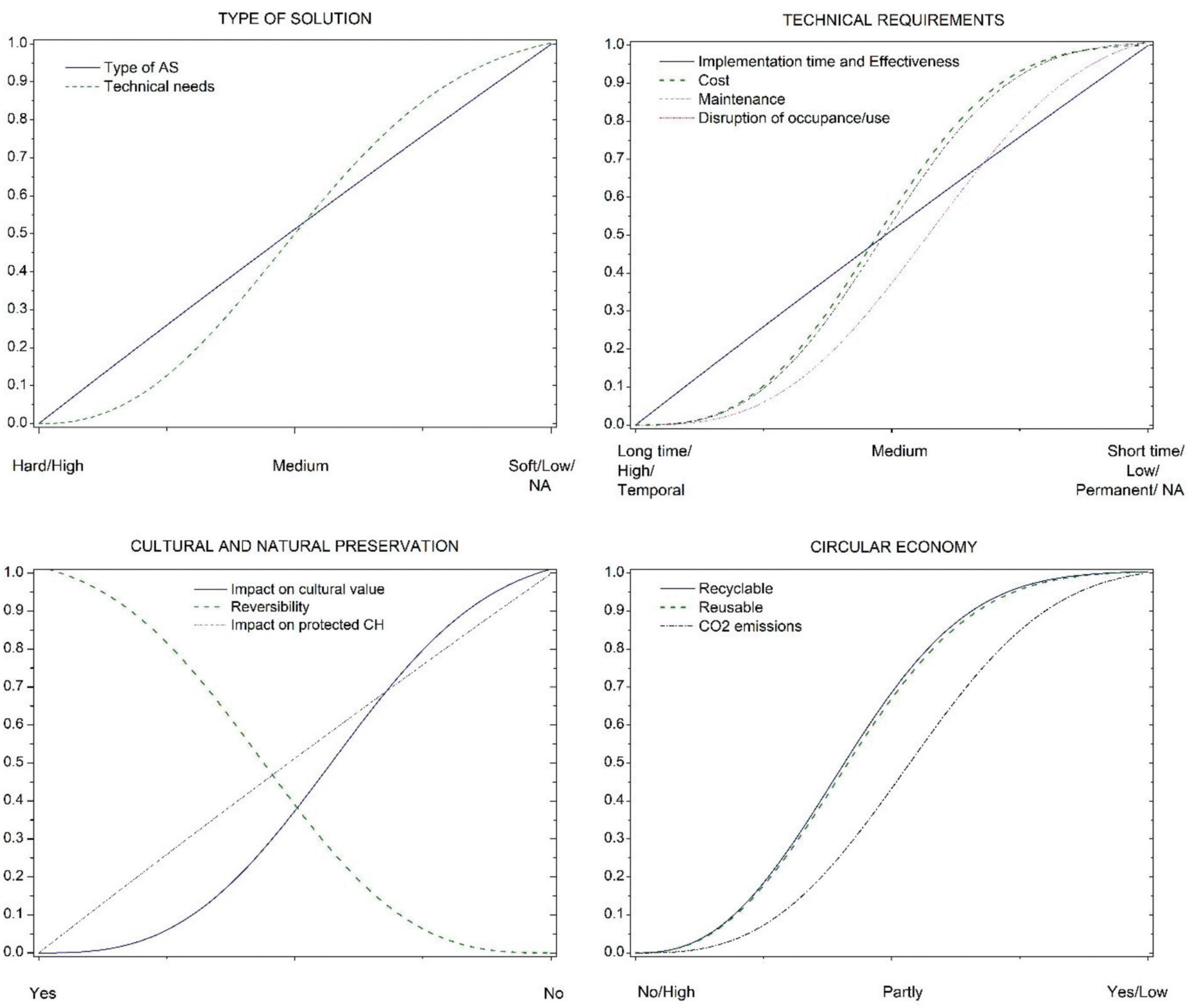


Figure 3. Value function curves for each indicator.

Pi: Shape factor curve (concave: <1; convex and "S-shaped" >1 and straight ≈ 1)

Ci: abscissa value corresponding to the inflection point on a curve where Pi > 1

ki: Ci point ordinate.

B: standardization factor

Depending on the nature of the indicator, the value function curve can be plotted as concave, convex, S-shaped, or straight. The panel of expert defined the value function curve and the results were validated in discussion with the stakeholders of the open labs of the SHELTER project. Figure 3 shows the value function curve after applying Eq. (1) of each indicator grouped according to the defined criterion. In this case, the indicators are defined as either S-shaped curves or straight curves. The corresponding value is assigned to each solution depending on the qualitative value that was previously assigned.

3.3. Relative weight assignation

At this point, having defined the value function of each indicator, it is necessary to define the level of importance of each criterion and indicator. To do so, and with the aim of assigning an objective weight, a survey was administered to the panel of experts. The scale used for the evaluation of importance ranged from 1 (extremely insignificant) to 9 (extremely important), based on the Saaty scale (Saaty 1990).

The relative weights of criteria and indicator are used in MIVES. However, an absolute weight was assigned to each criterion/indicator on the basis of the survey results. A relative weight for each criterion/indicator

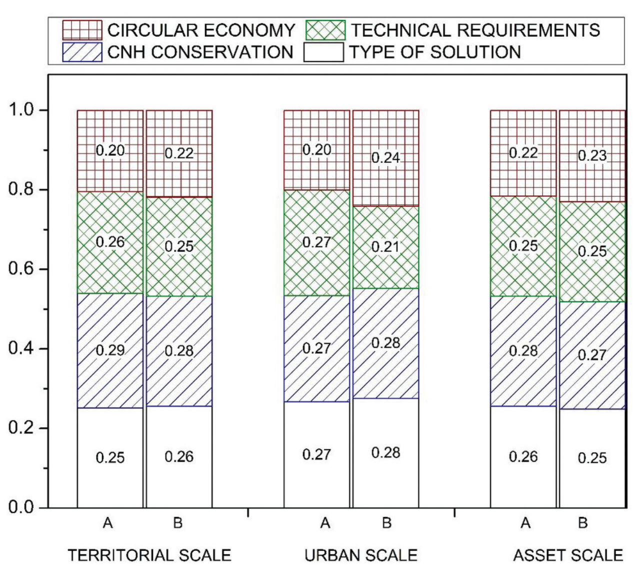


Figure 4. Relative weight values of criteria (w_c). Column A: Emergency phase; Column B: General phase.

was then defined from that value and a pairwise comparative matrix was developed. The Consistency Ratio (CR) was evaluated according to Eq. (3) and (4), to ensure the reliability of the pairwise comparative matrix. A CR value of 0.1 or lower was obtained for each matrix, which guaranteed the consistency of the results (da S Trentin et al. 2019; Saaty 2008).

$$CR = \frac{Consistency\ Index(CI)}{Random\ Index(RI)} \tag{3}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

Where λ_{max} is the maximum eigenvalue and n is the pairwise comparative matrix size. The Random Index, an experimental value depending on the matrix size, was obtained from a table presented by Saaty (Saaty 1990).

