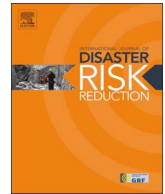




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## Critical review of existing built environment resilience frameworks: Directions for future research

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## ABSTRACT

Resilience, in general, is widely considered as a system's capacity to proactively adapt to external disturbances and recover from them. However, the existing resilience framework research is still quite fragmented and the links behind various studies are not straightforwardly accessible. The paper provides a critical state-of-the-art review of both quantitative and qualitative considerations of resilience, approached from a built environment engineering perspective, with a focus on geo-environmental hazards. A research gap is identified and translated into a holistic and systemic approach to conceptualise resilience, factoring in related concepts such as vulnerability, adaptive capacity and recoverability. A generic built environment resilience framework is proposed informed by a critical and comprehensive review of the related literature. The paper concludes with insights into four key strategic areas requiring further research, namely: (a) risk based cost optimal resilient design and standards of buildings and infrastructures, (b) model based evaluation and optimisation of buildings and infrastructures, (c) integrated risk modelling, inference and forecasting, and (d) heterogeneous disaster data acquisition, integration, security and management.

### 1. Introduction

Recent disasters worldwide highlight the vulnerability of our built environment and stress the often dramatic consequences of disasters, as illustrated in Fig. 1. This is directly linked to [often] unplanned urban development and ecosystems [1]. Disasters lead to a wide range of consequences, including human and financial losses [2]. Figs. 2a–2c illustrate the trend (dotted line) in terms of damaged buildings of different typologies (i.e., housing, education and healthcare facilities) between 1990 and 2013 in relation to extensive natural disasters. Although the real distribution of the dataset (solid line) varies over time, the trend appears to be clearly positive for all the three typologies of buildings, highlighting a positive tendency in the increasing amount of structures significantly affected by geo-environmental hazards.

A noteworthy example of the devastating consequences of earthquakes can be found in the Wenchuan territory following the 2008 earthquake, exacerbated by major landslides. Damages affected both buildings and infrastructures leading to the relocation of entire city districts, such as the case of the Old Beichuan. The area of Qipan gully has been affected by debris flow, consisting of a mixture of high-diameter rocks (up to 1 m, from field observations) and flow-type fractions, leading to the overall destruction of the majority of the building stock. Previous research has also pointed out the extensive damages

undergone by industrial facilities [3] with the consequent risks related to the release of chemical substances in the environment and also improper applications of building codes that led to severe collapse modes, contrasting with the strong column-weak beam system [4].

Moreover, from a climate change perspective, effects are already being felt through increases in heat waves and hot spells; risk of drought in continental areas; extreme precipitation events; and storms and hurricanes [5]. The effects on the built environment are both structural and non-structural, affecting all three components of a building: fabric, systems and occupants (discomfort from overheating), as well as its energy consumption and Greenhouse Gases emissions. While the energy and emissions consequences of climate change have been widely discussed [6], other life-threatening aspects have not attracted the right attention, such as building structural consequences of climate change, and effects of temperature rise and prolonged heating that may result in thermal expansion strains in construction materials. Higher atmospheric temperature results in increased rates of carbonation and chloride penetration, which accelerate the effect of carbonation-induced damage to structural components such as concrete [7] and environmental aggressiveness leads to critical corrosion of structural components through time [8]. Linked to high temperatures, increased solar UV levels accelerate the degradation of materials, affecting their lifespan. Climate change also affects the global ocean and sea level,

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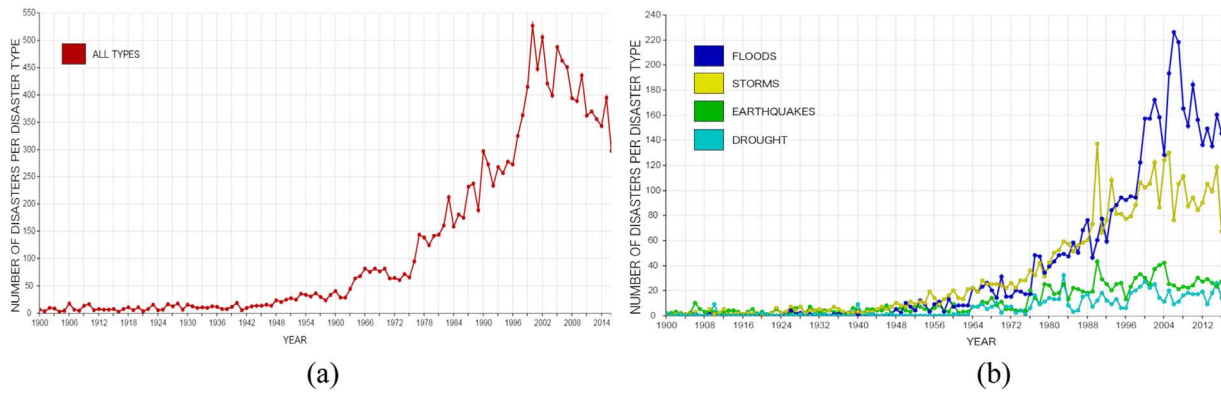


Fig. 1. Disaster trends from 1900 to 2015. All types of disasters (a); Specific hazard categories (b) [<http://www.emdat.be>].

putting a risk coastal areas and consequently increasing floods likelihood and similarly the hazards in relation to the built environment [9,10].

