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Urban-scale framework for assessing the resilience of buildings informed by a delphi expert consultation

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ABSTRACT

The integration of resilience in disaster management is an emerging field as evidenced by an abundant literature. While resilience has been widely explored in several domains, its application demands the consideration of the entire ecosystem and its lifecycle, including disaster stressors and consequences, recovery process, and ultimately the prevention phase. In this paper, a qualitative characterization of resilience for buildings on an urban scale of analysis is achieved throughout the conduct of a Delphi-based expert consultation. The aim is to elicit and validate relevant criteria to characterize the resilience of our built-environment in face of geo-environmental hazards through two phases of consultation involving 23 and 21 respondents, respectively. The initial set of criteria consisted of 40 indicators, increasing to 48 at the end of the survey. The different criteria are clustered into seven categories, ranging from environmental to socio-organizational and technical. The results from both rounds of consultation were then analysed by means of statistical analysis with MATLAB and discussed for each category. The preliminary version of the framework for buildings' resilience assessment on an urban scale is presented with a final set of 43 validated criteria.

1. Introduction

The extensive disaster resilience research points to the increasing frequency in natural hazards and their worldwide consequences [1,2]. For instance, several countries in 2017 have endured devastating storms and hurricanes with dramatic human and financial losses [3]. Conversely, floods have hit several regions in Europe and China with sizeable consequences on human settlements, harvests and crops [3].

In response to these threats, researchers have developed a wide range of methods, strategies, tools and techniques in response to disaster preparedness, mitigation and recovery needs. A key milestone in disaster mitigation was reached in the 2005 World Conference on Disaster reduction (WCDR) [4]. This paved the way to a plethora of research aimed at the integration of resilience as well as hazard preparedness strategies in disaster management. A positivist philosophical stance has then been adopted, focussing on how to enhance resilience as opposed to reducing risks, although the relationship between vulnerability and resilience remains blurred [5]. The United Nations Office for Disaster Risk Reduction (UNISDR) published several reports advocating a more inclusive approach towards resilience and its integration into disaster management strategies [6–8]. UNISDR also engaged in wide resilience-enhancing strategies, such as the Make My City Resilient tool [8,9], aimed at integrating urban development with disaster risk reduction.

A common drawback across different disruptions is that buildings and infrastructures experience significant damages after geo-environmental hazards, with the death toll continuously in the rise [10]. Poor construction quality can exacerbate the level of disruption due to the collapse of structures, putting at risk a higher amount of lives and amplifying the effects of the hazard itself. For this reason, the last decade has seen a steady growth in interdisciplinary resilience research applied across building engineering disciplines. However, the concept of resilience is not novel since its nature and applicability have been widely debated over time [11–13] and can concisely be defined as a systems' capacity to exhibit an acceptable level of performance after undergoing a disruptive event. More recently, resilience has attracted interest in the scientific domain as numerical formulations for its assessment were developed in different domains of engineering, such as structures [14], infrastructures [15], or networked systems [16]. The concept of resilience is also being integrated in risk management planning [17,18] to address safety considerations and the ability of recovering from a disruption. This applies widely to every type of hazard, including both natural hazards and other types of threats such as terrorism.

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The body of research addressing resilience broadly involves different levels and domains of action. Frameworks with the widest perspective generally address the urban context in its entirety in face of a wide range (i.e., generic) types of hazards [19–22], while more specific formulations can refer to the resilience of a single element (e.g., a building) in face of a specific threat (e.g., seismic hazard) [23,24]. Several resilience frameworks, such as the ones devised by Chang [25] and Labaka [26], refer to the TOSE conceptualization of resilience proposed by Bruneau et al. [27], including the four dimensions of resilience, namely: Technical, Organizational, Social and Economical. McDaniels et al. also deal with the topic of critical infrastructures (CIs) but addressing resilience from a management and organizational standpoint [28]. Labaka proposes instead a framework to nurture resilience of CIs employing a Delphi consultation [26], which makes it of relevance for the proposed research. Moreover, Labaka addresses resilience policies and their effectiveness while applied on CIs management. After identifying the main resilience dimensions (i.e., TOSE), a set of resilience policies are identified and their influence on different stages of resilience (i.e., prevention, absorption and recovery) is assessed based on a Delphi consultation. From a more focussed perspective at the single building level, Cimellaro and Bruneau provided their contribution in relation to seismic structural resilience of healthcare buildings [14,24,29,30]. Uzielli proposed a methodology to numerically assess the structural resilience of buildings in landslide prone-areas based on a multi-domain mapping [31].

A wider scale of analysis is encompassed instead in the work by Cutter et al. [22], proposing the 'disaster resilience of place' (DROP) framework which features the assessment of resilience through a set of six categories and relative indicators. However, the targeted application of this framework remains blurred, and therefore, it is not clear how the different indicators can be combined in order to achieve a concrete assessment. Similarly, the frameworks devised by Arup [19] and BuroHappold Engineering [20] contributed to foster the development of urban-scale resilience assessment. The improvements provided by these frameworks consist in the comprehensive perspective of urban centres' resilience when affected by various types of disruptions that can vary from earthquakes to epidemics. Although sharing an objective similar to Cutter's framework [22], Da Silva [19] and Field [20] research is underpinned by a more robust methodology where indicators can be measured and clearly factorized.

World-scale organizations such as UNISDR are also involved in fostering resilience as exemplified by the Hyogo Framework for Action (HFA) [4]. The HFA consists of a milestone for disaster management strategies, advocating the achievement of communities' resilience through the integration of sustainable development and Disaster Risk Reduction (DRR) policies. In addition, it fosters a stronger support to institutions and strategies for ensuring safety while informing disaster preparedness. Innocenti and Albrito [4] also highlight how the concept of "adaption" has been nurtured following to the Fourth Report released by the Intergovernmental Panel on Climate Change [32].

In light of the above, it is evident that while resilience is attracting considerable interdisciplinary research, urban-scale studies addressing resilience from the perspective of buildings and infrastructures, in face of natural hazards, is limited. Moreover, existing approaches either address a broad scale of analysis (e.g., urban level) or target a very specific domain (e.g., structural resilience on a single building level). In our view, existing research initiatives addressing urban-scale resilience [19,20] overlook relevant aspects of technical resilience (e.g., structures and infrastructures features), prioritizing socio-organizational factors. Conversely, detailed approaches for resilience quantification at the building level, such as the ones proposed by Cimellaro et al. and previously described in Refs. [14,24,29], are hardly applicable on an urban scale as these require sizeable computational work.

In order to address this gap, this research proposes a framework for the assessment of the built environment (i.e., buildings and infrastructures) resilience in face of geo-environmental hazards which includes both a qualitative evaluation and a quantitative approach [1]. The framework is grounded on the need for a scalable and concretely applicable resilience strategy that can address both levels of analysis (i.e., urban and building levels). Given that the proposed methodology is building agnostic (i.e., independent from building-specific features), its potential for application can range across different structural and building typologies. The quantitative dimension of the framework encompasses the structural assessment as a method to investigate the building's capacity to endure a specific disruption. Conversely, the qualitative approach integrates policy-making and disaster-management strategies that impact on the buildings' performance beyond their mere structural behaviour but in the context of a whole urban system.

Following this introduction, chapter 2 presents the methodology that underpins the research. Chapter 3 elaborates on the Framework structure design and its constituent dimensions. This is followed by chapter 3 that presents the results of the Delphi consultation, followed by a discussion (chapter 6) of the consensus-based framework for urban resilience assessment with its 48 criteria developed across seven domains. Chapter 7 concludes the paper and provides directions for future research.

2. Methodology

Fig. 1 shows a schematic of the methodology adopted for the proposed expert consultation, which was carried out in two rounds between November 2017 and August 2018. First, a literature review has been carried out in order to gather a set of representative criteria and dimensions to characterize resilience from the perspective of the built environment. This particular step has been achieved through the analysis of existing frameworks and it is thoroughly described in section 3. Next, the objective was to validate the identified indicators using a Delphi consultation process. A Delphi-based validation offers the advantage of factoring in different views from relevant experts in fields of interest within a specified time frame. This is particularly beneficial to account for the complexity of the domain of building resilience. Experts' feedbacks in relation to a particular topic are collected throughout

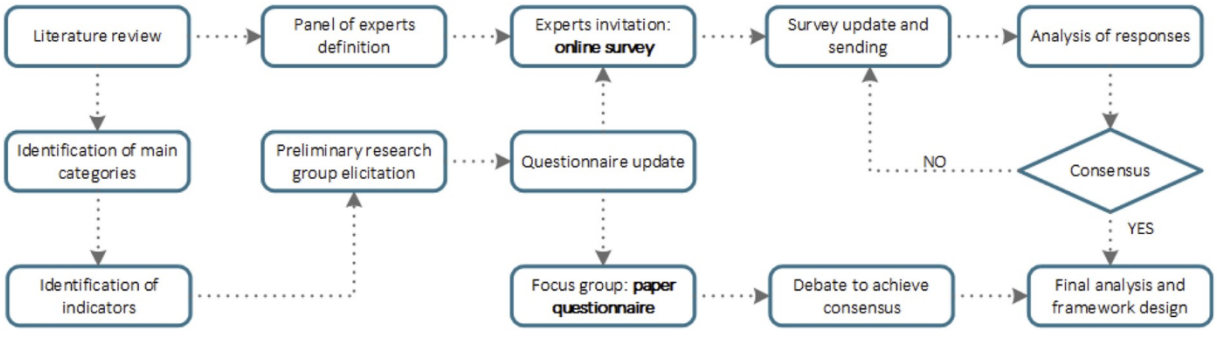

Fig. 1. Delphi consultation methodology.

different rounds of consultation [33]. The Delphi methodology has a consistent and supporting body of research as it has been widely implemented in different fields. Ameyaw et al. [34] provided an extensive overview of different applications in the construction engineering and management domain. However, existing research adopting Delphi methodologies focus on socio-organizational assessment of resilience or target the community in its entirety, hence not focussing on buildings and infrastructures. As an example, Alsheri et al. [21] pursued a socio-organizational assessment of resilience at the community level, characterized through socio-economic factors, whereas Labaka's work [26] revolved around the application of resilience management strategies.

2.1. Delphi expert consultation

The Delphi methodology consists in an iterative process involving the execution of two [35,36] or more rounds [37,38] adopted to collect feedback from experts in a specific domain and in relation to a targeted topic. In the context of this consultation, a panel of experts is elicited in relation to a series of statements to provide a score representing the perceived relevance based on the expert's personal professional background. This methodology has been widely employed in research to anonymously collect judgment from geographically spread experts when it is acceptable to get results in a longer timeline [39]. Past research initiatives praise the advantages of this methodology, highlighting four points, namely: (a) experts' anonymity; (b) the experts are allowed to change their opinion after each round completion; (b) the provision of feedback allows the communication of the outcomes of the previous round; (d) a statistical analysis of the final responses achieves a comprehensive consideration of each experts' feedback [21,40–42].

2.1.1. Panel of experts

As highlighted by Adler and Ziglio [43], the experts that eventually compose the panel need to (a) show willingness to take part in the survey, (b) be in possession of expertise relevant to the specific domain, (c) be able to allocate the necessary time in order to provide a suitable feedback, and (d) provide their opinion in an appropriate way relying on effective communication skills.

It is worth noting that the panel of experts can vary according to the targeted research, as illustrated in Table 1. The lack of a commonly agreed expert panel size has been discussed in the literature [37,44,45] arguing that this can be explained by a wide range of reasons, including time constraints and project objectives. Conversely, Witkins and Altschuld [46] recommend a panel size lower than 50 and Clayton [47] distinguishes between homogeneous and heterogeneous panels composed respectively by experts from the same or different domains of expertise. Authors such as Alsheri et al. [21] started with a panel composed by 71 experts. However, only 40 completed the three rounds. Regarding the research carried out by Labaka [26] in relation to the CIs' resilience, only 15 experts over 21 completed the entire Delphi process. Based on the above, and considering that the acceptance rate will inevitably be lower than the initial number of solicited experts, a minimum of 50 experts were contacted to provide a richer and holistic dataset of responses.

The experts were selected based on a review of the natural hazards resilience literature [1]. Additional experts were identified in the same institutions of this initial group of experts. Research institutes dealing with disaster management (e.g., seismic and geo-environmental hazards) have been considered as well as consulting companies and universities in order to create a comprehensive panel of experts with a view to gather interdisciplinary expertise. The combination of experts from different fields provides the advantage to consider problems from different viewpoints. The initial panel has also been enriched by the involvement of experts from China and United Kingdom who are collaborating with the authors in the context of a project aimed at investigating and improving resilience in the Wenchuan territory in China after the 2008 seismic event (please see acknowledgement section). With regard to the experts from China, a focused group was organized and a paper version of the questionnaire was distributed in two separate rounds. To this regard, Table 2 provides a breakdown of the experts' domain of expertise based on the respondents involved in the two rounds of consultation.

Overall, the initial panel of experts was composed of 70 people from 18 countries with different professional backgrounds. Out of the appointed experts, 23 completed the first round while 21 accepted to provide their feedback also for the second round. Table 3 provides a geographic breakdown of the initial panel of experts and the respondents after the first and second round of consultation. Table 4 illustrates instead the distribution by domain of the initial experts and those who remained after the first and second rounds. As it can be ascertained from Table 4, there is a predominance of experts in the academic domain that remained after the first round. However, a more balanced distribution is achieved in the second round with the percentage of Academics dropping to 38%.