The SHELTER project results were validated in five case studies. The necessities of each case study can be divided into three possible scales of action: territorial, urban, or asset. The priorities may vary, depending on the scale, and on the phase (general or emergency), so the relative weights were defined according to the scale and the phase that was to be addressed (one relative weight per scale and phase).

The results for the relative weights of each criterion are summarized in Figure 4, in the light of the three (territorial, urban, and asset) scales and two (general and emergency) phase. It can be seen that there was no relevant difference in the evaluations between the three scales; all the criteria represented around 25% of the final weight. Thus, the same criteria can be used when prioritizing a solution at the territorial, the urban, and the asset scale. Moreover, CNH conservation was in general the most highly valued criterion and the circular economy was almost the lowest valued criterion by the experts. In the case of a general phase at the urban scale with a value of 24%, the circular economy was ranked third, ahead of the technical requirement criterion, with a value of 22%. It suggests that decisions were focused more on reducing the impact on CNH rather than on the sustainability of the solution.

The results of all the relative indicator weightings used for the prioritization of the alternatives are shown in Figure 5. Indicators are grouped into criteria according to Table 2. The relative importance of the indicators was almost the same when each situation was compared, lending attention to the differences between an emergency phase and a general phase, at the asset scale and at the territorial scale. However, at the urban scale, there was greater variation in the relative weights of the indicators when comparing the emergency and the general phase.

3.4. Definition of the prioritization index for each solution

Having defined the value function of each indicator and the relative weights of each criterion and each indicator, the last step was to obtain the Prioritization Index (PI) of each alternative by applying the MIVES methodology summarized in Figure 2. In this case, two steps were needed for defining the PI since the requirement tree has two levels of information (criterion and indicator). First, the value of each criterion was calculated and, second, the PI of the solution according to Ec.5 and Ec.6, respectively.

$$V_{cr.j} = \sum\nolimits_{ind} w_i \cdot V_{ind} \tag{5}$$

Where w_i represents the relative weight of the indicator and $V_{cr.j}$ the value of the criterion.

$$PI = \sum\nolimits_{cri} w_c \cdot V_{cr.j} \tag{6}$$

where w_c represents the relative weight of the criterion.

The prioritization methodology was applied to the solutions portfolio with the goal of ensuring a sustainable and objective selection of the most suitable adaptive solution. As a result, a PI was defined for each solution.

In Tables 3–10, each PI obtained for each adaptive solution for the general phase and for the emergency phase are summarized according to the different hazards, DRM phase, and action scale.

However, some solutions can protect at more than one scale and/or phase. Depending on the protection that may be needed, the priorities of the experts will differ at each scale, something which is confirmed by the results of the relative weights summarized in Figures 4