The combined effects of geo-environmental hazards on buildings and infrastructures vary according to the type of threats, including:

- **Effects of flooding:** In addition to *fluvial* flooding (overflow of riverbanks and channels), the risk of *pluvial*, i.e. flooding resulting from continuous heavy precipitation is increasing, which is further exacerbated by increasing impervious urban surfaces and increased intense precipitation due to climate change. Unpredictable pluvial flooding causes huge destruction and disproportionately affect the vulnerable population [11]. Structural damage occurs from hydrostatic, hydrodynamic and impact loads [12], which can be amplified by the surrounding water absorbent soil underneath and surrounding the foundation, and can damage foundations, destruct structural walls and flooring; as well as increase the risk of the building to de-attach from its foundations from the downstream forces applied.
- **Effects of earthquakes:** Ground shakings from high-magnitude earthquakes (e.g., over  $M_w$  7.0) can induce in buildings shakings not considered in building regulations [13]. With regard to flexible steel framed buildings, welded connections are highly stressed leading to large displacements and nonlinear behaviour which cause hence major structural damages in the structure [13]. Moreover, ground movement can result in pounding between buildings or parts of the same building, which is one of the significant or even severely structural damage [14], resulting in economic and social losses, mortality. Earthquakes can also lead to major geological issues, including landslides, debris flows, rock falls or avalanches [15] such as during the 2008 Wenchuan earthquake [16] and hence provoking the collapse of structural and non-structural elements [17]. Earthquakes represent a major issue also when they take place in oceans, becoming tsunamis such as the 8.9-magnitude Tohoku earthquake that struck Japan in 2011, leading to the Fukushima calamity and

affecting worldwide-known industries' economies [18]. To give an idea of the extent of the built environment related damages due to seismic activities, the Government of the Republic of Haiti has calculated that following to 2010 earthquake the losses associated to the built environment accounted for the 80% of total direct losses and 47% of combined direct and indirect losses [2].

- **Effects of storms and high-intensity wind:** Building design must include a site-specific structure-tailored planning and calculation in face of wind actions [19,20] and regulations themselves address specific attention to wind-based design, especially if regarding slender or industrial structures. One of the main reason for that is grounded in the infill external surfaces that characterizes industrial-type buildings, which are often realized by means of light wall packages, compared to other types of non-structural elements. Moreover, in the context of industrial buildings the span between structural columns can be wider than the one of other types of buildings, hence the bending moment in the centreline can be greater depending on the span length. With regards to slender buildings, the threat addresses the buckling actions that can be generated given the non-linear vertical distribution of the wind speed profile, increasing with the height above the ground and lessened at the surface due to friction [21]. Rigorous preventative measures needs to be involved towards deformable elements, such as antennas, cable-suspended structures, bridges or chimney stacks since the action of wind could lead to structural vibrations and connections fatigue [19]. Effects of turbulence require as well to be taken into account in case of grouped nearby buildings of diverse shapes [22].

Another problematic issue is the tendency of stakeholders in prioritizing economic advantages over resilience enhancement opportunities. Based on that, stakeholders affirm that mentioning resilience-enhancement or hazard mitigation measures might discourage potential clients (e.g., property owners) in investing [23,24], given the (often) negative connotation that resilience might assume being associated to

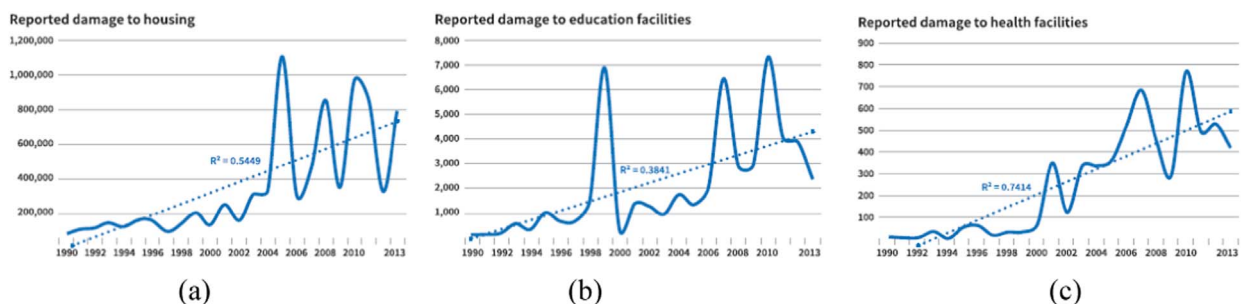


Fig. 2. Amount of damaged buildings (y-axis) between 1990 and 2013 (x-axis) from extensive disasters in different categories: housing (a), education (b) and healthcare facilities (c). [source: [2]]