The experts have been informed either by email or in person about the purpose of the research and the implications of a Delphi consultation. In addition, it has been highlighted that their anonymity would

Table 1
Characteristics of different Delphi methodologies.

Reference	Scale type	Initial panel size	Final respondents
Alsheri 2015	5-point Likert	71	40
Labaka 2016	5-point Likert	21	15
Elmer 2010	6-point bipolar	55	45
Jordan 2013	5-point scale	12	11

Table 2
Distribution of experts by domain of expertise.

Domain of expertise	After 1st round	After 2nd round
Earthquake engineering	3	2
Geotechnical engineering	4	4
Urban planning and sustainability	1	1
Geology and risk assessment	11	11
Multi-hazard and reliability analysis	2	1
Urban, social and environmental resilience	1	1
Geotechnical and earthquake engineering	1	1
TOTAL	23	21

Table 3
Geographic distribution of experts across the Delphi consultation rounds.

Country	Initial panel of experts	%	After 1st Round	After 2nd Round
Italy	17	24	2	1
United Kingdom	16	23	4	4
USA	12	17	4	3
China	7	10	7	7
Norway	3	4	1	1
Germany	3	4	0	0
Colombia	1	1	1	1
New Zealand	1	1	0	0
Spain	1	1	0	0
Austria	1	1	1	1
Slovenia	1	1	0	0
Netherlands	1	1	1	1
Saudi Arabia	1	1	1	1
Greece	1	1	0	0
Turkey	1	1	0	0
Iran	1	1	0	0
Canada	1	1	0	0
France	1	1	1	1
TOTAL	70		23	21

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Table 4
Distribution of experts by professional background.

Domain	Initial panel	%	After 1st round	%	After 2nd round	%
Academia	37	53	10	43	8	38
Independent research institutes	21	30	8	35	8	38
Consultancy and Industry	12	17	5	22	5	24

have been guaranteed as a fundamental part of the process. The invited experts have also been informed about the approximate duration of the survey that has been kept under 20 min. The survey has been conducted using two different strategies between the first and second round. Given the size of the initial panel, the formerly Bristol Online Survey (BOS) and current Online Survey tool has been employed (https://www.onlinesurveys.ac.uk/) for the first round. However, excel forms have been adopted instead in the second round to factor in the consultation results (e.g., previous response) from the first round for each respondent individually.

2.1.2. Delphi rounds

Research evidence suggests that the higher the amount of rounds, the lower response rate is achieved [37]. Dalkey et al. [48] observe that the higher accuracy in terms of responses is obtained with two-round Delphi consultations, since usually respondents tend to drop out after that two iterations. With respect to the use of a suitable score-assignment scale, Table 1 indicates that a 1–5 point Likert scale (1 = not relevant, 5 = most important) obtained the higher consent [21,49,50].

Prior to the formal consultation, a trial round has been carried out within the authors' research group to gather feedbacks from researchers, academics (including professors) and PhD students. Fig. 1 highlights the systematic update of new rounds of consultation thanks to the feedback provided in the previous ones. This has been attained by allowing experts to write comments or amendments to indicators, as well as proposing new ones. The same format was adopted for the Q&A session during the focus group with the Chinese experts' delegation, as elaborated in section 3.1.1. No conversation was allowed to avoid bias in the survey results. In this context, the questionnaire was handed over to the experts and completed manually; and after each round, the experts were given the chance of establishing a discussion aimed at achieving the consensus necessary to carry out the ensuing survey stage.

2.1.3. Consensus

In order to move from one round to the following, it is necessary to establish when an acceptable level of consensus amongst the feedbacks has been achieved. Several consensus measurement strategies are available in the literature [51]. However, according to Murphy et al. [52], the most reliable way of defining consensus is the interquartile range (IQR) index. Rayens et al. [53] argue that an IQR $\leq$ 20% of the rating scale is considered to be a good level of consensus. Therefore, based on a rating scale composed of 5 points, an IQR ≤ 1 means that the consensus achieved is in a suitable threshold, with 0 corresponding to the strongest value, while the closer it gets to 1, the lower the consensus will be. The standard deviation is used instead as an indicator of the dispersion of the dataset, hence the higher it is, the more scattered are the experts' responses [54]. According to Goldman et al. [55], standard deviation values greater than 1.5 correspond to a lower consensus. Based on the work by Greatorex and Dexter [54], mean values are considered as a valid pointer for the importance of the different indicators.

There is a debate as to when to stop a Delphi methodology, and based on which assumption. This is discussed in section 4.8. However, the literature does not provide absolute recommendations, while referring to the "hierarchical stopping criteria" [51] devised by Dajani et al. [56]. The later states that the achievement of the consensus itself (i.e., IQR indicator) is not sufficient to be considered as a stopping criterion, as significant fluctuations might occur between the rounds, and therefore stability is a more reliable concept. This can be assessed as described by English and Kernan [57] by means of the adoption of the Variation Coefficient which entails the calculation of the ratio between the standard deviation and mean across all the criteria. This indicator provides a tangible measure of the stability of the system as it advocates that if the difference between the variation coefficients between the two rounds is not significant, it is possible to terminate the process.

The analysis of results has been conducted initially with three different software in order to compare the results, namely Statistical Package for Social Sciences (SPSS), MATLAB and Excel. However, MATLAB has been retained as the definitive analysis tool.

3. Framework structure design

This section describes the process behind the development of the framework and its structure. In line with other resilience approaches [19–21], the framework is structured into a series of criteria which are further grouped into categories according to their topic. Both criteria and categories were identified based on the literature review and enriched with the authors' experience in the fields of analysis.

Seven categories have been identified based on the review of existing frameworks for resilience assessment. Some of these frameworks [19–21] adopt a holistic perspective to community resilience in face of disruptions with a comprehensive approach that does not just address the physical domain but also the human aspects. Burton [58] highlights a persistent set of categories that recur in resilience-related studies and that can be similarly found in the other analysed frameworks with slight adaptations since some aspects might be differently grouped. For instance, "health & wellbeing" does not appear as a main category in the framework devised by Field et al. [20], although it is considered as a subcategory in the "society & community" one.

Table 5 provides an overview of the above-mentioned categories highlighting how the current framework partially shares the view of existing research, but at the same time introducing new elements while leaving out others, which are not functional for the purpose of the analysis. In fact, while the other studies mostly address resilience from an urban standpoint, the current research, in particular, focuses on the resilience of the built environment in the urban context. Therefore, the proposed framework partially shares the existing structure from the state-of-the-art, while also bringing in new embodiments to specifically consider the implications of hazardous events on the built environment. Four categories are thus shared by all the approaches, namely: governance, economy, infrastructures and environment. Specifically, in relation to the economic aspect, it is explicitly mentioned in the work of Alshehri [21] and Da Silva [19], while it is considered as part of the category "Business & Trade" in Field et al. [20].

With respect to the features of the proposed framework that distinguish it from the others, it is possible to consider for instance the involvement of urban morphology and how it can affect the assessment of the impact of a natural hazard. Godshalk [59], for instance, thoroughly discusses how there is a call for more compact urban systems to foster resilience, although some maintain that dispersed frameworks might be more advantageous in face of specific disruptions. The aforementioned category therefore accounts for specific indicators

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Table 5
Categories in existing resilience frameworks and correlation with the proposed one.

Proposed framework	Alsheri et al., 2015	Field et al., 2016	Da Silva, 2016	Burton, 2012	Cutter et al., 2008
Scale of analysis					
Urban	Community	Community/urban	Community/urban	Community	Community
Categories					
Environment				Natural/ecological	Ecological
Governance & Planning	Governance	Governance & Economy	Leadership & Strategy	Institutional	Institutional
Utility Services					
Infrastructures	Physical & Environmental	Environment & Infrastructure	Infrastructure & Ecosystems	Infrastructural	Infrastructure
Emergency & Rescue systems					
Economy	Economic		Economy & Society	Economic	Economic
Land use & urban morphology					
				Community	
	Information & Communication				Community competence
	Health & Wellbeing		Health & Wellbeing		
	Social	Society & Community		Social	Social

characterizing urban features such as: sprawl, density, elevation and distribution of urbanized lands. Burby et al. [60] also argue that urban containment policies might not be always effective to prevent hazardous events to spread, implying that urban planning has an impact on the vulnerability of inhabited areas. This category is also embedded in the review carried out by Sharifi and Yamagata [61] regarding the resilience of urban energy supply networks, highlighting how urban morphology significantly influences the access to energy and its distribution in case of disruption. More recently, urban morphology has been addressed more dynamically and organically, with the development of strategies that actively integrate resilience with spatial morphology and urban ecology, such as the work devised by Marcus and Colding [62]. Similarly, Dhar and Khirfan propose a framework for resilient development of urban contexts in face of climate change [63] based on the panarchy model proposed by Gunderon and Holling [64] for ecological systems.

Utility services are explicitly included given their impact on an urban system's resilience, including all the networks developed for the provision of energy and water supplies. Diversification of energy supply sources, water and energy autonomy as well as availability of back up energy sources are all considered in this category. The infrastructural domain constitutes a vital aspect of resilience and a whole body of research is already in place showing its relevance [26,65,66]. As a matter of fact, infrastructures allow the establishment of physical connections between urban centres and allow rescue services to access the disrupted areas. Situations like the aftermath of the 2008 seismic event in Beichuan (Wenchuan region in China), led to the isolation of the city preventing emergency rescue services to access the area and hence preventing thousands of people from being rescued. In order to avert these occurrences, health-monitoring systems have to be put in place on CIs and this aspect is also accounted for in the current category.

With respect to common categories, a more detailed explanation will be provided to contextualize them in the proposed framework. Firstly, the category named “Environment” encompasses the vulnerability of the system addressing the hazard-related features (e.g., hazard return period) as well as properties of the surroundings (e.g., soil typology). As elaborated in the following section, and to avoid duplication in case a hazard assessment of the area is already available, some of the indicators included therein can be omitted while applying the framework. “Governance & Planning” accounts for the potential presence and application of prevention, mitigation and recovery strategies. The “Economic” category encompasses instead the ability of the local economy of sustaining the costs of recovery, potentially relying also on NGOs or international aids. In the following subsections, the different dimensions are thoroughly analysed and discussed highlighting the underlying reasons driving the choice of the different criteria.

3.1. Environment

Environmental awareness aims to build forward-looking strategies to soften the impact of the hazard and promptly recover from it. It entails a deep knowledge of the surroundings, including the natural environment as well as the exposure and vulnerability of the area, providing an overview of the potential threats in order to foster preparedness.

The first selected indicator is the potential occurrence of simultaneous disruptions, since multi-hazard scenarios produce higher losses because they challenge the vulnerability of the system on several aspects. Related to it, the geographical scale of the hazard needs to be taken into account given its strong influence in terms of prevention, mitigation and recovery planning.

In order to define an indicator that is able to take into account the hazard in a specific area, it should be necessary to characterize three main elements: magnitude of the event, spatial, and temporal measurements [67]. Specifically in relation to earthquakes, a clear distinction has to be made between the definition of hazard and risk. The first is defined as “the probabilistic measure of ground shaking associated with the recurrence of earthquakes” [68], whereas risk involves the potential damage that might occur to the population when a certain hazard is involved. Generally, risk is defined as the combination of hazard, exposure and vulnerability [69]. For the purpose of this research, and more specifically seismic solicitations, the hazard is investigated given that the final framework should address the resilience of the physical built environment system (i.e., buildings and infrastructures). To this regard, the likelihood of occurrence of a specific scenario [70] in probabilistic terms is equivalently expressed by means of the return period. With respect to geo-hazards, such as rock falls or landslides, their forecasting is not straightforward. Tsunamis instead, can be strongly related to the occurrence of an earthquake and crustal-deformation monitoring can contribute to the hazard forecasting [71]. Hazard forecasting is in general hard to achieve and perhaps the ones about which we have the best estimation are earthquakes, but generally the prediction is associated to a probabilistic approach based on historical data.

Additionally, vulnerability, exposure and local amplification factors were listed as indicators for this specific category. Vulnerability generally accounts for the likelihood of undergoing a certain level of damage while affected by a disruptive event of given magnitude. When dealing with natural hazards, the vulnerability usually applies to the physical system, hence structures and infrastructures. Therefore, indicators related to the maintenance level are particularly relevant given that a poor maintenance negatively affects the resistance of the structure even prior to the hazard occurrence. This is also related to local standards and in-effect regulations. Local amplification factors, such as a high acidity rate in rainfall water or pollution [72], are strongly damaging for buildings and infrastructures.

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Giardini [68] includes date and time of the seismic event as a vulnerability factor for seismic risk evaluation. However, these factors are difficult to include given the high uncertainty implied and the scale of analysis. For the purpose of resilience, it is not necessary to include the magnitude of the event as an indicator, given that the return period is already a flag for the hazard intensity.