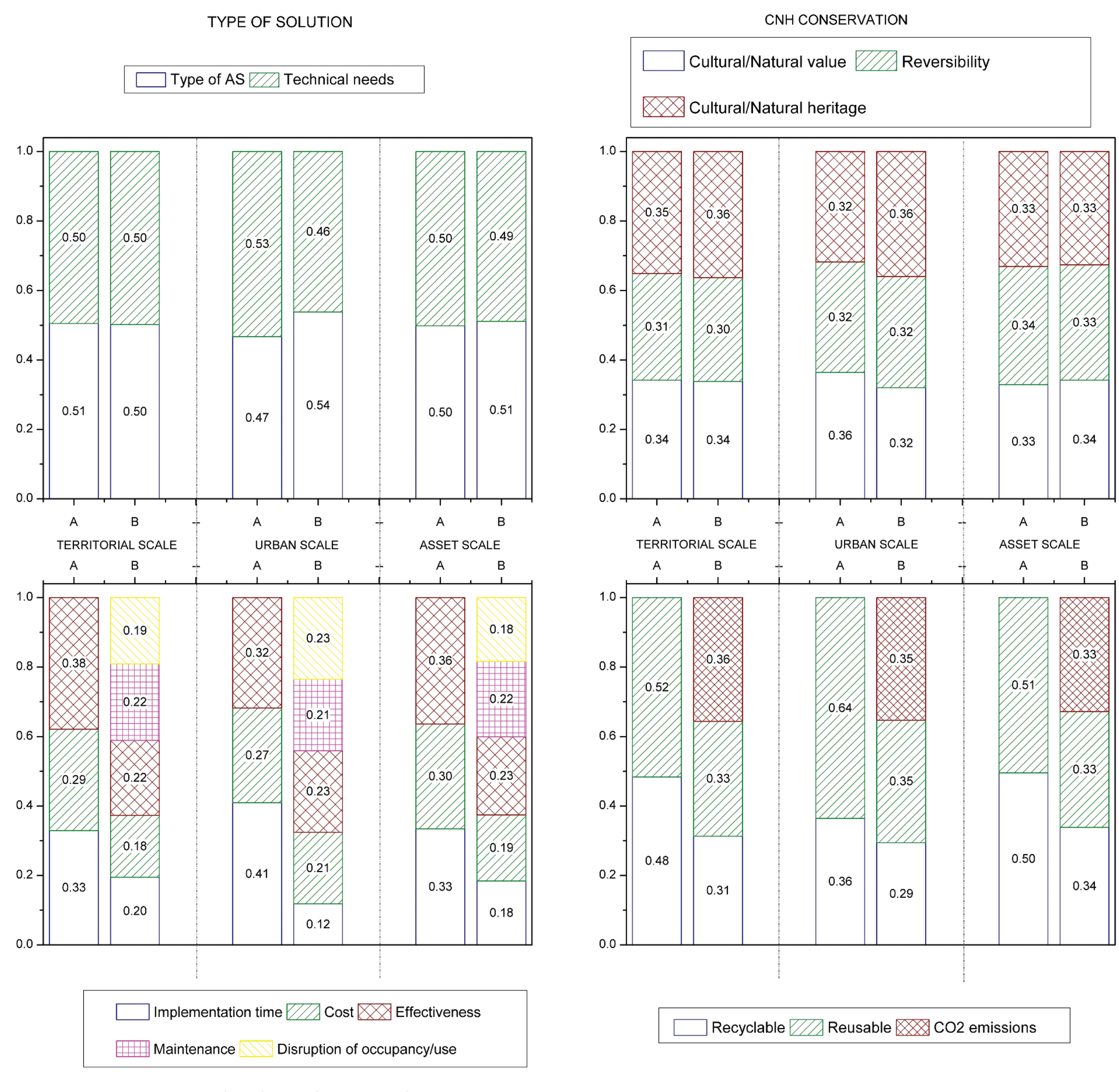


Figure 5. Relative weight values of all indicators (w_i) grouped into criteria. Column A: Emergency phase; Column B: General phase.

and 5. When a solution is applicable at more than one scale and/or phase, a different PI is obtained for each scale and/or phase.

4. Discussion of prioritization methodology results

4.1. Discussion of relative weight results

Differences were appreciated when comparing the general and the emergency phases in separate analyses of the relative weight of the criteria at each scale (Figure 4). The differences were notably greater at the urban scale.

Figure 6 shows the variation of criteria at the urban scale, considering both the emergency and the general phase. The importance of the type of solution and CNH conservation criteria was almost the same in both phases. These differences were appreciated in the circular economy and the technical requirements criteria; the circular economy criterion was 22% less important in the emergency phase when compared with the general phase. This reduction almost matched the 20% increase in the technical requirements criterion.

With reference to the relative weight of the indicator of each criterion (Figure 5), some differences were appreciated depending on scale and phase. At both the territorial scale and the asset scale, the relative importance of each indicator for type of solution and CNH conservation criteria was balanced and the values were almost the same for the general and the emergency phases. Nevertheless, some differences could be appreciated at the urban scale. In the case of type of solution criterion, the importance of technical requirements was 15% higher in the emergency phase. With regard to CNH conservation criterion, it can be appreciated that the importance of reversibility at the urban scale was maintained, regardless of the phase, as shown in Figure 7. The importance of conserving tangible heritage increased by 13% for the general phase. This rise in CNH matched the decline of cultural/natural value.

Analyzing the technical requirements criterion, the number of indicators varied depending on the phase. This fact complicated any direct comparison between the importance of the indicators throughout both the emergency and the general phase. In most cases, cost was the least valuable indicator. It was only in the general situation when the intervention was needed at an urban scale that the value of the cost was 75% higher than the implementation time. In any other situation, its value was lower or equal to other indicators.

Figure 8 shows the variation of the technical-requirement-criterion indicators for the emergency phase. The values were similar at the territorial and the asset scale. However, implementation time gained importance at the urban scale, as it was 25% and 22% higher than at the territorial and the asset scale, respectively. The relative weight values of the indicators varied, as shown in Figure 9, in the general phase. The territorial and the asset scale values were quite similar and the relative weight values were balanced for both scales. A notable difference was appreciated when both were compared with urban-scale values. At an urban scale, implementation time lost importance and was 40% and 36% less important than at the territorial and the asset scale, respectively. On the contrary, the disruption of occupancy/use indicator gained importance and was 23% higher than at the territorial scale and 28% higher than at the asset scale.

Finally, re-usable solutions were valued more highly than recyclable ones under the circular economy criterion in the emergency phase, reaching the highest value of 75% for intervention at the urban scale. The CO_2 emissions indicator was also considered in the prioritization of the solution for intervention criteria in the general phase.

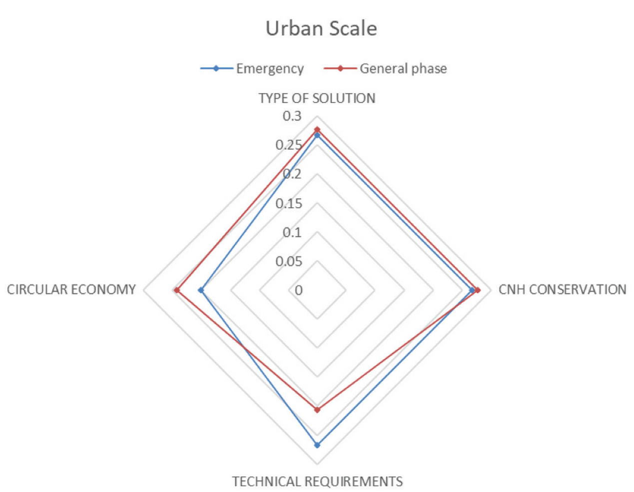


Figure 6. Relative weight results of criteria at an urban scale.

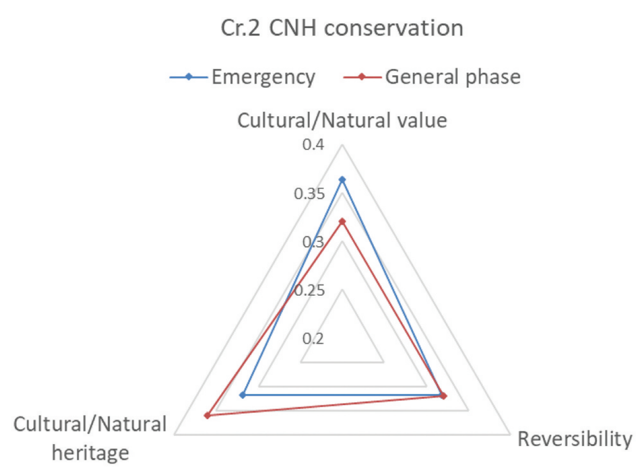


Figure 7. Relative weights of indicators defined for the CNH conservation criterion at the urban scale.