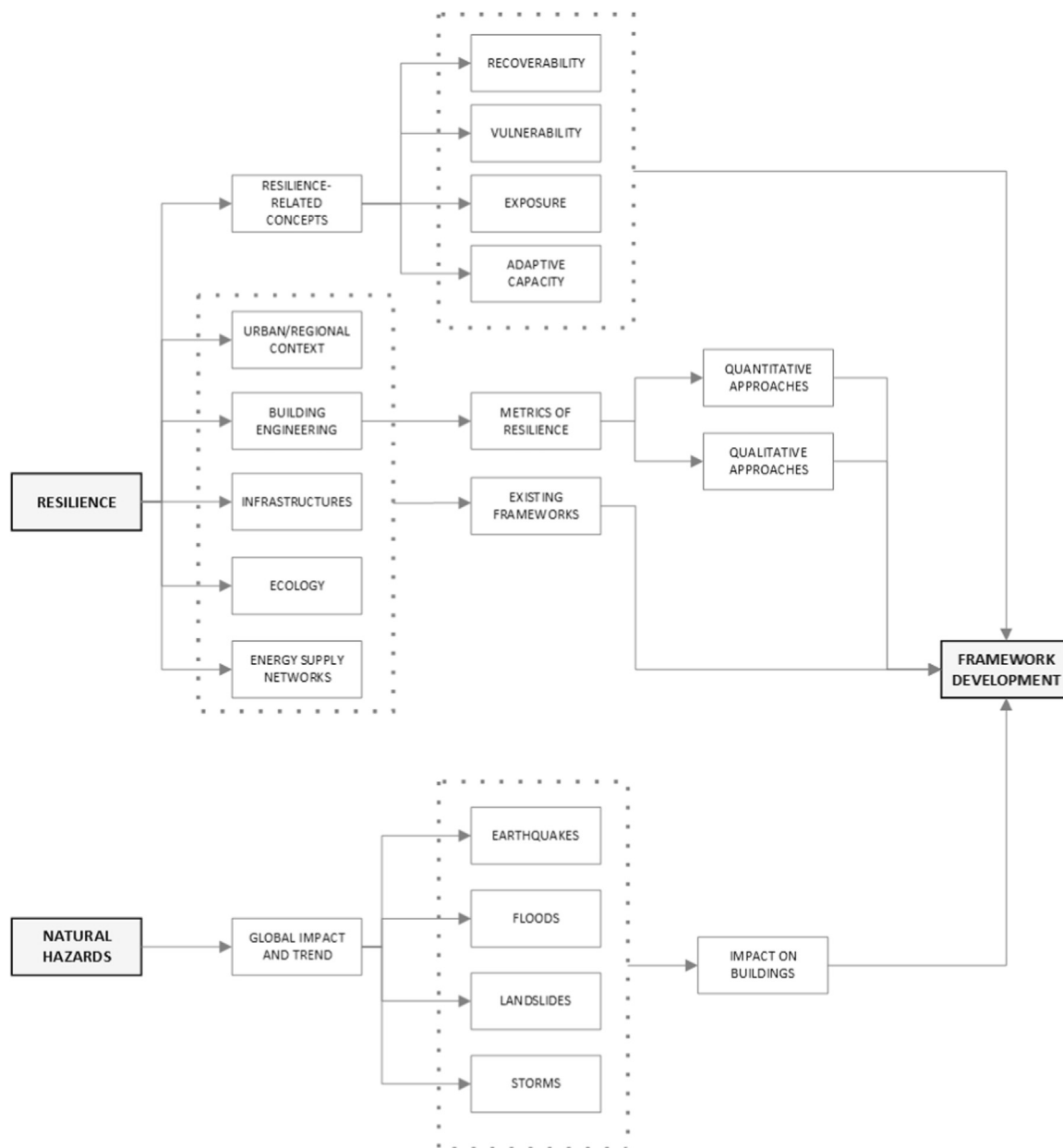


Fig. 3. Methodology overview.  
[source:authors]

unforeseeable negative events [25]. Contrasts are also registered between the application of resilience on a local or national level, as thoroughly devised by Chmutina [26]. To this regard, while adopting a narrow perspective and a bottom-up approach, different stakeholders might tend to favour specific resilience implementation techniques over others according to their domain of expertise and area of knowledge or economic convenience. This issue can result in disagreement and consequently lead to negative outcomes in the context of a project, causing delays and hence significantly increasing costs as well. Besides, stakeholders (e.g., property owners or industrial entities) are often involved in emergency planning development and application [27] providing a concrete standpoint, but their divergent intents could potentially have negative implications on the recovery process. However, recent events have raised the criticality linked to the unsuitable timing related to the necessary collaboration amongst the diverse figures that should be involved in the emergency planning process, which occurs just in extreme emergency situations [28]. In order to deal with this urgency several authors in the literature have been recently stressing the positive

outcomes resulting from a broader collaboration between different entities aimed at the development of emergency plans [23,27,29,30]. The demand for a tighter cooperation between private and public sectors accounted also for the high contribution provided by the private domain in terms of worldwide investments [31], hence providing a wide margin of improvement. Therefore it is argued the importance of a holistic perspective while dealing with resilience, in order to adopt a view able to embrace different perspectives and pursuing the same objective with common priorities as also stated in the 2015–2030 Sendai Framework [32].

The paper presents a critical review of the state-of-the-art research of built environment resilience to geo-environmental disasters, with a special focus on building resilience. An initial description of the underpinning methodology used in the paper is provided in Section 2. Relevant and authoritative research papers are then critically analysed in Section 3 and classified into two different categories according to their either qualitative or numerical approach to the assessment of resilience to geo-environmental hazards. A short overview of resilience-

related topics (i.e., vulnerability, adaptive capacity and recoverability) is then given. The latter has informed the development of the preliminary resilience assessment framework described in Section 4.

## 2. Review methodology

The review has been carried out through a critical analysis of the existing literature by means of a top down and system-engineering approach. Different publication search tools have been employed including Scopus, Google Scholar and Web of Science. The main body of the work investigated is composed by journal papers, but relevant books, conference papers and technical reports have also been taken into consideration. Priority has been given to recent publications, with exceptions for the literature that has contributed significantly to the underpinning research. Diverse combinations of keywords have been employed through the above search engines to ensure completeness of the review.