The intensity of a given hazardous event is a fundamental indicator to be assessed in relation to the resilience of a specific site. Prior to the description of the aforementioned indicator, a clarification has to be made between the indicator "intensity" and the definition of intensity provided in relation to earthquakes, which is different from the concept of magnitude too. In this instance, intensity applies to a qualitative assessment of the hazardous event and its scale has been inferred from the mostly employed magnitude or intensity scales for the different typologies of natural hazards, such as earthquakes, tornadoes, floods, tsunamis. The modified Mercalli scale, for instance, adopts intensity whereas Richter measures the magnitude.

Moreover, it is necessary to consider site-specific features that can affect the integrity of the urban system and lead to secondary effects triggered by the main hazard. Amongst these features, it is possible to include for instance soil properties, general weather conditions and exposure to snow and adverse weather conditions. The presence of potential mappings of the ground is also investigated, being of primary importance for structures and infrastructure design but also for the assessment of the vulnerability of the site. To this regard, it has to be highlighted that where a previous hazard assessment has already been done and is regularly updated, indicators from 1.1 to 1.12 can be neglected to avoid duplications.

3.2. Governance & Planning

This category accounts for the implementation of preventive measures put in place by governmental institutions and the strategies adopted to cope with hazard occurrence. Moreover, this directly applies to the "scale of hazard governance strategies", meaning the geographic extent of hazard prevention or recovery policies in place. These can include for instance immediate post-disaster assessments, relocation of people in the aftermath of a disaster or even allocation of resources for countermeasures and reconstruction. To this regard, it is meaningful to evaluate the scale of the plans devised by local governments, which is also strengthened in other frameworks for resilience management [19,61].

The second indicator of this category applies to the compliance to the existing regulatory landscape, which is of primary importance as it informs building planning, thus preventing unauthorized constructions often located in hazardous areas with a higher vulnerability. Furthermore, the regulatory landscape usually accounts for the specific vulnerability of specific zones, for instance areas located close to rivers or coasts; it is therefore, vital to be considered in this assessment.

The presence of data sensing strategies is also fostered by Sharifi and Yamagata [61], consisting in a useful tool for technical figures to inform governmental institutions in order to produce highly accurate hazard assessments. As an example, data sensing is of primary importance when it comes to the stability assessment of slopes prone to landslides. This technology is highly implemented in China for early warning systems.

Ultimately, education helps younger generations to develop sensitivity to, and understanding of, hazard-related matters. A higher awareness of the vulnerability of existing buildings and different hazard typologies, as well as regular training, can foster prompter reactions when the hazard occurs.

3.3. Utility services

Utility services include energy and water provision networks and their management strategies in case of disruption. This accounts for the urban capacity of providing energy and water coverage even in case the city finds itself isolated as a consequence of an infrastructural failure. Energy and water autonomy demand fundamental requirements [61]. Da Silva argue about the importance of "adequate continuity for critical assets and services" [19]. Field [20] simply embeds utility services into the "resources" category. The set of building –related indicators presented in this section, such as water discharge systems, energy provision, and telecommunications, have to be suitably incorporated to both new and existing structures. This requires careful planning as well as a comprehensive state of the art assessment of existing buildings.

As the concept of resilience applies to before, during and after the disaster, an urban centre has to be provided with systems in place suitable to ensure continuity of energy provision in order to overcome the disruption effects that can potentially delay emergency services. This applies to water, telecommunications and electricity, with an emphasis on the concepts of redundancy and diversification of energy sources or generation strategies [61]. This can be achieved through the diversification of fuels or generation strategies for energy production. The importance of redundancy has also been highlighted by Sharifi [73] by applying this concept not only to energy stocks but also to infrastructures and connections.

Another interesting approach to this topic is provided by Roege et al. [74], who devise a matrix of indicators for the assessment of resilience in the context of energy systems. Of prominent interest is their proposal for a functional redundancy metric, which turns out to be significant, especially in the occurrence of hazards that jeopardize energy provisions. Roege et al. thus devised a 7 points-based scale which qualifies the functional redundancy of a system, defined as "the ability of functionally similar elements to partly or fully substitute for each other" [74].

Telecommunication systems include for instance Internet, mobile and cable lines. In order to assess the resilience of telecommunication systems in case of disruption, the proposed indicator should be able to assess the level of integration of technologies that can be independent from potential damages resulting from natural hazards. Therefore, satellite systems would probably represent the most reliable telecommunication technology. Nonetheless, satellite telecommunication systems can hardly be found in at-risk areas, and for this reason it could be more convenient to invest in the redundancy of network systems. In this manner, users could easily rely on back up communication systems in the occurrence of a break down [75].

In order to avoid chain failure of electric systems, circuit breakers and analogous strategies need to be put in place [61]. Local energy power generators and uninterruptible power systems (UPS) [76] can be taken into account as indicators of backup solutions, although they might not be sufficient to cover the demand of essential infrastructures such as hospitals.

With respect to water, inhabitants have to be able to access potable water. Therefore, treatment of used water has to be made in order to be potentially made drinkable again [61,77]. This relates also to the water autonomy of the urban autonomy that has to be known prior to any disruptions, as well as the aforementioned elements.

3.4. Infrastructures

Infrastructures are broadly classified as the physical and organizational assets, essential for the functional operation and connection of elements inside and outside a defined system (i.e., urban centre). This includes for instance: bridges, road assets, transportation networks and tunnels. Moreover, some building regulations [78] classify specific types of infrastructures (and structures) as "strategic", meaning that they play a key role in case of emergency. This category embeds for example bridges, as well as environmental infrastructures such as dykes. To this regard, tailored strategies, such as structural health monitoring (SHM) [79], are usually employed to assess their conditions over their service life in order to adapt maintenance strategies

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accordingly.

Real-time structural health monitoring particularly might contribute to the prevention of secondary disasters triggered by the initial failure of the infrastructure. For instance, dykes and water reservoirs can fail after a seismic event leading to floods and putting at stake the integrity of urban centres nearby. As also mentioned above, SHM techniques can inform maintenance strategies contributing to sustain the efficiency and safety of the infrastructural system. Therefore, the maintenance regime plays a key role for the achievement of resilience, as identified by previous research [28], including the frameworks proposed by Field et al. [20] and Da Silva [19].

Service continuity of infrastructures is also achieved through redundancy. A redundant system is in fact provided with additional elements that would be necessary to sustain its function, and hence be able to maintain a minimum required level of functionality in case of failure. It is then crucial to assess the level of connectivity provided by an infrastructural network for it to be reliable and resilient.

3.5. Emergency & rescue systems

Recovery is a vital portion of the resilience process and it is achieved through the provision of an effective emergency network. This has to include both services and infrastructures which all have to be redundant [73] but also provide an efficient coverage of the territory in order to avoid exposed areas. The whole set of indicators presented in this section is highly dependent both on the urban structure and its planning strategies but also entails a close adjustment of existing buildings where they do not comply with safety regulations.

As an example, the spatial distribution of critical infrastructures such as hospitals, encompasses a constant update and adjustment to building and urban planning regulations to ensure the most efficient service possible in case of disaster. Equally important is the access to evacuation information and their availability in order to make people aware of the location of potential shelters of safe spots. Emergency evacuations plans have to be regularly revised and updated and these information have to be as accessible as possible to the public. To this regard, buildings such as schools and hospitals have to be steadily assessed when the amount of users increase compared to the initial design, not to compromise potential evacuation strategies.

3.6. Economy

Financial aspects are key for building resilience and they can highly affect the quality of the physical system. Specifically, the performance of a building during and after a disaster is highly conditional on the quality of the structure, which is itself dependent on the technologies in place. Moreover, poor quality materials and structural systems are often the primary cause of lack of performance.

Briguglio et al. [80] proved that the Gross Domestic Product is a strong influencing indicator for the economic resilience of a country. Evidence suggests that countries with a more consistent financial availability are known to be more resilient in face of natural hazard [80], even when potential international aids are available. In fact, Greene et al. [81] pointed out that the GDP can be classified as a pointer for quality standard of constructions, therefore resulting in poor resilience in deprived economies. It is renowned that the poorest districts of urban agglomerations are characterized by scarce construction quality. This factor becomes extremely relevant in the context of megacities (e.g., Mexico City) and villages in underdeveloped or developing economies.

The availability of financial support to renovate a structure in order to comply with updated regulations can improve and enhance building resilience significantly. Similarly, assessing the quality of the building in the immediate aftermath of a disaster can foster more effective recovery strategies, preventing further deterioration or damage increase. Faster recovery times also allow people to be relocated more efficiently and hence reduce discomfort and costs deriving from temporary accommodations.

3.7. Land use & urban morphology

A suitable land use is widely acknowledged to contribute to resilience when taking into account the urban development [19]. Population density is also embodied as an indicator [20] given its influence on an urban scale. However, this criterion alone would lead to misunderstanding given the different impact that a hazard can have on comparable densely populated cities, with varying levels of preparedness and infrastructural robustness. Therefore, quantifiable parameters are also embedded to gather an accurate characterization of the urban fabric in terms of building heights, zoning and development pattern.

Urban density is recognized in the literature [81] as a significant indicator which can help clarify the correlation between population density and specific building typologies, therefore informing the variation in population distribution throughout the urban complex. In fact, population density is usually measured as an average value, hence “flattening” potential fluctuations to a unique number. The latter is however not representative of the effective distribution of the inhabitants of an urban centre (e.g., metropolises). Loo and Ong [82] strengthen this view, maintaining that population density can significantly vary from one urban area to another. To this regard, the authors [82] suggest to address the index specifically to differentiate between highly dense residential areas, suburban or business areas.

In addition, from an urban perspective, it is also relevant to understand how these densities (i.e., population and building) are physically spread over the land surface and in relation to time, since density represents an average value assuming an even distribution over the territory, which is unlikely to be the case in reality. In order to achieve this, Marinosci et al. [83] analysed a set of 73 cities in the Italian territory and, by means of GIS techniques they calculated several indicators to represent the urban compactness (i.e., Largest Class Path Index, LCPI), the tendency of urban boundaries to expansion, and the diffusion of peripheral areas. Two more indicators have been taken into account with regard to the urban dispersion phenomenon, namely the dispersion index and the ratio between low-density areas and the overall municipality boundaries. Based on these factors it has been possible to devise a categorisation of urban structures in four main typologies, namely: 1) Monocentric, 2) Monocentric with a tendency to dispersion; 3) Diffuse urban structure; 4) Polycentric. A breakdown of several types of urban structures is also provided by different researchers [61,81,84], who identify four main urban patterns, namely: rural-urban, boundary, sprawl and compact. On the other hand, a more detailed approach has been adopted by Marinosci [83] who attempts to highlight the urban structure based on the sprawl index.

In order to achieve a more thorough understanding of the urban structure, there is a need to introduce the building density as an indicator that can be achieved through the embodiment of a series of factors herein described. A necessary differentiation between the diverse indexes involved in the urban domain has to be done, specifically in relation to the Floor Area Ratio (FAR) and the Building Coverage Ratio (BCR). The first accounts for the ratio between the overall summation of the building's floor surfaces over the related land area, whereas the second represents the ratio between the external contour of a building, as seen from the top, and the area of the site [85]. The FAR reveals to be more representative in this context, providing an idea of the volumetric occupation of the building, and not just its shape, as is provided instead by the BCR. The latter, in fact, would imply just an understanding of the overall coverage of the territory, while in this context it is vital to acknowledge also the vertical distribution of the urban stock. As a matter of fact, two land areas with the same extent might show the same BCR index but completely different FAR because the vertical extent of the buildings is different. In order to enrich the dataset of information related to the buildings' height profile, Digital

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Table 6
Summary of results.

Dimension	Round 1			Round 2		
	Total criteria	Successful criteria	%	Total criteria	Successful criteria	%
Environment	12	8	67	13	11	85
Governance & Planning	4	2	50	4	4	100
Utility Services	8	8	100	10	9	90
Infrastructures	3	3	100	4	3	75
Emergency & Planning	4	4	100	4	4	100
Economy	4	1	25	7	6	86
Land use & urban morphology	5	4	80	6	6	100
Overall	40	30	75	48	43	90

Surface Models (DSM) techniques can be employed.

4. Results and analysis

The Delphi expert consultation was carried out between November 2017 and August 2018, involving an initial panel of 70 experts tasked to review 40 indicators. Two rounds were performed through an online survey, in addition to a focus group meeting with project partners and a trial round involving academics in the authors' institution. The final set of indicators involve 48 different criteria grouped into seven dimensions. The final number of respondents is 23.

Table 6 summarises the dimensions selected for resilience assessment with a breakdown of the results after the first and second round of consultation. The following subsections describe how the indicators have been modified based on the experts' feedbacks, and elaborate on the corresponding statistical analysis.

Prior to the detailed analysis, it is worth mentioning that the first round outputs were processed with three different tools (i.e., MATLAB, SPSS and Excel), as previously highlighted in section 3. MATLAB was adopted for consistency reasons. The related research is presented in section 2. The IQRs obtained with the three tools presented a discrepancy of ± 0.25 in relation to some of the criteria. The latter can be justified by the different mathematical methods adopted by the software that, combined with the small dimension of the dataset, lead to higher discrepancy [86]. After the second round, the consensus rate increased, with just 5 indicators deemed not satisfactory. The economic category registered a significant surge both in terms of successful indicators and consensus at the end of the survey, although resulting as the weakest after the first round of consultation.