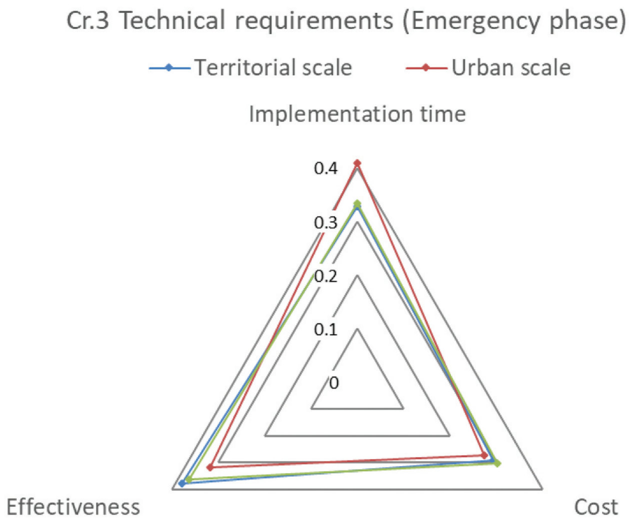


Figure 8. Relative weights of indicators defined for technical requirements criteria in an emergency phase at the three different scales.

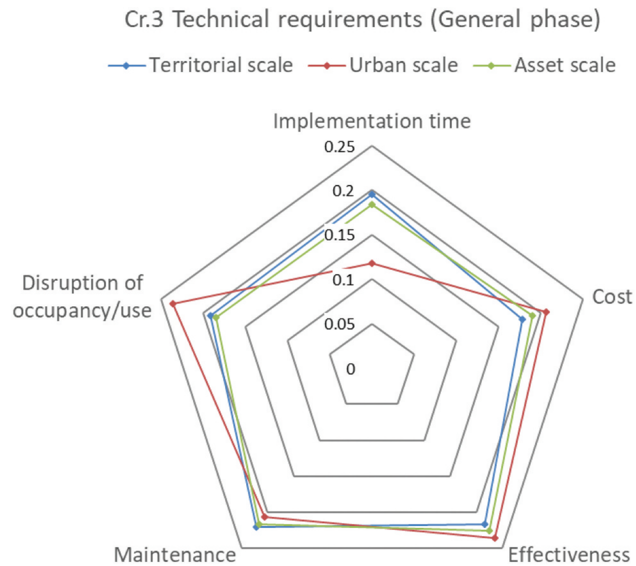


Figure 9. Relative weights of indicators defined for technical requirements criterion in a general situation.

The ratings attached to the indicators of the circular economy criterion in the general phase are shown in Figure 10. At the territorial and at the urban scale, the CO_2 emissions indicator was the most important indicator. The difference was more obvious when compared with the recyclable indicator; 14% at the territorial scale and 20% at the urban scale. The importance of the three indicators was balanced at the asset scale.

4.1.1. Discussion of PI results

Some adaptive solutions can be implemented for protection at different scales and in different situations. The results of the relative weights showed that the priorities varied accordingly. As a consequence, the PI can differ according to the results of the methodology. In this section, the results of the PI values for both the emergency and the general-phase solutions that offer protection at different scales are analyzed.

Table 11 collects some non-reusable adaptive solutions that are valid for both the general and the emergency phase. Solutions with a PI value below 0.5 corresponded to solutions that alter the conservation of CNH. The value of PI increased above 0.7 for solutions that in no way altered CNH conservation. In a comparison of the emergency and the general phases, the emergency solutions received higher ratings. The re-usable indicator affected the circular economy criterion, as shown in Figure 4. The criterion gained importance when there was a need to improve the current conditions in the general phase and non-reusable solutions therefore penalized the PI value.

As mentioned before, three different scales were defined to respond to the needs of the project case studies (asset scale, urban scale, and territorial scale), and some solutions can protect at more than one level. Depending on the protection that is needed, the priorities of the experts at each scale were not the same, and the value of the index varied, as the relative weight results showed (Figures 4 and 5). The adaptive solutions for a general phase that can protect at any of the three scales are summarized in Table 12. The adaptive solutions are ranked according to the PI for territorial-level protection and the rating of each criterion is also summarized. According to relative weight values (Figure 5), CNH conservation criterion was the most highly valued ($w_c = 0.28$) and circular economy criterion the least

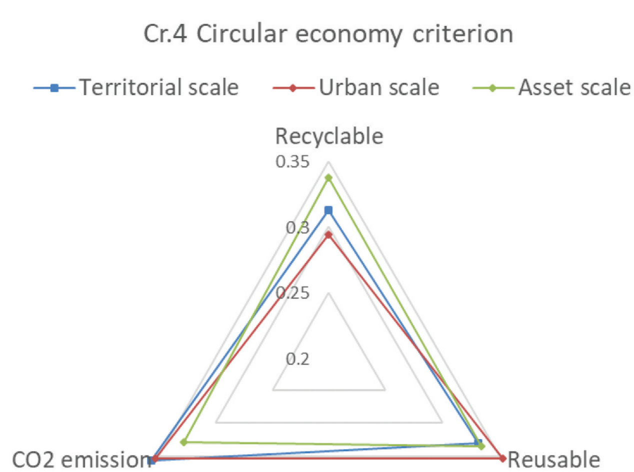


Figure 10. Relative weights of indicators defined for the circular economy criterion in the general phase.

Table 3. List of adaptive solutions that are defined to confront flooding in a general situation.

							PRIORITIZATION INDEX		
				DRM PHASES			Scale		
Adaptive solution	Hazard		Prev.	Prep.	Resp.	R.& BBB	Territorial	Urban	Asset
Structural soil	Flooding	Subsidence	X		X				0.70
Vegetation engineering systems for slope erosion control	Flooding		X		X		0.60	0.61	0.66
Redesign natural and semi-natural water bodies and hydrographic network to limit floods	Flooding		X		X		0.45	0.45	0.48
Green area for water management	Flooding		X		X		0.63	0.64	0.64
Seawalls	Flooding	Storm	X			X	0.27	0.25	0.27
Debris Basin	Flooding	Wildfires	X				0.21	0.23	0.22
Shoreline structure	Flooding	Storm	X			X	0.37	0.36	0.38
Sand or gravel basement filling	Flooding		X			X			0.63
Permanent floodwalls and gates for openings	Flooding		X			X			0.52
Surface protection for materials vulnerable to wash-out effects	Flooding		X			X			0.62
Wet-floodproofing interventions	Flooding		X			X			0.45
Dykes or dams	Flooding	Storm	X			X	0.27	0.30	0.29
Urban floodwalls and barriers	Flooding		X			X	0.31	0.31	0.33
Identification of adequate storage facilities for movable heritage	Flooding		X	X					0.68
Floating basement	Flooding		X			X			0.37
IMMERSITE®	Flooding		X				0.53	0.52	0.54

Table 4. List of adaptive solutions that are defined to confront storms in a general situation.