Given the multiple domains involved in the concept of resilience, the review started with different standpoints connected to geo-environmental hazard-vulnerable elements such as buildings, infrastructures, energy supply networks and also city and regional scale frameworks. Conversely, an accurate analysis of reports authored by authoritative institutions has been carried out to acknowledge the present situation with regard to the trend of natural hazards and hence allowing a better understanding of the need for resilience. In general, several frameworks dealing with resilience have been examined, but the main focus has been given to building-related resilience metrics, especially quantitative ones.

The review can be generally divided into two stages, i.e., literature search/review stage and preliminary resilience framework development step. The first stage has been devised with the aim of embracing a wider vision of resilience, to illustrate its multi-objective nature, and the interrelations between each facet involved (Fig. 3). This has been developed through a deep analysis and collection of definitions and frameworks of resilience adopted over time and in the diverse domain of knowledge, highlighting four main categories, including: ecological, socio-ecological, built environment and networks. Based on the input from the first stage (the various existing research related to the built environment resilience), the second stage then involved the development of a preliminary framework for the assessment of resilience in the context of geo-environmental hazards.

Fig. 4 illustrates the steady increase of interest in the theme of resilience between 2010 and 2016. The analysis was then refined with a focus on the built environment domain. Fig. 5 provides a breakdown of the amount of resilience-related publications against domains over the 2000–2016 period, emphasising the high relevance of the topic in the engineering discipline.

## 3. Review of existing approaches to resilience

According to the literature, the concept of resilience can be broadly conceptualised as a system's readiness in reacting towards disruptive

events [33]. Generally speaking, disruptions can be categorised as external or systemic according to their origin in relation to the system, hence whether triggered respectively by an outer or internal factor [34]. The current research focuses on external disruptions with particular consideration to geo-environmental hazards, but taking into account relevant interactions between related domains by means of a holistic and system-engineering approach.

Table 1 summarises the most influencing references with respect to present research and specifically addressing either qualitative or quantitative definition of resilience and its assessment in several domains. The early stage of the review involved a broad spectrum of researches in order to acknowledge the development of resilience from its first employments [35–41]. In order to provide a clear breakdown of the different approaches, four main categories have been identified, namely: ecological, socio-technical, built environment and networks. The first category includes all those publications addressing to Socio-Ecological Systems (SES), whereas “socio-technical” relates to frameworks developing practical measures aimed at the enhancement of resilience mainly in urban contexts. “Built environment” is meant to include both buildings and infrastructures related publications; while the last category addresses interconnected systems analysed on a larger scale, such as energy distribution or infrastructural networks, but also road systems on a regional or urban scale. In addition, it has been determined whether the methodology is qualitative or quantitative and which kind of natural hazards is dealt with.

Given the categorisation provided in Table 1, the most significant approaches addressing resilience are analysed separately, according to their qualitative or quantitative formulation. With respect to the former (qualitative), no further categorisation is provided since these approaches share a broad viewpoint resulting more in a resilience *qualification* rather than a real assessment. In contrast, quantitative methodologies are further divided according to the employed methodology and the analysed hazard(s). These two approaches are elaborated in the following sections.

## 4. Qualitative approaches to resilience

The origins of the concept of resilience are nebulous and controversial according to the literature. Part of that is keen on identifying its first employment in the field of psychology and psychiatry, linking resilience to Norman Garnezy, Emmy Werner and Ruth Smith [51,72,73]. Interestingly, more recent researches highlighted probable previous uses of the concept, dating back till the first century B.C. in the poem “Nature of Things” by Lucretius [74]. In contrast to this view, Alexander identifies its origins in the Classical literature by noteworthy authors such as Seneca the Elder, Pliny the Elder, Ovid, Cicero and Livy [75]. From an etymological viewpoint resilience finds its root in the Latin verb “resilire”, meaning “to jump back” [75,76]. Pizzo [74] instead is likely to ascribe the roots of the word both to Latin and Greek, but the resulting meaning does not differ significantly from the one proposed by the previous researches.

In relation to physics and engineering, resilience refers to the energy absorptive ability during the elastic phase of its behaviour and the capacity of recovering deformations when unloaded [51,77], as it can be confirmed by the steel tensile test diagram [78]. In this context resilience can be mathematically derived as the integral of the stress function evaluated between the initial situation and the end of the elastic behaviour [77].

Perhaps, one of the most influencing authors has been recognized by the literature in Holling [35,79], who explored resilience by providing a novel point of view distinguishing between ecological and engineering resilience in Socio-ecological Systems (SES). Ecological resilience entails a dynamic behaviour, allowing the existence of different equilibrium conditions achievable by the system after potential disruptions [35,79,80]. In contrast, a more rigid conceptualisation of resilience is implied by the engineering interpretation, stating that a disrupted

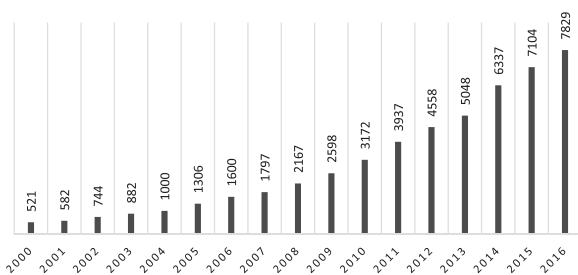


Fig. 4. Resilience-related publications over the period from 2000 to 2016. [source: Scopus, 7.4.2017]