The first round was carried out using the online tool "Online Survey" (formerly BOS), while for the second phase a dedicated excel form was used. This was motivated by the need to provide a bespoke form and given the impossibility of implementing previous rounds' results in the Online Survey tool. This constraint would have prevented the provision of the feedback. Therefore, the excel forms were customised for each expert, including: a) mean values for the whole responses; b) standard deviation for the total dataset; c) individual response for the former round; d) IQR for the different criteria. The form was also augmented with additional space for the experts to devise modifications to the indicators or suggest new ones.

The indicators were differentiated according to three categories:

- Blue: New scoring not required in case the respondent did not change opinion because the criterion did not undergo changes and consensus has been achieved;
- Orange: New scoring required because the criterion has been updated from the first round even though an acceptable level of consensus has been achieved.
- Red: New scoring required as either consensus has not been achieved or the indicator has been implemented just in the second round.

The following sections provide the boxplots and statistical breakdown for the criteria included in each of the domains. The boxplot is represented by a rectangle where the upper and lower sides correspond respectively to the third and first quartiles, while the line contained in the rectangle is the median value. The dashed lines end with whiskers representing the maximum and minimum value of the dataset.

4.1. Environment

A first glance at Fig. 2 reveals that between the first and second round there is an increase in the consensus and a general higher score assignation to the different criteria. The dispersion of the dataset visible from both Fig. 2 and Table 7 shows an improvement from round 1 to round 2 since the height of the rectangles, including the extensions, decreases. However, some criteria have been rephrased between the two rounds in light of the experts' opinions.

The first indicator has been judged confusing in the first formulation, hence it has been rephrased in a more linear form. The potential co-occurrence of more than one hazard has been considered significant. Indicators from 2 to 10 in the first round have been pointed out as significant especially when a hazard assessment is lacking. The authors agree with the experts and to this regard, in section 3.1, a similar specification has been pointed out regarding the adoption these indicators in the absence of a hazard assessment. The "scenario

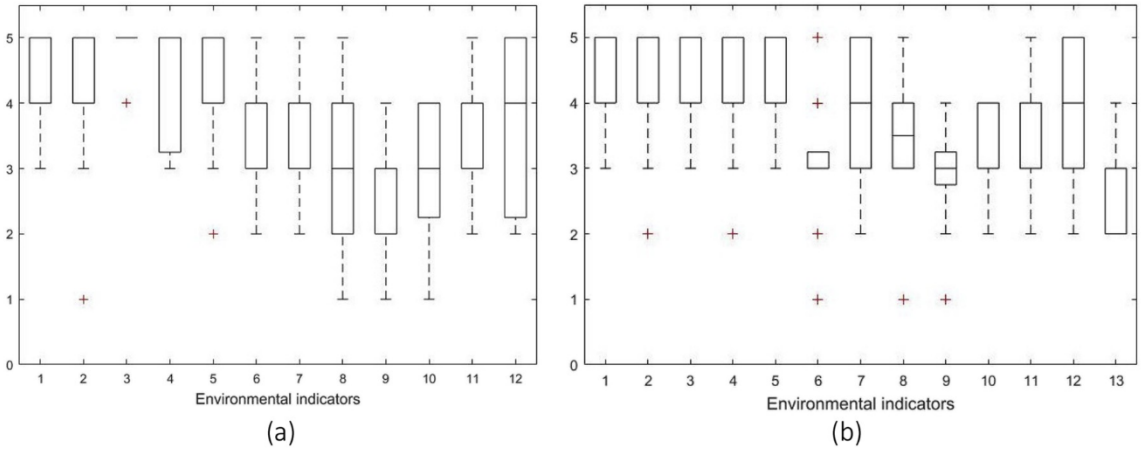

Fig. 2. Environmental boxplots after the first (a) and second (b) rounds of consultation.

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Table 7
Environmental criteria consensuses, *(IQR): interquartile range.

	First round	Mean	St.Dev.	IQR*
1	Single hazard (e.g., flood, earthquake, landslide, tsunami) vs multiple hazard occurrence (e.g., flood-earthquake, landslides- earthquake, earthquake- tsunami)	4.18	0.795	1
2	Geographical scale of hazard(s) (e.g., local, regional, territorial)	4.18	0.958	1
3	Intensity of hazard(s)	4.82	0.395	0
4	Scenario probability (i.e., likelihood of occurrence of a specific disruptive condition)/identification of the most probable scenario	4.23	0.869	1.75
5	Site location (e.g., altitude, urban or country area, flat or mountainous site)	4.32	0.780	1
6	Local environmental factors (e.g., pollution, chemical aggressiveness, vibrations)	3.23	0.685	1
7	Geotechnical awareness of the area (e.g., drill cores, investigations, maps)	3.36	0.902	1
8	Ground typology (e.g., classification according Eurocodes)	2.91	0.971	2
9	Level of exposure to snow (according to Eurocodes)	2.50	0.859	1
10	Class of exposure to wind and terrain category (according to Eurocodes)	3.00	0.976	1.75
11	Level of engineering alterations with potential impact on the soil properties (e.g., mines, deforestation, fuel extraction)	3.36	0.902	1
12	Presence of hazardous industrial areas (e.g., nuclear plants)	3.77	1.307	2.75
	Second Round			
1	Number and specific typology of hazard(s) simultaneously occurring in the disaster scenario	4.33	0.730	1
2	Geographical scale of hazard(s) (e.g., local, regional, territorial)	4.24	0.831	1
3	Intensity/magnitude of hazard(s)	4.52	0.680	1
4	Hazard return period	4.10	0.831	1
5	Site location (e.g., altitude, urban or country area, flat or mountainous site)	4.29	0.644	1
6	Local amplification and environmental factors (e.g., pollution, chemical aggressiveness, vibrations)	3.10	0.831	0.25
7	Geotechnical awareness of the area (e.g., drill cores, investigations, maps)	3.86	1.153	2
8	Soil typology (e.g., classification according Eurocodes)	3.50	1.118	1
9	Level of exposure to snow (according to Eurocodes)	2.95	0.805	0.5
10	Class of exposure to wind and terrain category (according to Eurocodes)	3.19	0.602	1
11	Level of engineering alterations with potential impact on the soil properties (e.g., mines, deforestation, fuel extraction)	3.57	0.746	1
12	Presence of hazardous industrial areas for potential disaster chain occurrence (e.g., nuclear plants)	3.86	1.014	2
13	General climatic type according to Köppen classification (e.g., continental, temperate, tropical)	2.46	0.660	1

probability" has been considered inaccurate in its formulation. It has hence been rephrased specifying the reference to the return period. Indicators 6 and 7 in the first round have not been recognized as relevant for resilience, and particularly in relation to the "geotechnical awareness of the area" (i.e., 7) where the consensus has not been achieved through the second round. Some experts argued that the geotechnical awareness is more significant throughout the design phase rather for resilience enhancement. However, a suitable geotechnical awareness of the area can help inform mitigation and prevention strategies, in addition to address vulnerability reduction in specific areas known for being prone to hazards.

Indicators 8–10 were considered as hazard and site-specific but over the second round the experts achieved an agreement in relation to an average importance. Indicators such as 6, 8, 9, and 10 registered a considerably lower score compared to the other indicators, which is surprising considering the impact that these environmental factors can have on buildings' durability and stability. However, the experts pointed out that these factors, particularly "local environmental factors" (i.e., 6) and exposure to snow and wind (i.e., 9 and 10), are meaningful over a design phase, similarly to the observations for indicator 7. However, it is argued that it would be possible to enhance the structures' resilience by acting on more effective maintenance strategies where potentially dangerous environmental conditions are found (e.g., chlorides, pollutants). The "general climatic type" has been implemented in the second phase following experts' feedback but a weak agreement has been reached in relation to its scarce importance. The relevance attributed to the potential presence of hazardous industrial areas (i.e., criterion 12) was rather low and surprising, considering the lessons learnt from Fukushima and the disaster chain that characterized that catastrophe.

4.2. Governance & planning

This category showed little success over the first phase whereas a stronger consensus and overall higher scores have been obtained in the second round, as illustrated in Fig. 3 and Table 8. The scale of hazard management strategies sustained a high score throughout the two rounds, whereas the "level of compliance to existing regulatory landscape" showed a higher disagreement in the second round. This indicator has been considered meaningful and experts commented that its relevance is highly conditional on the quality of the existing regulations in terms of hazard mitigation. Indicators 15 has been rephrased for the second round into "presence of monitoring and data collection" as this formulation allows to also include early warning strategies. This change is reflected in a higher score even if the standard deviation shows a considerably spread range of opinions around this indicator. This is surprising given the impact that early warning systems have on hazard management and maintenance strategies, especially in relation to CIs such as bridges. Real time monitoring of landslide-prone gullies, for instance, can enhance preventive strategies and more effective evacuation plans can be devised to promptly rescue the population when the hazard is expected. The indicator addressing education and training strategies has been deleted. Although some experts pointed out that the criterion is important, there is disagreement about its utility in the context of built environment resilience assessment.

4.3. Utility services

Utility services appear to be one of the most successful categories registering considerable improvements from one round to the other in terms of score and compactness of the dataset, as illustrated in Fig. 4. All the indicators scored more than 4 apart from the "separation of used water into grey and black flow" which achieved 3.38 in the second round. The experts argued however that cross-contamination can escalate the impact of a hazard at the city scale. Table 9 shows that the average score is high for all the criteria and in particular the "vulnerability of energy supply network", which registered an outstanding result with 4.83 and the lowest level of dispersion of the whole category. The vulnerability assessment of energy supply networks plays a crucial role especially in the aftermath of a disaster. It is hence important that potential faults are detected as they occur. This indicator has been introduced in the second round based on experts' suggestions

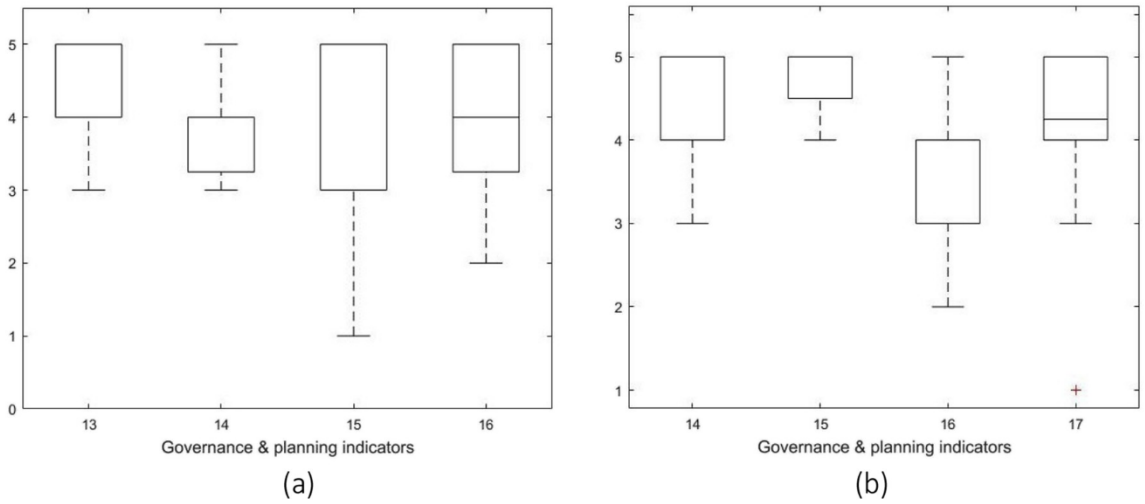

Fig. 3. Governance & planning boxplots after the first (a) and second (b) rounds of consultation.

as well as the "integrity and connectivity of telecommunication and energy supply networks". This is motivated by the need of relying on well-connected and stable communication systems that can perform even in face of a disruption, enhancing the recovery process and facilitating the rescuing measures.

4.4. Infrastructures

In Table 10 and Fig. 5, it is visible how the current category displays a series of criteria which scored considerably high, ranging from 3.95 in the first round to 4.63 in the second one. The indicator representing the level of maintenance registered a lower score than anticipated in the second round, while having the lowest assigned importance for both phases. As discussed in the previous sections, maintenance plays a key role in CIs' performance under external disruptions. Besides, structures are subjected to degradation over time and in order to preserve their performance an effective and regular maintenance is vital. An additional indicator (i.e., 31) has been implemented in accordance with the suggestions provided by some of the experts'. It is indeed relevant to take into account the accessibility to infrastructures in order to foster recovery and allow a smooth intervention for emergency rescue services.

4.5. Emergency & rescue systems

As it can be observed from Table 11, the indicators between the two rounds remain unchanged, as well as the dispersion and consensus of the dataset. Given that the discrepancies between the two rounds is very small, there is no visible difference in the two boxplots of Fig. 6. In this phase, some experts argued that the availability of contingency plans (i.e., criterion 31 in round 1) refers more to a community resilience assessment rather than a building-related one. However, elements such as evacuation strategies and traffic management are tightly related to the recovery of buildings. In fact, the smoother is the evacuation process the easier for example the fire brigade can intervene and extinguish a fire, thus avoiding the complete collapse of a structure. The spatial distribution of CIs has been judged considerably relevant in relation to the coordination of post-immediate response and recovery, in agreement with several experts' feedbacks.