							PRIORITIZATION INDEX		
				DRM PHASES			Scale		
Adaptive solution	Hazard		Prev.	Prep.	Resp.	R.& BBB	Territorial	Urban	Asset
Breakaway walls	Storm	Flooding	X	X					0.42
Pile foundation reinforcement	Storm	Flooding	X	X		X			0.42
Load Paths	Storm		X						0.55
Elevate Building on Piles	Storm	Flooding	X			X	0.19	0.18	0.19
Storm detector	Storm		X	X			0.62	0.58	0.60
Lightning rod	Storm		X	X			0.78	0.76	0.77
Aquadam	Storm	Flooding	X	X			0.57	0.54	0.56
Underground drainage system	Storm	Flooding		X		X	0.38	0.36	0.37

Table 5. List of adaptive solutions that are defined to confront earthquakes in a general situation.

Adaptive solution	Hazard		DRM PHASES Prev.	Prep.	Resp.	R.& BBB	Asset
Timber Laced Masonry construction	Earthquakes		X	X		X	0.79
Load absorbing structural connections between structural elements	Earthquakes		X			X	0.81
Foundation drainage methods in vernacular architecture	Earthquakes	Flooding	X			X	0.84
Lightweight timber structures	Earthquakes	Storm	X			X	0.81
Load-bearing wall construction for citadels	Earthquakes		X	X	X	X	0.81
Reinforcement of non-engineered vernacular buildings	Earthquakes		X	X	X	X	0.81
Kerbs	Earthquakes					X	0.24
Reinforced perforations made with steel bars	Earthquakes					X	0.22
Application of composite material strips to vaults and arches	Earthquakes					X	0.43
Artificial dilations	Earthquakes					X	0.37
Jacketing with composite material strips	Earthquakes					X	0.35
Coccioforte vault consolidation	Earthquakes					X	0.36
Steel hooping for columns, pillars and beams	Earthquakes					X	0.54
CAM hooping for columns, pillars and beams	Earthquakes					X	0.54
FRP hooping for columns, pillars and beams	Earthquakes					X	0.34
Expansion of foundation system	Earthquakes					X	0.29

Table 6. List of adaptive solutions defined to confront wildfires in a general situation.

Adaptive solution	Hazard		DRM PHASES Prev.	Prep.	Resp.	R.& BBB	PRIORITIZATION INDEX Scale Territorial	Urban	Asset
Straw wattle	Wildfires				X	X	0.70	0.69	0.70
In-channel Tree Felling	Wildfires	Flooding			X	X	0.70	0.70	0.70
Firebreak	Wildfires		X	X			0.16	0.17	0.21
Check dam	Wildfires		X				0.76	0.76	0.76
Cleaning under high voltage lines	Wildfires			X			0.56	0.54	0.55
Design access paths	Wildfires			X			0.60	0.62	0.64
Early Warning System: territorial level	Wildfires		X	X			0.95	0.96	0.95
Stream Bank Armouring	Wildfires				X		0.30	0.34	0.35
Road decommissioning	Wildfires				X	X	0.45	0.47	0.46
Debris Basin	Wildfires		X				0.21	0.23	0.22
Culvert Modification	Wildfires	Storm	X			X	0.41	0.37	0.39
Debris Rack and Deflectors	Wildfires				X		0.65	0.68	0.68
Trail Stabilization	Wildfires				X		0.59	0.61	0.59
Controlled weed burning	Wildfires		X				0.97	0.99	1.00
Reforestation	Wildfires					X	0.95	0.98	0.95
Prohibition of stubble burning in high fire-risk situations	Wildfires		X				1.00	1.00	1.00
Biomass management	Wildfires		X	X			0.84	0.87	0.85

Table 7. List of adaptive solutions defined to confront heat waves in a general situation.

							PRIORITIZATION INDEX		
			DRM PHASES				Scale		
Adaptive solution	Hazard		Prev.	Prep.	Resp.	R.&BBB	Territorial	Urban	Asset
Climber green wall	Heat waves		X		X				0.70
Planter green wall	Heat waves		X		X				0.64
Greenwall system	Heat waves		X		X				0.55
Vegetated pergola	Heat waves		X		X				0.73
Intensive and semi-intensive green roof	Heat waves	Flooding	X		X				0.46
Extensive green roof	Heat waves	Flooding	X		X				0.61
Parks and gardens	Heat waves	Flooding	X		X		0.54	0.57	0.59
Nature-based solutions and structures associated with urban networks	Heat waves	Flooding	X		X		0.74	0.78	0.79
Green waterfront	Heat waves	Flooding			X		0.38	0.40	0.43
Green pavements	Heat waves	Flooding	X		X				0.80
Floodplain and floodable park	Heat waves	Flooding	X		X		0.62	0.62	0.62
Natural ventilation (and design for)	Heat waves	Flooding	X	X		X			0.67
Green urban furniture	Heat waves		X				0.80	0.80	0.80
Sun screens and shading in vernacular architecture	Heat waves			X		X			0.77
Courtyards and building layout in traditional urban patterns	Heat waves		X			X			0.76
Architectural form of vernacular buildings for hot climate zones	Heat waves		X			X			0.81
External thermal insulation composite system (ETICS): synthetic organic insulation	Heat waves		X			X			0.46
External thermal insulation composite system (ETICS): synthetic inorganic insulation	Heat waves		X			X			0.46
Internal thermal insulation system: natural and mineral insulation	Heat waves		X			X			0.79
Internal thermal insulation system: synthetic organic insulation	Heat waves		X			X			0.79
Vacuum insulated panels (VIP). External application	Heat waves		X			X			0.64
Vacuum insulated panels (VIP). Internal application	Heat waves		X			X			0.77
Cavity wall insulation	Heat waves		X			X			0.68
Internal thermal insulation system: aerogel	Heat waves		X			X			0.72
Phase Change Materials (PCM)	Heat waves		X			X			0.72
External thermal insulation of roofs	Heat waves		X			X			0.61
Internal thermal insulation of roofs	Heat waves		X			X			0.78
Insulated glazing	Heat waves		X			X			0.65

(*Continued*)

Table 7. (Continued).