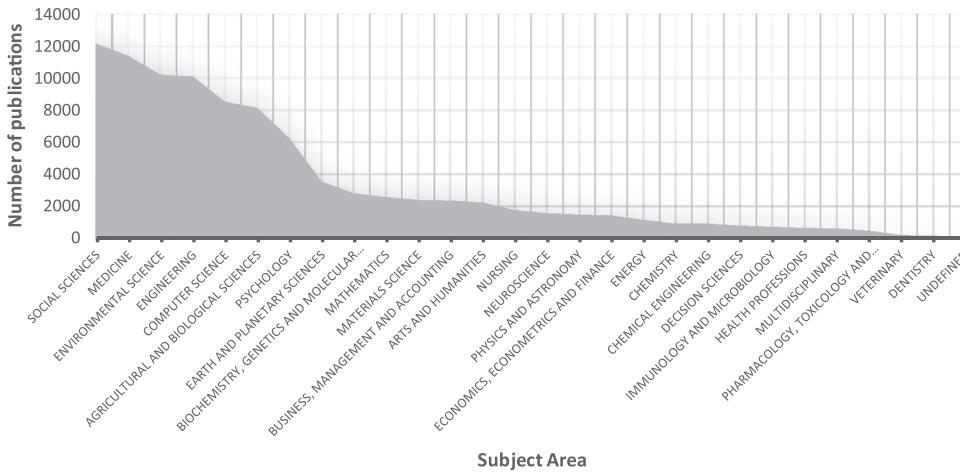


Fig. 5. Resilience-related publications between 2000 and 2016 divided by domain. [source: Scopus, 7.4.2017]

Table 1

Categorization of relevant approaches dealing with resilience (G = General disruptions, F = Floods, E = Earthquakes, RF = Rock Falls, SMS = Slow-moving slides, RFS = Rapid Flow-type slides).

Author(s)	Ecological	Socio-technical	Built environment	Networks	Hazard						Quantitative	Qualitative
					G	F	E	RF	SMS	RFS		
Bruneau et al. [42]	x		x	x			x					x
Chang et al. [43]			x				x				x	
Kircher et al. [44]			x			x	x	x	x	x		
Cimellaro et al. [45]		x	x				x			x		
Bruneau and Reinhorn [46]		x	x				x			x		
Cimellaro et al. [47]		x	x				x			x		
Cutter et al. [48]	x	x				x						x
Kaynia et al. [49]			x					x		x		
McDaniels et al. [50]		x		x				x				x
Cimellaro et al. [51]		x	x				x			x		x
Cimellaro et al. [52]		x	x				x			x		x
Cimellaro et al. [53]			x				x			x		
Folke et al. [54]		x		x			x					x
Miles and Chang [55]		x	x			x	x	x	x	x		x
McAllister [56]		x	x				x					x
Henry and Emmanuel Ramirez-Marquez [57]		x		x		x				x		
Ouyang et al. [58]			x	x		x	x	x	x	x		
Zobel and Khansa [59]				x		x	x	x	x	x		
Francis and Bekera [60]			x	x		x	x	x	x	x		
Mavrouli et al. [61]			x					x	x	x		
Alshehri et al. [62]												
Barberis et al. [63]	x											x
Franchin and Cavalieri [64]			x							x		
Uzielli et al. [65]			x						x			
UN/ISDR [66]		x	x			x						x
Vona et al. [67]			x					x				x
Field et al. [68]		x	x			x	x	x	x	x		
Labaka et al. [69]		x	x		x	x	x	x	x			x
Mahsuli [70]			x					x				x
Karamouz and Zahmatkesh [71]		x	x				x			x		

system will tend to achieve the stable condition that it showed prior to the disturbance [35,79,80]. The concept of resilience started undergoing a shift when being seen not anymore as an inherent feature of a system like in Holling's works, but as a continuously evolving process, involving a significant dynamic component of uncertainty that had not taken into account in the former literature. Madni shared a similar approach in relation to conceiving resilience as a continuously developing process and not a static objective [81]. Folke started to embed the evolutionary factor in his view of socio-ecological resilience [54], whereas Simmie and Martin posit the linkages between economy and resilience in terms of it as a ceaselessly changing process [82]. The concept of evolutionary resilience has been addressed later on by several other researches [24,30,80,83], allowing a more refined vision of resilience either as a process or the positive outcome of it.

The influence of Holling's research has been felt in first instance in the ecological domain [54,84]. The author in fact outlined the existing differences in relation to stability and resilience [35,85] and devising the concept of "domain of attraction", later or recalled by following researches [39,40]. In detail, Holling identifies the "domain of attraction" as the area in which a stable behaviour can be expected by the system [35] and defines resilience as the endurance of a system towards hazardous events and its ability in preserving the pre-disruption relationships between key components. In contrast, stability differs from resilience by expressing a system's ability in getting back to the pre-disruptive equilibrium condition, and in this sense a resilient system is capable of responding to larger changes of condition compared to a stable one [86].