4.6. Economy

This category showed contrasting feedbacks after the first round. In fact, it has been significantly modified for the second phase of consultation, as evidenced in Table 12. Fig. 7 illustrates how the first three criteria show coherence between the two rounds and the assigned relevance ranges in the final round between 4.05 and 4.62. However, the indicator addressing financial support for disaster post-response (i.e., 34 in the first round) registered a higher level of disagreement over the second round as well as a higher dispersion.

There is a strong level of consensus in relation to the moderately low relevance of factors such as the GDP, even though it is known that wealthier countries have more margin to invest in performing structures and can provide more resources to boost the recovery process. The presence of Non-governmental Organizations (NGO) and the availability of foreign aids represent an additional criterion pointed out by

Table 8
Governance & planning criteria consensuses, *(IQR): interquartile range.

	First round	Mean	St.Dev.	IQR*
13	Scale of hazard governance strategy (e.g., flood prevention strategies at local, regional and national level)	4.61	0.739	1
14	Level of compliance to existing regulatory landscape	3.86	0.640	0.75
15	Presence of data sensing and acquisition for hazard forecasting	3.91	1.342	2
16	Education (from elementary or secondary school), training and communication	4.05	0.999	1.75
	Second round			
14	Scale of hazard governance strategy for hazard prevention and recovery (i.e., post-disaster reconstruction)	4.43	0.746	1
15	Effectiveness of previous disaster governance strategies	4.75	0.500	0.5
16	Level of compliance to existing regulatory landscape	3.76	0.831	1
17	Presence of monitoring and data collection (i.e., early warning systems)	4.13	1.170	1

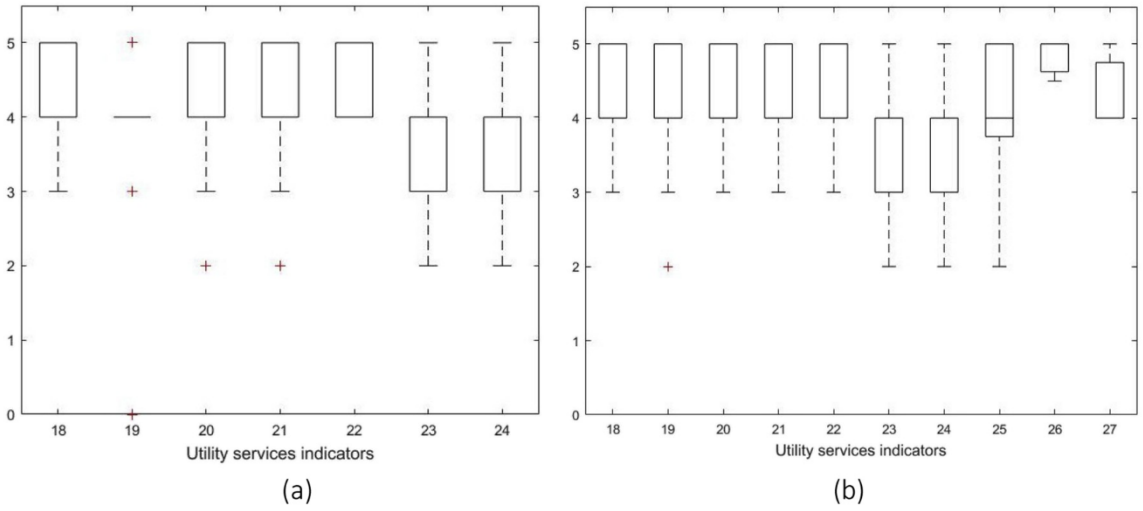

Fig. 4. Utility services boxplots after the first (a) and second (b) rounds of consultation.

some of the experts and considered vital especially for countries that cannot rely internally on significant financial funds. The lowest score has been registered for the criterion addressing the different types of industries able to support the local economy, which was assigned 3.21 in the second round with the experts agreeing on its low relevance for this research context. However, the implementation of this indicator was motivated by the feedback received from the first round, highlighting the need for an indicator taking into account the drivers of the local economy.

4.7. Land use & urban morphology

Table 13 shows how the indicators between the first and second round remained unchanged apart from the implementation of the criterion addressing the prevailing land use, which has been highlighted thanks to the experts' feedback. However, this criterion scored just 3.71 on average in the second round, with a considerably general agreement given the IQR of 0.5. Overall, Fig. 8 displays a significant improvement in the level of consensus and compactness of the dataset. This category is not considered by the experts to be particularly influencing for the resilience of the built environment apart from population density, which is the only indicator scoring more than 4 in both rounds with a stable level of agreement.

However, urban indexes such as the ones represented by the criteria 38, 39 and 40 (i.e., 45, 46 and 47 in the second round) provide a tangible, measurable and practical characterization of the city landscape. This consequently informs the urban-scale distribution of different types of buildings, allowing a more comprehensive understanding of the underlying vulnerabilities. This observation also applies to the urban fabric criterion, which appears to not contribute to the enhancement of resilience in the experts' view.

4.8. Termination criteria of the delphi process

As anticipated in section 3.1.3, Dajani et al. [56] classify as a termination option the achievement of stability in combination with the consensus target fulfilment. Stability is defined as the statistical consistency between two values for the same variables across two rounds of the consultation. In order to be quantitatively assessed, the methodology devised by English and Kernan is adopted [57]. In section 3.1.3, the methodology devised by English and Kernan [57] has been introduced in reference to the work by Dajani et al. [56]. Based on the values of mean and standard deviation, the variation coefficient has been calculated and its trend is presented in Fig. 9. The line

Table 9
Utility services criteria consensuses, *(IQR): interquartile range.

	First round	Mean	St.Dev.	IQR*
17	Level of energy autonomy (e.g., backup energy sources, stocks of energy)	4.41	0.666	1
18	Operational system protection (e.g., system relief, circuit breakers)	4.05	0.653	0
19	Diversification of energy supply (e.g., fuel mix, multi-sourcing, type of generation)	4.05	0.785	1
20	Level of functional redundancy (i.e., the ability of functionally similar elements to partly or fully substitute for each other)	4.05	0.999	1
21	Level of water autonomy (e.g., reservoir capacity, water supply network capacity)	4.59	0.503	1
22	Separation of used water into grey and black flows	3.41	0.908	1
23	Level of waste water discharge capability (e.g., soil absorption, green or grey infrastructures)	3.55	1.011	1
24	Diversity and redundancy of telecommunication systems (e.g., cable internet lines, wireless technologies, satellite)	4.27	0.827	1
	Second round			
18	Level of energy autonomy (e.g., backup energy sources, stocks of energy)	4.52	0.602	1
19	Operational system protection (e.g., system relief, circuit breakers)	4.14	0.854	1
20	Diversification of energy supply (e.g., fuel mix, multi-sourcing, type of generation)	4.14	0.655	1
21	Level of functional redundancy (i.e., the ability of functionally similar elements to partly or fully substitute for each other)	4.19	0.680	1
22	Level of water autonomy (e.g., reservoir capacity, water supply network capacity)	4.43	0.598	1
23	Separation of used water into grey and black flows to avoid cross contamination	3.38	0.740	1
24	Level of waste water discharge capability (e.g., soil absorption, green or grey infrastructures)	3.43	0.811	1
25	Diversity and redundancy of telecommunication systems (e.g., cable internet lines, wireless technologies, satellite)	4.00	0.949	1.25
26	Vulnerability of energy supply network (e.g., gas pipes, water reservoirs)	4.83	0.289	0.375
27	Integrity and connectivity of telecommunication and energy supply networks	4.33	0.577	0.75

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Table 10
Infrastructural criteria consensuses, *(IQR): interquartile range.

	First round	Mean	St.Dev.	IQR*
25	Presence of structural health monitoring systems of critical infrastructures (e.g., reservoirs, dams)	4.36	0.902	1
26	Connectivity level of transportation networks (e.g., railway stations, airports)	4.32	0.716	1
27	Level of maintenance regime of public infrastructures	4.05	0.722	0.75
	Second round			
28	Presence of structural health monitoring systems of critical infrastructures (e.g., reservoirs, dams)	4.33	0.856	1
29	Connectivity level of transportation networks (e.g., railway stations, airports)	4.33	0.796	1
30	Level of maintenance regime of public infrastructures	3.95	0.973	1.25
31	Accessibility and transport network proximity to emergency services	4.63	0.644	0.75

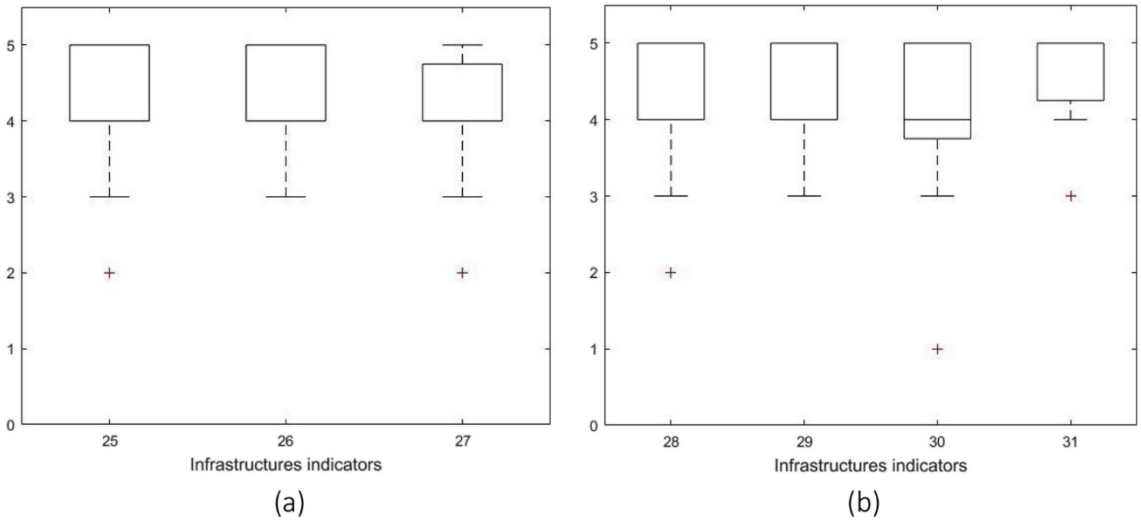

Fig. 5. Infrastructures boxplots after the first (a) and second (b) rounds of consultation.

Table 11
Emergency & rescue services criteria consensuses, *(IQR): interquartile range.

	First round	Mean	St.Dev.	IQR*
28	Redundancy of critical infrastructures (e.g., hospitals)	4.45	0.671	1
29	Spatial distribution of critical infrastructures	4.32	0.716	1
30	Emergency communications, access to warning systems and evacuation information	4.64	0.581	1
31	Availability and update of contingency plans (e.g., evacuation strategies, traffic management)	4.41	0.666	1
	Second round	**Mean**	**St.Dev.**	**IQR***
32	Redundancy of critical infrastructures (e.g., hospitals)	4.48	0.750	1
33	Spatial distribution of critical infrastructures	4.24	0.700	1
34	Emergency communications, access to warning systems and evacuation information	4.52	0.680	1
35	Availability and update of contingency plans (e.g., evacuation strategies, traffic management)	4.38	0.740	1

representing the first round data set appears scattered in some points because of the additional indicators implemented for the second phase. The x axis contains the reference number for the criteria of the second round, but the corresponding first-round criteria can be easily retrieved in Tables 7–13 The dotted line represents the absolute difference between the variation coefficients between the two rounds.

English and Kernan establish that a variation coefficient between 0 and 0.5 is acceptable to consider consensus achieved and hence terminate the process. Firstly, it has to be observed that overall the criteria fulfils the requirement of stability and hence justify the termination after two rounds. Fig. 6 displays a significant stability of the dataset, registering a peak of variation of 0.151 for indicator 18 (i.e., 17 in the first round), corresponding to “Level of energy autonomy (e.g., backup energy sources, stocks of energy)”. The difference between the variation coefficients has just been calculated for the common values, so the new indicators have not been considered.

5. Discussion

Fig. 10 shows the final framework for urban resilience assessment with the 48 criteria clustered into seven domains. The wind rose diagram also summarises the mean value for each indicator according to the results presented in Section 4, in line with the second round of consultation. Overall, the majority of the indicators scored over 4 points, while a minority was rated between 3 and 4.