						PRIORITIZATION INDEX		
		DRM PHASES				Scale		
Adaptive solution	Hazard	Prev.	Prep.	Resp.	R.&BBB	Territorial	Urban	Asset
Solar control glass	Heat waves	X			X			0.62
Vacuum Insulating Glass	Heat waves	X			X			0.62
Aerogel Insulating Glass	Heat waves	X			X			0.60
Solar protection film	Heat waves	X			X			0.79
Passive smart glass	Heat waves	X			X			0.59
Active smart glass: electrochromic glass	Heat waves	X			X			0.59
Passive smart glass: Phase Change Material (PCM)	Heat waves	X			X			0.59
Cool coverings	Heat waves	X						0.53
Cool Pavements	Heat waves	X			X	0.51	0.48	0.49
Ventilated facade	Heat waves	X			X			0.38
Shade sails	Heat waves	X				0.78	0.78	0.78
Shade elements for facades	Heat waves	X			X			0.83
Heat pump systems: geothermal heat pumps	Heat waves	X			X			0.54
Heat pump systems: air to air	Heat waves	X			X			0.46
Air conditioning	Heat waves	X			X			0.80
Co-generation	Heat waves	X			X			0.41
Low-tech traditional practices of thermal regulation	Heat waves	X			X			0.76

Table 8. List of adaptive solutions mainly defined to confront wildfire in an emergency phase.

			PRIORITIZATION INDEX		
			Scale		
Adaptive solution	Hazard		Territorial	Urban	Asset
Contour-felled logs (LEBs)	Wildfires		0.76	0.76	0.77
Straw wattles	Wildfires		0.72	0.72	0.72
In-channel Tree Felling	Wildfires	Flooding	0.72	0.70	0.72
Firebreak	Wildfires		0.21	0.23	0.26
Straw mulches	Wildfires		0.64	0.63	0.62
Wood mulches	Wildfires		0.49	0.53	0.52
Hydro-mulches	Wildfires		0.21	0.25	0.24
PolyAcrylaMide (PAM) as soil binder	Wildfires		0.22	0.26	0.25
Silt Fence	Wildfires	Storm	0.77	0.83	0.83
Sodium bentonite-based coating	Wildfires		0.66	0.67	0.65
Grade Stabilizer	Wildfires		0.85	0.88	0.87
Fire Hydrant	Wildfires		0.67	0.68	0.66
Sprinkler	Wildfires		0.64	0.63	0.62
Early Warning System: building level	Wildfires		0.97	0.98	0.97
Fire Curtains	Wildfires		0.46	0.42	0.45
Crowdsourcing Solutions	All		0.84	0.84	0.84

Table 9. List of adaptive solutions mainly defined to confront earthquakes and subsidence in an emergency phase.

			PRIORITIZATION INDEX		
			Scale		
Adaptive solution	Hazard		Territorial	Urban	Asset
Vertical Timber Props (Support system)	Earthquakes	Subsidence	0.87	0.87	0.87
Vertical Steel Props (Support system)	Earthquakes	Subsidence	0.90	0.92	0.91
Sloped Timber Props (Peg contrast system)	Earthquakes		0.87	0.87	0.87
Sloped Timber Props (Base contrast system)	Earthquakes		0.71	0.70	0.71
Horizontal Timber Props (Unloading contrast system)	Earthquakes		0.67	0.64	0.67
Horizontal Timber props (Equal contrast system)	Earthquakes		0.71	0.70	0.71
Sloped Steel Props (Contrast system)	Earthquakes		0.71	0.70	0.71
Steel Props (Contrast system)	Earthquakes		0.75	0.74	0.75
Timber support system for openings	Earthquakes	Subsidence	0.87	0.87	0.87
Steel support system for openings	Earthquakes	Subsidence	0.90	0.92	0.91
Timber rib for arches	Earthquakes	Subsidence	0.84	0.84	0.84
Steel rib for arches	Earthquakes	Subsidence	0.87	0.88	0.87
Timber rib for vaulted structures	Earthquakes	Subsidence	0.71	0.70	0.71
Steel rib for vaulted structures	Earthquakes	Subsidence	0.75	0.74	0.75
Steel tie rods for arches	Earthquakes		0.36	0.31	0.32
External steel tie rods for masonry without crosspieces	Earthquakes		0.75	0.74	0.75
Internal steel tie rods for masonry: steel-cased system for walls	Earthquakes		0.37	0.32	0.33
Polyester hoop system for columns and pillars	Earthquakes		0.87	0.88	0.87
Polyester hoop system for building portions	Earthquakes		0.75	0.74	0.75
EEWS: PRESTo	Earthquakes		0.72	0.68	0.71
Resin Injections	Subsidence		0.28	0.29	0.27
Grouting	Subsidence		0.28	0.29	0.27

Table 10. List of adaptive solutions defined mainly to confront storms and flooding in an emergency phase.

			PRIORITIZATION INDEX		
			Scale		
Adaptive solution	Hazard		Territorial	Urban	Asset
Breakaway walls	Flooding	Storm	0.50	0.48	0.48
Pile foundation reinforcement	Flooding	Storm	0.50	0.48	0.48
Temporary flood protection systems: Sandbags (buildings)	Flooding		0.87	0.87	0.87
Temporary flood protection systems: Container systems (districts)	Flooding		0.87	0.87	0.87
Temporary flood protection systems: shields and panels (building)	Flooding		0.90	0.92	0.91
Temporary flood protection systems: Free-standing and frame barriers	Flooding		0.90	0.92	0.91
Installation of check systems and pumps (building)	Flooding		0.80	0.84	0.80
Installation of check systems and pumps (district)	Flooding		0.73	0.77	0.73
Early Warning System	Flooding		0.76	0.77	0.75
Seawalls	Flooding	Storm	0.29	0.23	0.28
Temporary flood protection systems: shields and panels (building)	Flooding		0.90	0.92	0.91
Rapid Damage Assessment	Flooding	Wildfires	0.74	0.77	0.74
Rapid installation panel shutters	Storm		0.77	0.79	0.77
Aquadam	Flooding	Storm	0.61	0.63	0.61
Back-up power generator	Flooding		0.77	0.81	0.77

Table 11. Prioritization index (PI) results for potential solutions both in the emergency and in the general phase.

			Emergency			General phase		
Adaptive solution	Hazard		Territorial scale	Urban scale	Asset scale	Territorial scale	Urban scale	Asset scale
Breakaway walls	Flooding	Storm			0.48			0.42
Pile foundation reinforcement	Flooding	Storm			0.48			0.42
Seawalls	Flooding	Storm	0.29	0.23	0.28	0.27	0.25	0.27
Firebreak	Wildfire		0.22	0.24	0.26	0.16	0.17	0.21
In-channel Tree Felling	Wildfire	Flooding	0.72	0.70	0.73	0.71	0.70	0.70
Straw wattles	Wildfire		0.72	0.72	0.72	0.70	0.69	0.70

Table 12. List of solutions that protect at any scale.