Within SESs, resilience is tightly related to homeostasis,

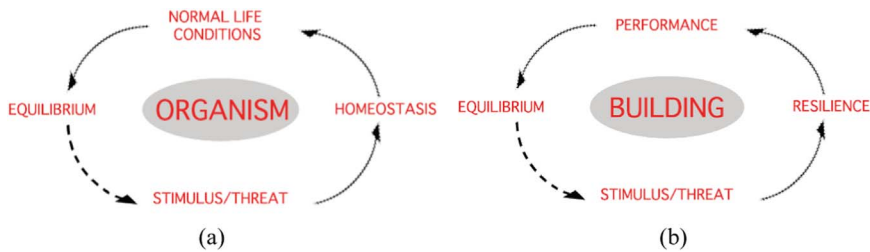


Fig. 6. Analogy between the concept of homeostasis for living organisms (a) and the concept of resilience for buildings (b). [source: authors]

representing “the tendency towards a relatively stable equilibrium between interdependent elements, as maintained by physiological processes” [87]. Thus, similarly to a SES which needs to achieve a stable equilibrium in face of external threats (e.g., viruses), a building should be resilient in order to overcome disruptions (e.g., geo-environmental disasters) and proactively adapt itself to maintain a reliable state (Figs. 6a–6b). The feature of homeostasis in the context of resilience has been framed by Wildavsky as the ability of a system to proactively learn in order to adapt to different types of potential disruptions [88,89]. The tight connection existing between SESs and built environment has been underpinned also by Anderies [90]. He posits that the built environment should be considered as part of SESs, in the context of the overall environment given the dependence of building design on the surroundings elements and systems. Though, this approach is already taken into account in recent architectural and structural building design, hence research should push forward on how to effectively implement resilience in a holistic perspective in relation to buildings. Recent trends in building design are already projected towards an organic approach involving a strong component of adaptability of the buildings, as it will be further devised in Section 5.

A noteworthy issue has been raised by Wildavsky differentiating the concept of anticipation from resilience, since they might be erroneously coupled [89]. While Hollnagel underpinned the importance of anticipation in relation to potential disruption [85], Wildavsky stated that despite being anticipation an essential component of a system's design (i.e., buildings), it is not a sufficient condition for ensuring safety. In fact, even though predictions might be reliable, there is always a certain component of uncertainty that needs to be embedded in the design [89]. As a consequence and in light of the foregoing, the concept of resilience has been unfolding, embedding in recent conceptions a level of uncertainty [88] that strengthens the modern evolutionary approach described above.

In relation to the ability of a system in recovering from disruptions, one of the most notable conceptualisation of resilience can be found in the “adaptive cycle theory” [36,39,91] stating the systems’ tendency to undergo four main phases during their lifespan (i.e., growth and development, conservation, collapse and eventually renewal). Similarly, Gama Dessavre and Henry [57,92] identified resilience as the continuous process starting from a reliable initial condition, followed by a vulnerability-survivability state after a disruptive event and eventually a recoverability phase aimed at achieving a new stable equilibrium condition.

On the contrary, other researches attempted to define resilience through its features and system's functionality, rather than by considering its phases separately. One of the first steps towards a more engineered definition of resilience has been made by Bruneau [42] by representing its multifaceted nature through the identification of four related dimensions – Technical, Organizational, Social and Economic (TOSE) – and the development of a framework for a qualitative resilience assessment [42,93]. In addition, the research presented resilience as being characterized by four properties, the so-called “four Rs” (robustness, redundancy, resourcefulness and rapidity) and proposed a measure of resilience as the area defined by the system's performance function. This formulation of resilience recalls the one described above in relation to the engineering domain, as the area under the elastic

portion of the steel tensile test graph [77]. Notwithstanding the undisputed novelty of the research, an effective and clear functionality formulation was not achieved, focussing on a conceptual and qualitative level. Based on this framework, a variety of applications have further been developed in order to specifically evaluate the resilience in the healthcare domain addressing earthquake disruptions and evaluating the performance for both building structures and services provided [46,47,53].

Some clarifications are worth highlighting in relation to robustness and redundancy, consisting in two of the “four Rs” identified by Bruneau as properties of resilience and then deeply analysed also by Tierney [42,93]. Redundancy is a fundamental property of resilient systems, both on a macro (e.g. urban/regional level) and micro (e.g. single buildings or infrastructures) scale, and describes the capacity of a system in general to create alternative paths in case of failure. Building up redundant networks with a functional diversity assures the presence of elements able to provide the same or equivalent function replacing the disrupted ones [94], such as what happen in infrastructural networks [93]. From a macro point of view (e.g. urban/regional level), interconnections between elements become relevant since the strong interrelation that characterize modern urban systems can become a drawback and an element of fragility in case of disruption [95]. The latter can lead to chain failures, as a result of infrastructure interdependencies as described in [96] or other cascading failures such as the ones experienced in the 2011 Tohoku earthquake event [18]. Hence, including redundancy in resilience-related analysis becomes of primary importance given the continuous implementation of new functions inducing a higher complexity in networks and hence making them more exposed to threats [97]. With regard to the micro scale (e.g. buildings), redundancy coincides with the capacity of creating new load paths for redistributing the load amongst other structural elements different from the disrupted ones [98].

On the other hand, robustness has been identified as a feature that the system should present from the immediate aftermath of a disruption, hence the more the damage increases the less robust is the system [43]. On the contrary, in the context of buildings, it may be more proper to define this feature as “the residual functionality right after the extreme event” [51,53]. Despite the pragmatism distinguishing Chang's approach considering resilience as the ability of meeting the performance standards with time and probability, recalling in this sense also Haimes [99], the loss of functionality could not be identified as robustness.