On the whole, a significant increase in the consensus rate has been registered moving from one round to the other, raising the number of satisfactory indicators for each round from 30 to 40 and 43 to 48, respectively, with an overall success of about 90% after the second round. However, five indicators did not meet the consensus criteria, while two

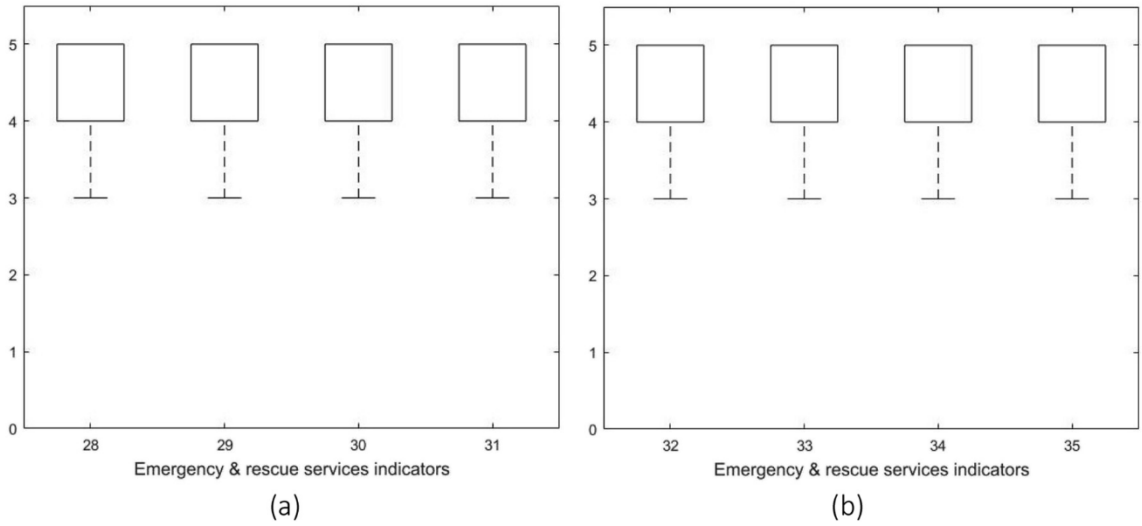

Fig. 6. Emergency & rescue services boxplots after the first (a) and second (b) rounds of consultation.

Table 12
Economy criteria consensuses, *(IQR): interquartile range.

	First round	Mean	St.Dev.	IQR*
32	Availability of post-disaster financial assessment	4.05	0.785	1.75
33	Availability of financial support to comply with existing regulations (e.g., structural interventions to comply to new building regulations)	3.95	0.785	2
34	Availability of financial support for immediate post-crisis response (e.g., governmental, insurance coverage, contingency funds)	4.68	0.568	0.75
35	Country Gross Domestic Product (GDP)	3.27	1.032	1.75
	Second round			
36	Availability of post-disaster financial assessment	4.05	0.740	1.25
37	Availability of local financial support to comply with existing regulations (e.g., structural interventions to comply to new building regulations)	4.12	0.705	1
38	Availability of financial support for immediate post-crisis response (e.g., governmental, insurance coverage, contingency funds)	4.62	0.669	1
39	Mixture of resources available for post-crisis response (e.g., partly supplied by government, partly underwritten by insurance)	3.83	1.115	1
40	Country Gross Domestic Product (GDP) and its influence on prevention and recovery	3.48	0.928	1
41	Presence of NGOs and capability of using foreign aid	3.42	0.793	1
42	Classification of industrial structures and type that support local economy	3.21	1.157	0.75

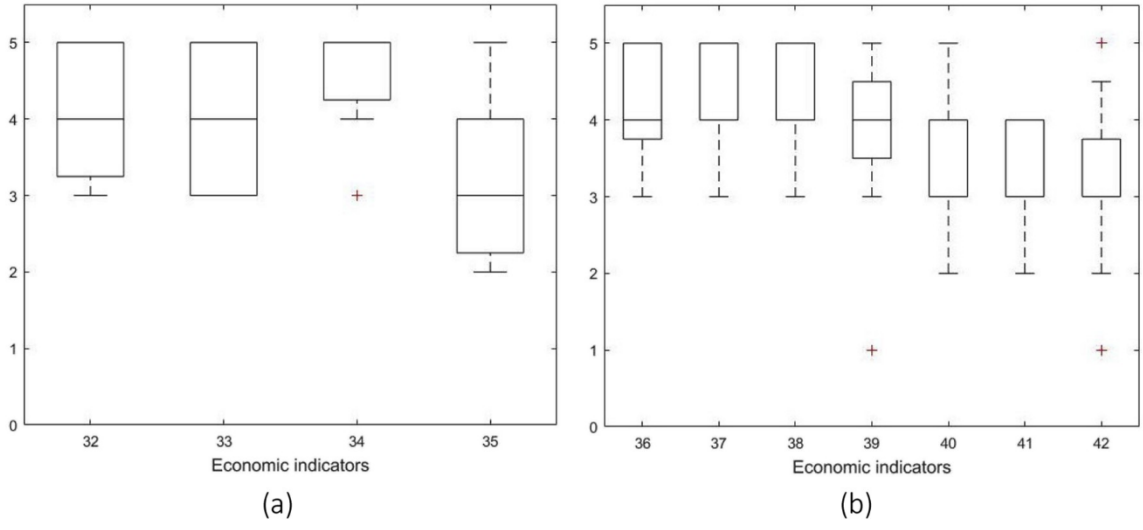

Fig. 7. Economy category boxplots after the first (a) and second (b) rounds of consultation.

scored less than 3 hence deemed not relevant. As it can be observed in Table 6, three dimensions reached a satisfactory level of consensus, while four of them presented two (i.e., environment) or one unsatisfactory indicator (i.e., infrastructure, utility services and economy).

The criteria which have not been judged as important to enhance resilience in the built environment belong to the environmental domain and consist in the level of exposure to snow and the general climatic type. It is acknowledged that the common view of the experts is against the involvement of these indicators for two main reasons: (a) the two factors are usually accounted in the design phase, so some experts

Table 13
Land use & urban morphology criteria consensuses, *(IQR): interquartile range.

	First round	Mean	St.Dev.	IQR*
36	Urban fabric and development pattern	3.45	0.963	1
37	Population density (i.e., concentration of people per square kilometre)	4.41	0.590	1
38	Floor area ratio (FAR) on an urban scale (i.e., ratio between the sum of the buildings' floor surfaces and the urban centre area)	3.68	0.839	1
39	Building coverage ratio (BCR) on an urban scale (i.e., ratio between the sum of building external footprints and the urban area)	3.68	0.945	1.75
40	Buildings' height profile (e.g., Digital Surface Models techniques)	3.32	0.995	1
	Second round			
43	Urban fabric and development pattern	3.33	0.796	1
44	Population density (i.e., concentration of people per square kilometre)	4.38	0.669	1
45	Floor area ratio (FAR) on an urban scale (i.e., ratio between the sum of the buildings' floor surfaces and the urban centre area)	3.71	0.845	1
46	Building coverage ratio (BCR) on an urban scale (i.e., ratio between the sum of building external footprints and the urban area) based on satellite imageries and GIS techniques	3.69	0.814	1
47	Buildings' height profile (e.g., Digital Surface Models techniques)	3.52	1.167	1
48	Predominant Land use/type	3.71	0.916	0.5

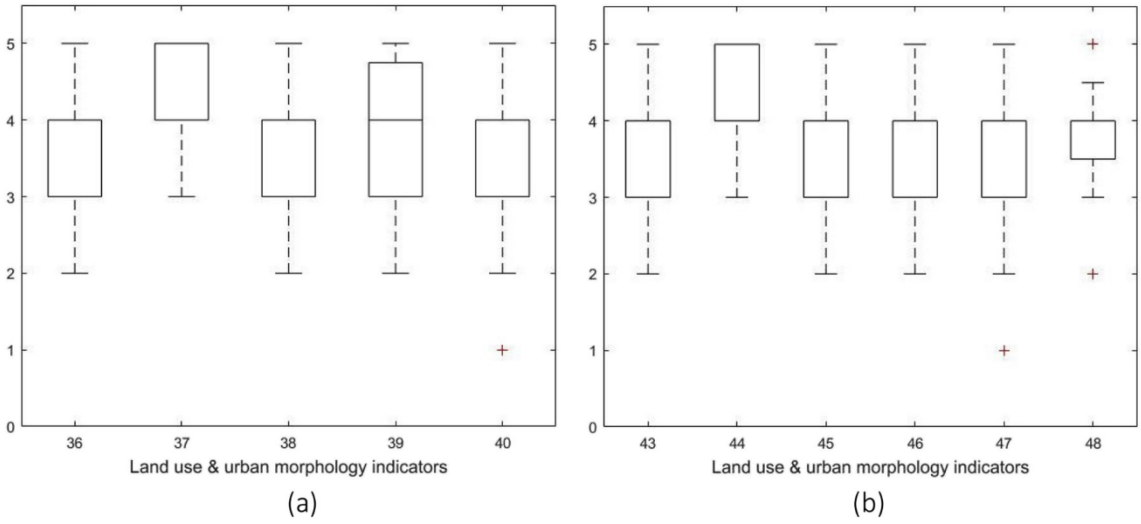

Fig. 8. Land use & urban morphology boxplots after the first (a) and second (b) rounds of consultation.

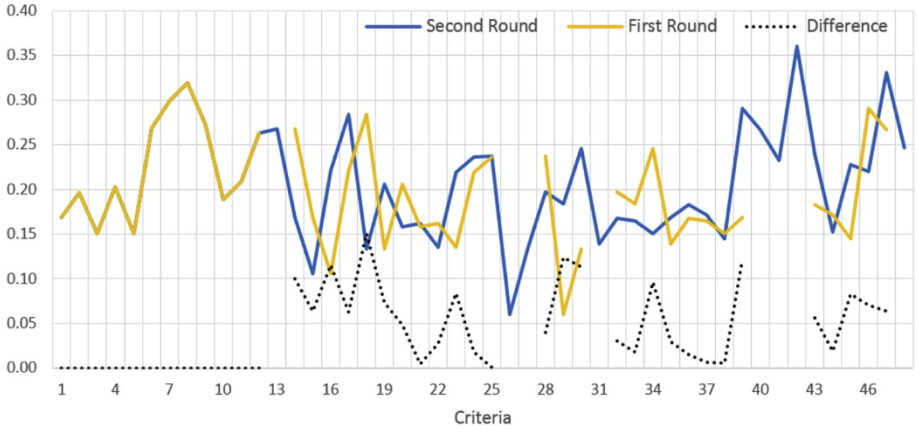

Fig. 9. Variation coefficients for the criteria over the two rounds of consultation.

argued about the redundancy of this indicators, and (b) other comments involved the overlapping of these information with the hazard assessment. However, as thoroughly observed in section 4 in relation to the environmental criteria, the indicators in section 1 have to be considered as a substitute of the hazard assessment in case the latter is not present. With respect to the geotechnical awareness of the area, a relatively low score was registered and this is rather surprising as a suitable awareness of the soil and its investigation is crucial to ensure the correct level of stability and reliability of the superstructure. However, it is believed that the experts might have considered this indicator more impacting in the design phase than for a potential resilience assessment. The authors however argue about the relevance of this indicator throughout all the considered phases, as for both existing buildings and new structures, soil awareness is one of the main factors requiring investigation in an early stage of analysis.

It is worth noting that the criterion dealing with the potential

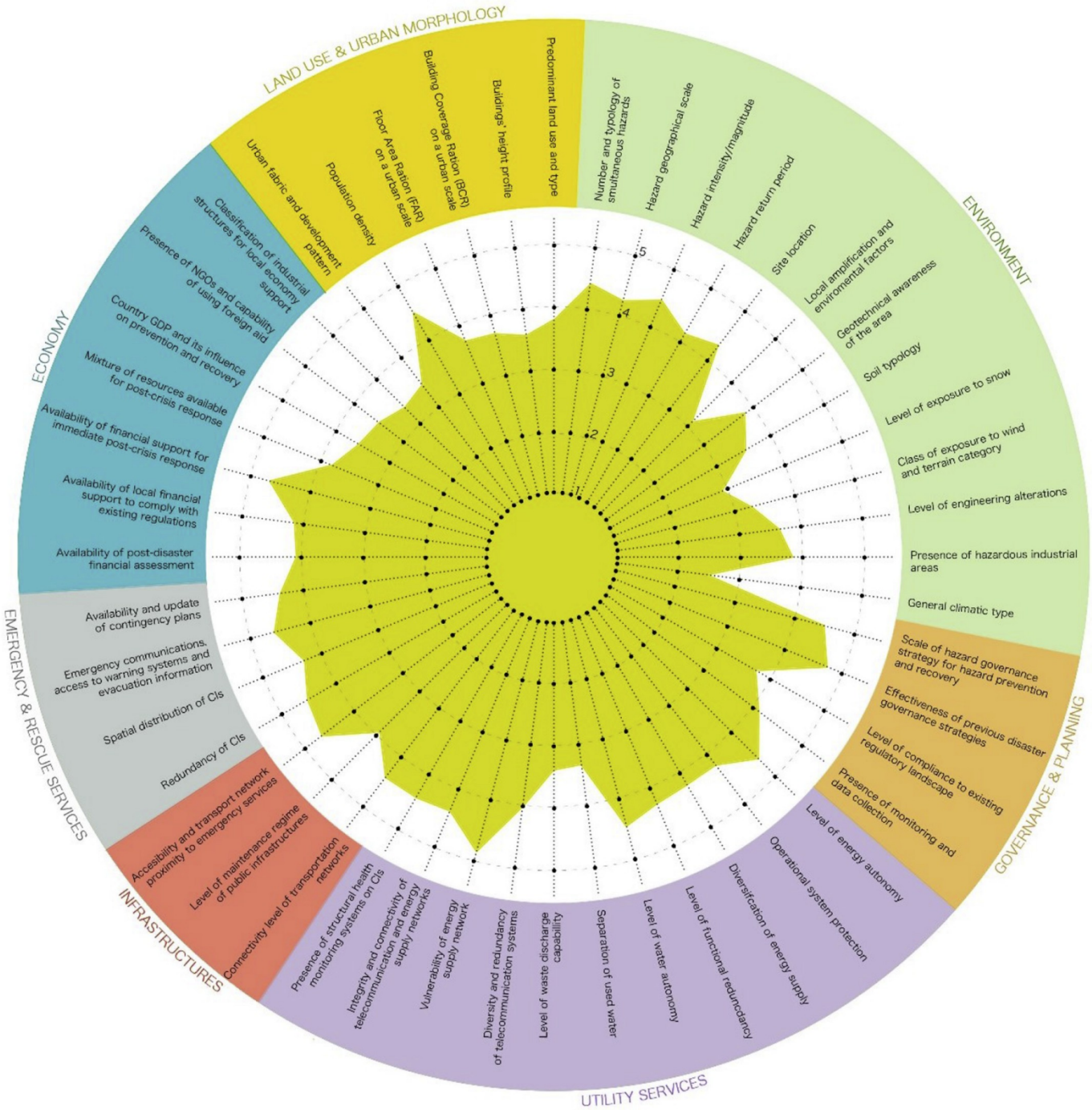

Fig. 10. Final framework for urban-scale resilience assessment.

presence of hazardous industrial areas was part of the group of criteria that did not meet the consensus threshold, even after the second round, despite the importance of this criterion in assessing the risk of engendering a disaster chain. The geotechnical awareness of the area registered a lower level of consensus over the second round, and this is probably due to the experts' assessment of it being more a design parameter rather than a resilience enhancement criterion. In addition, diversity and redundancy of telecommunication systems registered some disagreement considering that the calculated consensus rate is 1.25. Similarly, the maintenance regime of CIs scored 3.95 while registering an insufficient consensus level of 1.25.