	PI			Cr1			Cr 2			Cr 3			Cr 4		
Adaptive solution	Territorial scale	Urban scale	Asset scale	Territorial scale	Urban scale	Asset scale	Territorial scale	Urban scale	Asset scale	Territorial scale	Urban scale	Asset scale	Territorial scale	Urban scale	Asset scale
Prohibition of stubble burning in high fire-risk situations	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Controlled weed burning	0.97	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.90	0.98	0.99	1.00	1.00	1.00
Early Warning System: territorial level	0.95	0.96	0.95	1.00	1.00	1.00	0.82	0.81	0.81	1.00	1.00	1.00	1.00	1.00	1.00
Reforestation	0.95	0.98	0.95	1.00	1.00	1.00	0.81	0.88	0.82	1.00	1.00	1.00	1.00	1.00	1.00
Biomass management	0.84	0.87	0.85	0.75	0.77	0.76	0.62	0.69	0.63	1.00	1.00	1.00	1.00	1.00	1.00
Green urban furniture	0.80	0.80	0.80	0.75	0.77	0.76	0.82	0.81	0.81	1.00	1.00	1.00	0.59	0.59	0.60
Lightning rod	0.78	0.76	0.77	0.50	0.46	0.49	1.00	1.00	1.00	0.69	0.65	0.63	1.00	1.00	1.00
Shade sails	0.78	0.78	0.78	1.00	1.00	1.00	0.78	0.76	0.77	0.66	0.68	0.66	0.64	0.65	0.67
Check dam	0.76	0.76	0.76	1.00	1.00	1.00	0.90	0.90	0.90	0.66	0.68	0.66	0.47	0.45	0.48
NBS structures associated to urban networks	0.74	0.78	0.79	0.75	0.77	0.76	0.60	0.64	0.61	0.73	0.82	0.92	0.89	0.88	0.89
In-channel Tree Felling	0.70	0.70	0.70	1.00	1.00	1.00	0.42	0.38	0.41	1.00	1.00	1.00	0.31	0.29	0.34
Straw wattles	0.70	0.69	0.70	1.00	1.00	1.00	0.42	0.32	0.40	1.00	1.00	1.00	0.31	0.29	0.34
Debris Rack and Deflectors	0.65	0.68	0.68	1.00	1.00	1.00	0.60	0.58	0.59	0.50	0.64	0.65	0.47	0.45	0.48
Green area for water management	0.63	0.64	0.64	0.75	0.77	0.76	0.78	0.76	0.77	0.60	0.66	0.66	0.36	0.35	0.33
Storm detector	0.62	0.58	0.60	0.50	0.46	0.49	0.92	0.91	0.92	0.69	0.65	0.63	0.36	0.35	0.33
Floodplain and floodable park	0.62	0.62	0.62	0.25	0.23	0.24	0.80	0.84	0.81	0.66	0.68	0.66	0.79	0.79	0.78
Vegetation engineering systems for slope erosion control	0.60	0.61	0.66	0.00	0.00	0.00	0.90	0.94	0.91	0.73	0.82	0.92	0.79	0.79	0.78
Design access paths	0.60	0.62	0.64	1.00	1.00	1.00	0.53	0.52	0.54	0.75	0.87	0.96	0.00	0.00	0.00
Trail Stabilization	0.59	0.61	0.59	1.00	1.00	1.00	0.52	0.58	0.52	0.60	0.66	0.66	0.15	0.15	0.14
Cleaning under high voltage lines	0.56	0.54	0.55	0.50	0.54	0.51	0.63	0.58	0.63	1.00	1.00	1.00	0.00	0.00	0.00
Parks and gardens	0.54	0.57	0.59	0.25	0.23	0.24	0.68	0.74	0.69	0.39	0.50	0.58	0.89	0.88	0.89
IMMERSITE®	0.53	0.52	0.54	0.00	0.00	0.00	0.70	0.70	0.71	0.66	0.68	0.66	0.79	0.79	0.78
Cool Pavements	0.51	0.48	0.49	1.00	1.00	1.00	0.63	0.58	0.63	0.34	0.31	0.29	0.00	0.00	0.00
Road decommissioning	0.45	0.47	0.46	0.50	0.54	0.51	0.50	0.49	0.50	0.60	0.66	0.66	0.15	0.15	0.14
Redesign natural and semi-natural bodies of water and hydrographic networks to limit flooding	0.45	0.45	0.48	0.00	0.00	0.00	0.92	0.91	0.92	0.50	0.64	0.65	0.36	0.35	0.33
Culvert Modification	0.41	0.37	0.39	0.00	0.00	0.00	0.72	0.70	0.71	0.70	0.68	0.67	0.15	0.15	0.14
Green waterfront	0.38	0.40	0.43	0.25	0.23	0.24	0.68	0.74	0.69	0.09	0.18	0.24	0.57	0.55	0.56
Underground drain system	0.38	0.36	0.37	0.00	0.00	0.00	0.44	0.44	0.44	0.70	0.68	0.67	0.36	0.35	0.33

(*Continued*)

Table 12. (Continued).

	PI			Cr1			Cr 2			Cr 3			Cr 4		
Adaptive solution	Territorial scale	Urban scale	Asset scale	Territorial scale	Urban scale	Asset scale	Territorial scale	Urban scale	Asset scale	Territorial scale	Urban scale	Asset scale	Territorial scale	Urban scale	Asset scale
Shoreline structure	0.37	0.36	0.38	0.50	0.46	0.49	0.63	0.68	0.63	0.19	0.20	0.25	0.15	0.15	0.14
Urban floodwalls and barriers	0.31	0.31	0.33	0.00	0.00	0.00	0.62	0.64	0.62	0.56	0.66	0.65	0.00	0.00	0.00
Stream Bank Armouring	0.30	0.34	0.35	0.00	0.00	0.00	0.63	0.68	0.63	0.16	0.32	0.30	0.47	0.45	0.48
Seawalls	0.27	0.25	0.27	0.00	0.00	0.00	0.44	0.44	0.44	0.34	0.31	0.29	0.31	0.29	0.34
Dykes or dams	0.27	0.30	0.29	0.00	0.00	0.00	0.41	0.47	0.41	0.26	0.34	0.32	0.44	0.44	0.46
Debris Basin	0.21	0.23	0.22	0.00	0.00	0.00	0.41	0.47	0.41	0.26	0.34	0.31	0.15	0.15	0.14
Debris Basin	0.21	0.23	0.22	0.00	0.00	0.00	0.41	0.47	0.41	0.26	0.34	0.31	0.15	0.15	0.14
Firebreak	0.16	0.17	0.21	0.00	0.00	0.00	0.53	0.52	0.54	0.12	0.23	0.28	0.00	0.00	0.00

Table 13. List of solutions that protect at asset scale for the general phase.