Referring to the MCEER previous researches [42], Mc Daniels led research team tackled the topic of resilience for infrastructure systems and healthcare facilities against hazardous events such as earthquakes, devising a framework aimed at facilitating pre and post-disruption decision making process [50]. However, the described methodology is not a sufficient tool as it neglects some relevant technical aspects that should be considered for both buildings and infrastructures, such as the physical vulnerability of the structure itself in relation to the specific hazardous event (e.g., earthquakes). The inclusion of McDaniels's research in this section is driven by the lack of a numerical evaluation of resilience, keeping the framework on a high-perspective level.

It has been argued in recent literature that emergency planning is significantly influencing when aiming at enhancing resilience [27,67].

Alexander [27] addresses the issue from a higher and comprehensive perspective pointing out that emergency planning consists, similarly to resilience [24,80], in a continuous process involving monitoring, risk prevention and forecasting. Madni shared this view agreeing with conceiving resilience not as an inherent feature of the system, but a process needing a regular and accurate monitoring in order to be suitably pursued [81] and not addressed just in case of extreme emergency [74]. Though, a certain component of uncertainty needs to be taken into account, and current trends in planning tend to be to less deterministic and more probabilistic (e.g., PBD approaches in structural design). Risk mitigation hence involves three components (i.e. Technical, Organisational and Social) characterized by different scales of application [27], wider for the social one and more limited for the technical. How can emergency planning fit the concept of resilience though? As described above, both resilience and emergency planning require accurate and constant monitoring, in order to tailor the response to the soliciting threat. In addition, Alexander posited that countermeasures are needed for achieving a good emergency planning [27] and the UNISDR in the context of the campaign “Making cities resilient” devised a list of 10 “Essentials” for pursuing resilience. Within them it is strengthened the need for a pragmatic planning both for the disaster-anticipatory phase and the recovery one [100]. In the context of this initiative Venice has been designated as a “Model for resilience” [100] thanks also to the remarkable series of barriers against the risk of flood, the so-called MOSE [101]. Similarly, other countries have been able to proactively embed resilience-enhancing interventions in their risk mitigation planning, for example Netherlands with the Maeslantkering and Oosterschelde barriers or England devising in London the Thames Barrier. A similar perspective in relation to the need for an efficient mitigation planning but referring to earthquakes, has been debated by Vona [67]. The author deals with the underestimation associated to emergency planning and risk mitigation measures in the context of several seismic events in the Italian territory, to be contrasted by devising a city-level resilience planning.

A knotty issue related to resilience is that when employing countermeasure such as the ones described above (i.e. flood barriers), the achievement of resilience sometimes might not be the final objective. Most of the times this type of interventions are not designed to be part of a bigger picture (e.g., a regional resilience planning including several objectives) but just a one of a kind operation leading to resilience as a side effect, or as a “by-product” [102].

In light of the foregoing, it appears evident the increasing trend in approaching resilience from several standpoints [23,75] and that can lead to a twofold interpretation. The first one might be a proof of versatility and potential of applicability in several domains, whereas the second one could confirm the opinion of some authors labelling resilience as the new “buzzword” after “sustainability” [28,74,80,103]. This last consideration stems on the weak concrete implementations of resilience in the context of urban politics and building design, apart from situations such as the case of Cuba [30] or the research carried out by Labaka in relation to Critical Infrastructure (CI) interconnectivity respect to stakeholders and its effect on resilience [69]. As far as the Cuban context is concerned, a strict control over risk-prone areas prior to construction, combined with a tightly interconnected policy and governmental system related with stakeholders able to prioritize safety over economic benefits has been saving meaningful amount of human lives [30]. Labaka led research team instead, aimed at filling the lack of research related to how resilience is influenced by the involvement of stakeholders in managing a crisis within CIs.

The review highlighted also a strong turning point in the way resilience has been defined, especially in the last decade. New approaches to resilience, in fact, should involve a more positivistic approach fostering a tendency in looking for new equilibrium conditions in the future rather than in the past, thus encouraging change and adaptation [80]. This stems on the risk lying on the possibility that “bouncing back” to a pre-disrupted condition might not be always the best option.

Therefore, the former interpretation of resilience seeing “bouncing back” as a positive outcome can be identified as “elastic” resilience, in accordance to the mechanic definition of elastic behavior [77]. Conversely, the recent approach of resilience implementing uncertainty and adaptation can be defined as “ductile” resilience, comparing it to a material showing large deformations when a stress is applied [77] and hence able to adapt. Accordingly to Chandler’s interpretation, it could be possible to define the “bounce-back” or “elastic” approach as *homeostatic*, while the evolutionary or “ductile” resilience can be recognized in the *autopoietic* one [25]. Chandler also identifies an even more sophisticated resilience trend, which he devised as less engaged with the time-related dimension, hence neither projected in the past (i.e., homeostatic) nor in the future (i.e., autopoietic), but aiming at elaborating contextual opportunities in the present in terms of narrow-scale decision making processes [25].

Evolutionary resilience applied in the engineering domain can be identified for instance in the context of a building/urban centre disrupted as a consequence of an earthquake or another kind of hazardous event. Given that, it is not beneficial rebuilding or restoring according to the situation prior to disaster (i.e., “elastic” or homeostatic resilience) [104], since the structures as they were built turned out not to be suitable for that condition. This is the case of what happened in the context of Port au Prince after the 2010 earthquake striking Haiti [105]. Agreeing in adopting this methodology would lead to an overestimation of the resilience abilities but also to a lack of understanding from the event that led to the failure of the urban centre [105]. Clearly, if no warning has been gained by the disruption, it is likely that few vulnerability reduction measures would be employed because the entity of the hazard has not been understood.