By the end of the second round, the availability of immediate post-disaster financial assessment registered also an unsuitable 1.25 consensus level but an average score of 4.05. In the work by Alshehri [21], the insurance coverage-related indicator scored instead 3.75 with a satisfactory consensus level of 1 in a 5-Likert scale. However, it has to be pointed out that the post-disaster damage assessment for a financial perspective is of particular relevance for insurance coverage [21], therefore boosting the recovery process and the prioritization of reconstruction planning activities. Insurance coverage is accounted as an influencing criterion also in the framework by Da Silva [19]. It is acknowledged that most private households could be uninsured or information might not be available. However, the weight of this criterion becomes significant when dealing with public-owned buildings and infrastructures (e.g., schools, hospitals, road networks).

It is worth highlighting the relevance of the maintenance regime

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criterion for all the frameworks reviewed in section 3 [19,20], and specifically for the one proposed by Labaka regarding CIs resilience [26]. This not only applies to preventive strategies but also to the structure's robustness. Given that the latter is broadly defined as the ability of the element to provide an adequate resistance when subjected to a certain level of stress [30], it is interesting to note how this relates to the structure's immediate response to a disruption.

6. Conclusions and future work

The framework presented in the paper is part of a comprehensive conceptualization of buildings' resilience factoring in two scales of analysis, namely macro and micro, as anticipated in the work by Cerè et al. [1]. In this context, a framework for the qualitative assessment of resilience of buildings in face of geo-environmental hazards has been devised. Resilience is a multifaceted concept, characterized by different dimensions, identified through an in-depth review of several existing frameworks for resilience assessment. A wider review allowed to devise a set of indicators which have been assessed through the adoption of the Delphi consultation methodology. The results of the two rounds of consultation have been herein presented and analysed in light of the experts' feedbacks and values of the relevant statistical parameters (i.e., mean, standard deviation and interquartile range).

The results show an overall increase in both consensus and compactness of the experts' opinion which has been registered throughout the two rounds. The final set includes 43 satisfactory indicators with 5 more showing an insufficient consensus rate. The criteria are grouped in seven dimensions, ranging from environmental factors, to financial and technical domains, in order to adopt a holistic approach that accounts for all the relevant aspects characterizing the resilience of the built environment.

The authors argue that the strength of the proposed framework, compared to existing ones, lies in its focussed scope. In fact, when the resilience assessment is too broad and attempts to embrace a wide range of aspects, these tend to suffer from information inconsistency and a lack of accuracy. Another advantage of the proposed methodology is its practical applicability through quantifiable indicators. The comprehensive structure of this framework and its scalable usability bridges the gap between existing methodologies targeting either single buildings structurally (i.e., micro scale) or entire cities from a community perspective (i.e., macro scale). Additionally, the proposed methodology allowed to gather experts' feedback from different professional and academic backgrounds, hence approaching the research from different standpoints.

Because of its nature and its unicity, the framework now encompasses the resilience of the physical system in face of geo-environmental hazard, namely buildings and infrastructures. However, future work could integrate further disciplines (e.g., social features) while preserving the double-scale (i.e., macro and micro) approach, which forms the main innovation of this strategy. Moreover, further work would benefit also from the use of an analytical hierarchy process (AHP) analysis in order to appropriately weight the criteria and make the framework usable in real-world situations. This forms the focus of our future work which also includes gathering relevant pre and post-disruption satellite imagery, to instantiate the framework using a case study area located in Old Beichuan County in the Sichuan province (China) [87], to assess the resilience of the site in relation to the 2008 Wenchuan Earthquake. The latter will be reported in a follow-on publication.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.ijdrr.2019.101079.

References

[1] G. Cerè, Y. Rezgui, W. Zhao, Critical review of existing built environment resilience frameworks: directions for future research, Int. J. Disaster Risk Reduct. 25 (2017) 173–189, https://doi.org/10.1016/j.ijdrr.2017.09.018.
[2] Munich Re, TOPICS GEO Natural Catastrophes 2015, (2016).
[3] Munich Re, TOPICS GEO Natural Catastrophes 2017, (2017).
[4] D. Innocenti, P. Albrito, Reducing the risks posed by natural hazards and climate change: the need for a participatory dialogue between the scientific community and policy makers, Environ. Sci. Policy 14 (2011) 730–733, https://doi.org/10.1016/j.envsci.2010.12.010.
[5] S.B. Manyena, The concept of resilience revisited, Disasters 30 (2006) 434–450, https://doi.org/10.1111/j.0361-3666.2006.00331.x.
[6] UNISDR, How to make cities more resilient, A Handbook for Local Government Leaders, Geneva, 2016, 2017 http://www.unisdr.org/campaign/resilientcities/assets/documents/guidelines/Handbook for local government leaders , Accessed date: 24 July 2017.
[7] UNISDR, Building Resilience to Disasters in Europe, (2012) http://www.flickr.com/photos/35240543N02/6291100711/ , Accessed date: 26 February 2017.
[8] Comune di Venezia, Making cities resilient, https://www.comune.venezia.it/archivio/82331, (2011) , Accessed date: 30 July 2017.
[9] UNISDR, Make my city resilient, (n.d.) https://www.unisdr.org/campaign/resilientcities/ , Accessed date: 24 December 2018.
[10] United Nations Office for disaster risk reduction (UNISDR), centre for reasearch on the epidemiology of disasters (CRED), the human cost of weather-related disasters 1995-2015, https://www.unisdr.org/files/46796_cop21weatherdisastersreport2015.pdf, (2015) , Accessed date: 26 January 2019.
[11] B. Walker, C.S. Holling, S.R. Carpenter, A. Kinzig, Resilience, adaptability and transformability in social-ecological systems, Ecol. Soc. 9 (2004).
[12] S. Carpenter, K. Arrow, S. Barrett, R. Biggs, W. Brock, A.-S. Crépin, G. Engström, C. Folke, T. Hughes, N. Kautsky, C.-Z. Li, G. McCarney, K. Meng, K.-G. Mäler, S. Polasky, M. Scheffer, J. Shogren, T. Sterner, J. Vincent, B. Walker, A. Xepapadeas, A. Zeeuw, General resilience to cope with extreme events, Sustainability 4 (2012) 3248–3259, https://doi.org/10.3390/su4123248.
[13] C.S. Holling, Resilience and stability of ecological systems, Annu. Rev. Ecol. Systemat. 4 (1973) 1–23, https://doi.org/10.1146/annurev.es.04.110173.000245.
[14] G.P. Cimellaro, A.M. Reinhorn, M. Bruneau, Seismic resilience of a hospital system, Struct. Infrastruct. Eng. 6 (2010) 127–144, https://doi.org/10.1080/15732470802663847.
[15] P. Franchin, F. Cavalieri, Probabilistic assessment of civil infrastructure resilience to earthquakes, Comput. Civ. Infrastruct. Eng. 30 (2015) 583–600, https://doi.org/10.1111/mice.12092.
[16] D.A. Reed, K.C. Kapur, R.D. Christie, Methodology for assessing the resilience of networked infrastructure, IEEE Syst. J. 3 (2009) 174–180, https://doi.org/10.1109/JSYST.2009.2017396.
[17] T. Mitchell, K. Harris, Resilience: A Risk Management Approach, (2012) www.odi.org.uk , Accessed date: 6 September 2018.
[18] J. Park, T.P. Seager, P.S.C. Rao, M. Convertino, I. Linkov, Integrating risk and resilience approaches to catastrophe management in engineering systems, Risk Anal. 33 (2013) 356–367, https://doi.org/10.1111/j.1539-6924.2012.01885.x.
[19] J. da Silva, City Resilience Index, (2016) https://assets.rockefellerfoundation.org/app/uploads/20140410162455/City-Resilience-Framework-2015.pdf.
[20] C. Field, R. Look, T. Lindsay, 12 Cities Assessment Resilience Insight, (2016) https://www.bre.co.uk/filelibrary/pdf/2016-Royal-Charter-International-Research-Award-BuroHappold-Resilience-Insight-12-Cities-Assessment-v2.pdf , Accessed date: 6 May 2017.
[21] S.A. Alshehri, Y. Rezgui, H. Li, Delphi-based consensus study into a framework of community resilience to disaster, Nat. Hazards 75 (2015) 2221–2245, https://doi.org/10.1007/s11069-014-1423-x.
[22] S.L. Cutter, L. Barnes, M. Berry, C. Burton, E. Evans, E. Tate, J. Webb, A place-based model for understanding community resilience to natural disasters, Glob. Environ. Chang. 18 (2008) 598–606, https://doi.org/10.1016/j.gloenvcha.2008.07.013.
[23] A. Decò, P. Bocchini, D.M. Frangopol, A probabilistic approach for the prediction of seismic resilience of bridges, Earthq. Eng. Struct. Dyn. 42 (2013) 1469–1487, https://doi.org/10.1002/eqe.2282.
[24] G.P. Cimellaro, A.M. Reinhorn, M. Bruneau, Quantification of seismic resilience, 8th U.S. Natl. Conf. Earthq. Eng. 2006 San Francisco.
[25] S.E. Chang, M. Eeri, M. Shinozuka, Measuring improvements in the disaster resilience of communities, Earthq. Spectra 20 (2004) 739–755.
[26] L. Labaka, J. Hernantes, J.M. Sarriegi, A holistic framework for building critical infrastructure resilience, Technol. Forecast. Soc. Change 103 (2016) 21–33, https://doi.org/10.1016/J.TECHFORE.2015.11.005.
[27] M. Bruneau, S.E. Chang, R.T. Eguchi, G.C. Lee, T.D. O'Rourke, A.M. Reinhorn, M. Shinozuka, K. Tierney, W.A. Wallace, D. von Winterfeldt, A framework to quantitatively assess and enhance the seismic resilience of communities, Earthq. Spectra 19 (2003) 733–752, https://doi.org/10.1193/1.1623497.
[28] T. McDaniels, S. Chang, D. Cole, J. Mikawoz, H. Longstaff, Fostering resilience to extreme events within infrastructure systems: characterizing decision contexts for mitigation and adaptation, Glob. Environ. Chang. 18 (2008) 310–318, https://doi.org/10.1016/j.gloenvcha.2008.03.001.
[29] G.P. Cimellaro, C. Fumo, A.M. Reinhorn, M. Bruneau, Quantification of disaster resilience of health care facilities, Tech. Rep. MCEER-09-0009, 2009, p. 212 c:%5CCS%5Call refs%5Ctechnical%5CMCEER reports%5C09-0009.pdf , Accessed