Adaptive solution	PI	Cr1	Cr2	Cr3	Cr4
Expansion of foundation system	0.287	0.000	0.511	0.000	0.590
FRP hooping for columns, pillars and beams	0.340	0.000	0.916	0.142	0.285
Jacketing through composite material strips	0.347	0.000	0.824	0.328	0.238
Coccioforte vault consolidation	0.359	0.245	0.916	0.000	0.250
Co-generation	0.408	0.000	0.501	0.455	0.658
Application of composite material strips to vaults and arches	0.434	0.245	0.916	0.328	0.250
Wet-floodproofing interventions	0.447	0.000	0.709	0.000	1.000
Intensive and semi-intensive green roof	0.457	0.000	0.806	0.783	0.274
Permanent floodwalls and gates for openings	0.516	0.245	0.916	0.231	0.636
Heat pump systems: geothermal heat pumps	0.541	0.511	0.525	0.455	0.658
Load Paths	0.546	0.489	0.885	0.142	0.628
Aquadam	0.557	0.489	0.401	0.672	0.668
Extensive green roof	0.606	0.000	1.000	0.783	0.646
Surface protection for materials vulnerable to wash-out effects	0.621	0.489	0.916	0.000	1.000
Solar control glass	0.622	0.755	0.824	0.231	0.645
Vacuum Insulating Glass	0.624	0.755	0.824	0.231	0.651
Sand or gravel basement filling	0.631	0.000	0.824	0.672	1.000
Vacuum Insulated Panels (VIP). External application	0.643	0.755	0.824	0.338	0.630
Insulated glazing	0.645	0.755	0.908	0.231	0.651
Natural ventilation (and design for)	0.668	1.000	0.631	0.000	0.967
Cavity wall insulation	0.676	0.755	0.916	0.338	0.668
Climber green wall	0.701	0.489	0.816	0.890	0.630
Internal thermal insulation system: aerogel	0.716	0.755	0.718	0.338	1.000
Phase Change Materials (PCM)	0.716	0.755	0.718	0.338	1.000
Vegetated pergola	0.728	0.489	0.908	0.890	0.644
Vacuum Insulated Panels (VIP). Internal application	0.765	0.755	0.916	0.338	1.000
Internal thermal insulation of roofs	0.777	0.511	1.000	0.561	1.000
Internal thermal insulation system: natural and mineral insulation	0.786	0.755	1.000	0.338	1.000
Internal thermal insulation system: synthetic organic insulation	0.786	0.755	1.000	0.338	1.000
Air conditioning	0.802	1.000	1.000	0.566	0.636
Architectural form of vernacular buildings for hot climate zones	0.812	1.000	0.816	0.783	0.658
Load bearing wall construction for citadels	0.812	1.000	0.816	0.783	0.658
Lightweight timber structures	0.812	1.000	0.816	0.783	0.658
Load absorbing structural connections between structural elements	0.812	1.000	0.816	0.783	0.658
Reinforcement of non-engineered vernacular buildings	0.812	1.000	0.816	0.783	0.658
Shade elements for façades	0.825	1.000	1.000	0.672	0.630

highly ($w_c = 0.22$) valued. It can be appreciated that solutions that protected CNH and in no way contributed to reducing the effect of climate change were rated at 0.7 or higher as long as there was little or no penalization due to other criteria.

The solutions for the general phase at the asset scale are summarized in Table 13. Comparing solutions at this scale, circular economy criterion was the least highly assessed ($w_c = 0.23$) and cultural natural conservation the most highly ($w_c = 0.27$) assessed. Analyzing the list of solutions implemented at the asset scale, it can be appreciated that solutions that are not exclusively designed for natural and climate-change hazards mitigation, but that do protect natural and cultural heritage, received ratings higher than 0.7, provided there was little or no penalization due to other criteria. However, the PI was reduced to values below 0.5 for solutions that apart from not being environmentally friendly, gave no protection to heritage. The solutions that partly altered heritage, but contributed to hazards mitigation, were found in the middle of the ranking.

5. Conclusion

CNH is a vital connection between past and future generations and heritage conservation is crucial for subsequent generations to make sense of past human existence. However, selecting suitable interventions that are focused on sustainable decision-making for CNH conservation is a problematic challenge, due to the variety of the criteria behind the three dimensions of sustainability that have to be considered through the lens of such a wide range of indicators. Moreover, experts within different fields take part in the decision-making process.

The results obtained for the relative weights reflected the concern to maintain CNH. The cultural and natural conservation criterion was the highest valued one, both in the general and in the emergency phase at all scales. Within this criterion, all indicators have similar relevance.

Regarding the rest of the criteria, there was a balance between the values of the relative weights of the indicators, and it corroborated the suitability of the indicators chosen to assess the solution.

The greatest diversity of results on criteria evaluation comparing emergency phase and general situation occurred when the intervention was at the urban scale. The higher value of the relative weight of implementation time in an emergency phase and of the disruption of occupancy/use in the general phase, lent support to the importance of minimal disruption to public life.

When an intervention is needed, the person responsible for the decision will not usually possess sufficient knowledge to assess each solution, considering all sustainability dimensions. Applying the MIVES tool, technicians may select the best solution that contributes most to sustainable development and CNH conservation. However, if the preferences of the end users are not in accordance with the preferences of the panel of experts, the ranking is hardly of any use. In this case, MIVES can be applied modifying the relative weight of the criteria and indicators.

The results obtained for the prioritization of the solutions showed higher scores for the adaptive solutions that attached greater importance to heritage and environmental conservation. These results are aligned with the objectives of the SHELTER project (resilience enhancement of historic areas promoting a sustainable reconstruction), corroborating the suitability of the MIVES methodology as a decision-making tool for heritage management.

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