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date: 8 February 2017.
[30] G.P. Cimellaro, A.M. Reinhorn, M. Bruneau, Framework for analytical quantification of disaster resilience, Eng. Struct. 32 (2010) 3639–3649, https://doi.org/10.1016/j.engstruct.2010.08.008.
[31] M. Uzielli, F. Catani, V. Tofani, N. Casagli, Risk analysis for the Ancona landslide-II: estimation of risk to buildings, Landslides 12 (2015) 83–100, https://doi.org/10.1007/s10346-014-0477-x.
[32] IPCC (International Panel on Climate Change), Climate change 2007: impacts, adaptation and vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the IPCC, 2007 Cambridge, UK.
[33] B.B. Brown, Delphi Process: a Methodology Used for the Elicitation of Opinions of Experts, (1968) http://www.dtic.mil/docs/citations/AD0675981 , Accessed date: 30 May 2018.
[34] E.E. Ameyaw, Y. Hu, M. Shan, A.P.C. Chan, Y. Le, Application of Delphi method in construction engineering and management research: a quantitative perspective, J. Civ. Eng. Manag. 22 (2016) 991–1000, https://doi.org/10.3846/13923730.2014.945953.
[35] A.M.J. Skulimowski, Expert delphi survey as a cloud-based decision support service, IEEE 10th Conf. Serv. Comput. Appl. 2017 Kanazawa, Japan.
[36] L. Hjarno, A.M. Syed, A.R. Aro, Report of Interview summaries and Delphi rounds, n.d, https://survey.erasmusmc.nl/SARSControlproject/picture/upload/D_8_5 Delphi rounds.pdf.
[37] S. Keeney, F. Hasson, H.P. McKenna, A critical review of the delphi technique as a research methodology for nursing, Int. J. Nurs. Stud. 38 (2001) 195–200, https://doi.org/10.1016/S0020-7489(00)00044-4.
[38] E.E. Ameyaw, Y. Hu, M. Shan, A.P.C. Chan, Y. Le, Application of Delphi method in construction engineering and management research: a quantitative perspective, J. Eng. Manag. 22 (2016) 991–1000.
[39] E. Jordan, A. Javernick-Will, Indicators of community recovery: content analysis and delphi approach, Nat. Hazards Rev. 14 (2013) 21–28, https://doi.org/10.1061/(ASCE)NH.1527-6996.0000087.
[40] J.L. Bailie, Effective online instructional competencies as perceived by online university faculty and students: a sequel study, J. Online Learn. Teach. 7 (2011), http://jolt.merlot.org/vol7no1/bailie_0311.pdf , Accessed date: 18 May 2018.
[41] E. De Vet, J. Brug, J. De Nooijer, A. Dijkstra, N.K. De Vries, Determinants of forward stage transitions: a Delphi study, Health Educ. Res. 20 (2004) 195–205, https://doi.org/10.1093/her/cyg111.
[42] J. Pill, The Delphi method: substance, context, a critique and an annotated bibliography, Socioecon. Plann. Sci. 5 (1971) 57–71 https://econpapers.repec.org/article/eeesoceps/v_3a5_3ay_3a1971_3ai_3a1_3ap_3a57-71.htm , Accessed date: 31 August 2018.
[43] M. Adler, E. Ziglio, Gazing into the Oracle: the Delphi Method and its Application to Social Policy and Public Health, (1996) Bristol.
[44] P.L. Williams, C. Webb, The Delphi technique: a methodological discussion, J. Adv. Nurs. 19 (1994) 180–186, https://doi.org/10.1111/j.1365-2648.1994.tb01066.x.
[45] C. Powell, The Delphi technique: myths and realities, J. Adv. Nurs. 41 (2003) 376–382, https://doi.org/10.1046/j.1365-2648.2003.02537.x.
[46] B.R. Witkins, J.W. Altschuld, Planning and Conducting Needs Assessment: A Practical Guide, SAGE Publications, Thousand Oaks, CA, 1995.
[47] M.J. Clayton, Delphi: a technique to harness expert opinion for critical decision-making tasks in education, Educ. Psychol. 17 (1997) 373–386, https://doi.org/10.1080/0144341970170401.
[48] N. Dalkey, B. Brown, S. Cochran, Use of self-ratings to improve group estimates, Technol. Forecast. 1 (1970) 283–291, https://doi.org/10.1016/0099-3964(70)90029-3.
[49] A.C. Mertens, K.L. Cotter, B.M. Foster, B.J. Zebrack, M.M. Hudson, D. Eshelman, L. Loftis, M. Sozio, K.C. Oeffinger, Improving health care for adult survivors of childhood cancer: recommendations from a delphi panel of health policy experts, Health Policy 69 (2004) 169–178, https://doi.org/10.1016/j.healthpol.2003.12.008.
[50] C. Duffield, The Delphi technique: a comparison of results obtained using two expert panels, Int. J. Nurs. Stud. 30 (1993) 227–237 http://www.ncbi.nlm.nih.gov/pubmed/8335432 , Accessed date: 23 May 2017.
[51] H.A. von der Gracht, Consensus measurement in Delphi studies: review and implications for future quality assurance, Technol. Forecast. Soc. Change 79 (2012) 1525–1536, https://doi.org/10.1016/J.TECHFORE.2012.04.013.
[52] M. Murphy, N. Black, D. Lamping, C. McKee, C. Sanderson, J. Askham, T. Marteau, Consensus development methods, and their use in clinical guideline development, Heath Technol. Assess. 2 (1998).
[53] M.K. Rayens, E.J. Hahn, Building consensus using the policy delphi method, policy, polit, Nurs. Prat. 1 (2000) 308–315 http://journals.sagepub.com/doi/pdf/10.1177/152715440000100409 , Accessed date: 24 May 2018.
[54] J. Greatorex, T. Dexter, An accessible analytical approach for investigating what happens between the rounds of a Delphi study, J. Adv. Nurs. 32 (2000) 1016–1024, https://doi.org/10.1046/j.1365-2648.2000.t01-1-01569.x.
[55] K. Goldman, P. Gross, C. Heeren, G. Herman, L. Kaczmarczyk, M.C. Loui, C. Zilles, Identifying important and difficult concepts in introductory computing courses using a Delphi process, ACM SIGCSE Bull. 40 (2008) 256–260.
[56] J.S. Dajani, M.Z. Sincoff, W.K. Talley, Stability and agreement criteria for the termination of Delphi studies, Technol. Forecast. Soc. Change 13 (1979) 83–90, https://doi.org/10.1016/0040-1625(79)90007-6.
[57] J.M. English, G.L. Kernan, The prediction of air travel and aircraft technology to the year 2000 using the Delphi method, Transp. Res. 10 (1976) 1–8, https://doi.org/10.1016/0041-1647(76)90094-0.
[58] C.G. Burton, The Development of Metrics for Community Resilience to Natural Disaster, (2012).
[59] D.R. Godschalk, Urban hazard mitigation: creating resilient cities, Nat. Hazards Rev. 4 (2003) 136–143, https://doi.org/10.1061/(ASCE)1527-6988(2003)4:3(136).
[60] R.J. Burby, A.C. Nelson, D. Parker, J. Handmer, Urban containment policy and exposure to natural hazards: is there a connection? J. Environ. Plan. Manag. 44 (2001) 475–490, https://doi.org/10.1080/09640560125021.
[61] A. Sharifi, Y. Yamagata, Principles and criteria for assessing urban energy resilience: a literature review, Renew. Sustain. Energy Rev. 60 (2016) 1654–1677, https://doi.org/10.1016/J.RSER.2016.03.028.
[62] L. Marcus, J. Colding, Toward an integrated theory of spatial morphology and resilient urban systems, Ecol. Soc. 19 (2014), https://doi.org/10.5751/ES-06939-190455.
[63] T.K. Dhar, L. Khirfan, A multi-scale and multi-dimensional framework for enhancing the resilience of urban form to climate change, Urban Clim 19 (2017) 72–91, https://doi.org/10.1016/J.UCLIM.2016.12.004.
[64] L. Gunderson, C.S. Holling, Panarchy: Understanding Tranformations in Human and Natural Systems, Island Press, Washington, DC, 2002.
[65] M. Ouyang, L. Dueñas Osorio, Time-dependent resilience assessment and improvement of urban infrastructure systems, Chaos an Interdiscip, J. Nonlinear Sci. 22 (2012) 033122, https://doi.org/10.1063/1.4737204.
[66] M. Panteli, P. Mancarella, D.N. Trakas, E. Kyriakides, N.D. Hatziargyriou, Metrics and quantification of operational and infrastructure resilience in power systems, IEEE Trans. Power Syst. 32 (2017) 4732–4742, https://doi.org/10.1109/TPWRS.2017.2664141.
[67] Kentucky Geological Survey, Earthquake Hazard and Risk, (n.d.), http://www.uky.edu/KGS/geologichazards/risks.htm , Accessed date: 4 June 2018.
[68] D. Giardini, The global seismic hazard assessment program (GSHAP) - 1992/1999, Ann. Di Geofis 42 (1999).
[69] P. Civile, Descrizione del rischio sismico, (n.d.), http://www.protezionecivile.gov.it/jcms/it/descrizione_sismico.wp?pagtab=2 , Accessed date: 16 February 2017.
[70] S. Mohagheghi, P. Javanbakht, Power grid and natural disasters: a framework for vulnerability assessment, Seventh Annu. IEEE Green Technol. Conf, IEEE, New Orleans, LA, USA, 2015, pp. 199–205, , https://doi.org/10.1109/GREENTECH.2015.27.
[71] Y. Ohta, T. Kobayashi, H. Tsushima, S. Miura, R. Hino, T. Takasu, H. Fujimoto, T. Iinuma, K. Tachibana, T. Demachi, T. Sato, M. Ohzono, N. Umino, Quasi real-time fault model estimation for near-field tsunami forecasting based on RTK-GPS analysis: application to the 2011 Tohoku-Oki earthquake (M_w 9.0), J. Geophys. Res. Solid Earth 117 (2012), https://doi.org/10.1029/2011JB008750.
[72] J. Shah, D.V.L. Hunt, I.F. Jefferson, Resilience assessment for geotechnical infrastructure assets, J. Asset Manag. 1 (2014).
[73] A. Sharifi, A critical review of selected tools for assessing community resilience, Ecol. Indicat. 69 (2016) 629–647, https://doi.org/10.1016/j.ecolind.2016.05.023.
[74] P.E. Roege, Z.A. Collier, J. Mancillas, J.A. McDonagh, I. Linkov, Metrics for energy resilience, Energy Policy 72 (2014) 249–256, https://doi.org/10.1016/J.ENPOL.2014.04.012.
[75] J.P.G. Sterbenz, D. Hutchison, E.K. Çetinkaya, A. Jabbar, J.P. Rohrer, M. Schöller, P. Smith, Redundancy, diversity, and connectivity to achieve multilevel network resilience, survivability, and disruption tolerance, Telecommun. Syst. 56 (2014) 17–31, https://doi.org/10.1007/s11235-013-9816-9.
[76] S. Maharjan, Y. Zhang, S. Gjessing, O. Ulleberg, F. Eliassen, Providing microgrid resilience during emergencies using distributed energy resources, 2015 IEEE Globecom Work. (GC Wkshps), IEEE, San Diego, CA, USA, 2015, pp. 1–6, , https://doi.org/10.1109/GLOCOMW.2015.7414031.
[77] V. Novotny, Water-energy nexus: retrofitting urban areas to achieve zero pollution, Build. Res. Inf. 41 (2013) 589–604, https://doi.org/10.1080/09613218.2013.804764.
[78] Ministry of Infrastructures and Transportations, Ministry of the Interior, Head of Department of Civil Protection, DM (Ministerial Decree) 17 January 2018, Nuove Norme Tecniche per le Costruzioni [New technical codes for constructions], 2018.
[79] J.M. Brownjohn, Structural health monitoring of civil infrastructure, Philos. Trans. A Math. Phys. Eng. Sci. 365 (2007) 589–622, https://doi.org/10.1098/rsta.2006.1925.
[80] L. Briguglio, G. Cordina, N. Farrugia, S. Vella, Economic vulnerability and resilience: concepts and measurements, Oxf. Dev. Stud. 37 (2009) 229–247, https://doi.org/10.1080/13600810903089893.
[81] R.P. Greene, J.B. Pick, Exploring the Urban Community. A GIS Approach, second ed., Prentice Hall, Upper Saddle River, NJ, 2012.
[82] C. Loo, P. Ong, Crowding perceptions, attitudes, and consequences among the Chinese, Environ. Behav. 16 (1984) 55–87, https://doi.org/10.1177/0013916584161003.
[83] I. Marinosci, F. Assennato, L. Congedo, T. Luti, M. Munafò, A. Ferrara, N. Riitano, F. Lucchesi, I. Zetti, Forme di urbanizzazione e tipologia insediativa, Qual. Dell'ambiente Urbano - X Rapp. 2014, pp. 72–83 http://www.isprambiente.gov.it/files/pubblicazioni/statoambiente/aree-urbane-2014/CAP_2_Suolo e territorio.pdf.
[84] S. Hanson, The weight of tradition, the springboard of tradition: let's move beyond the 1990s, Urban Geogr. 24 (2003) 465–478, https://doi.org/10.2747/0272-3638.24.6.465.
[85] A. Forsyth, Measuring Density: Working Definitions for Residential Density and Building Intensity, (2003) http://www.corridordevelopment.org/pdfs/from_MDC_Website/db9.pdf , Accessed date: 25 October 2017.
[86] IBM, SPSS Statistics Calculation of Percentiles, (n.d.), http://www-01.ibm.com/support/docview.wss?uid=swg21480663 , Accessed date: 6 June 2018.
[87] G. Cerè, W. Zhao, Y. Rezgui, R. Parker, T. Hales, B.H. MacGillvray, Y. Gong, Multi-objective consideration of earthquake resilience in the built environment: the case of Wenchuan earthquake, 2017 Int. Conf. Eng. Technol. Innov, IEEE, Madeira Island, Portugal, Portugal, 2017, , https://doi.org/10.1109/ICE.2017.8279929.