Following that approach would lead to no vulnerability reduction [105], which is instead what in building engineering (but not only) would be desirable. Hence, engineers tend to improve the buildings’ performances instead of replicating the situation that led to collapse (i.e., autopoietic or “ductile” resilience). A remarkable example of that can be identified in the founding principles of the so-called “conservative restoration”, which aims at embedding new technologies both from an architectural and structural viewpoint without distorting the image of the building and hence contextually avoiding imitations of the past [106]. The principles of “conservative restorations” thus do not share the will of attempting to achieve a past condition, but agree with making the structure more resilient in future through a decision-making process based present technologies and the awareness that adaptation is a more desirable aim than imitation.

Another conclusion that can be drawn is the limited and not concrete level of applicability of the analysed approaches, not suitable for a building-scale resilience numerical assessment. The only outcome would be a qualitative and quite subjective judgment of resilience (e.g., high or low resilience) without reaching an objective measure, comparable in the context of different systems. Furthermore, the plethora of different definitions provided for resilience creates a blurred border that makes it hard to understand what can and cannot be defined as “resilient” and what it is addressed [23,102]. This might lead to doubt about the effective applicability of resilience from a theoretical formulation to a concrete utilization, due to the multitude of attempts trying to frame its concept yet without providing opportunities for implementing it in tangible contexts [102]. Nonetheless, there are promising evidences showing the utility of resilience [23,30,52,53,55,69,107,108] and authors like Vale [109] and Reghezza-Zitt [105] underpinning its potential. Therefore, starting from the awareness of what resilience is and which are its benefits, it could be possible narrow the attention on how to achieve it practically. However, it must said that even if the strategies leading to the accomplishment of a resilient condition might be different according to the domain, at least the substantial meaning should be shared by the figures involved in its development and within the same field [25,109].

Based on these observations and considering the need for more

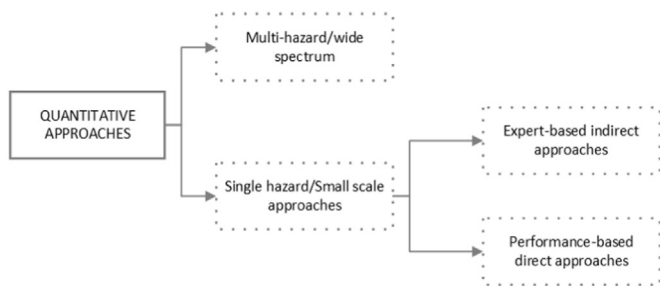


Fig. 7. Categorization of quantitative approaches to resilience in light of the literature review.

[source: authors]

technical resilience assessments methodologies, in the following section the focus is directed towards numerical-based approaches.

## 5. Quantitative approaches to resilience

Several attempts have been made to quantify resilience over time and there has been a shift from qualitative frameworks to more numerical metrics. Despite this differentiation, the meaning of resilience from a broad point of view is approximately the same for each considered domain, and can be identified as the system's ability of coping with change and maintaining its operations [71]. In Fig. 7 is depicted the differentiation between the two major mainstreams of numerical resilience assessments identified in light of the literature review, which are:

- Multi-hazard/wide scale approaches;
- Single-hazard/small scale approaches.

The first category involves the methodologies proposing a general evaluation of resilience, based on a mathematical framework and adopting a neutral approach to interconnected systems, without narrowing the attention to specific domains (e.g., infrastructures, buildings) and referring broadly to multi-hazard disruptive situations [57,59,92]. Conversely, the second group focuses on specific categories targeting a single typology of hazardous situation. A clear example of that is the research carried out by Cimellaro in relation to healthcare buildings affected by seismic events [47,51,53,110].

Multi-hazard approaches are not suitable for the scope of this research since they do not clearly answer to the questions or “resilience of what?” and “resilience to what?” [39], keeping the scale of their analysis on a level that is not suitable for a building-related analysis. On the other hand and as it will be thoroughly devised in this section, the more specific approaches lead to a general disagreement of how resilience should be achieved, despite agreeing on *what* resilience is and *to what* resilience needs to be developed for.

However, resilience needs a different approach according to the scale at which the analysis is being carried out. The methodologies explored in the quantitative category and specifically to the small scale approaches can be further divided into the following two types according to what summarized in Fig. 8:

- Expert-based indirect approaches;
- Performance-based direct approaches.

The first type, i.e., expert-based indirect approaches, usually involves districts and does not just focus on a building-level. It assesses the building performance indirectly, drawing on the identification of representative indicators as expressed in Fig. 8a, and eventually leading to a resilience formulation based on the input of such indicators. Conversely, Fig. 8b shows the process involved in performance-based direct methodologies which rely on fragility curves (expressing the

probability of a system exceeding a certain damage threshold, referring to a specific parameter such as floor acceleration or drift) in order to understand the effective performance of the construction. This procedure leads to a more continuous and precise evaluation of resilience operating at the building scale, hence involving more refined analysis compared to the ones employed in the first category.

Since the multi-hazard approaches are not of interest for the purpose of the research, as embracing a too much general perspective, they will not further explored. Conversely, the more detailed ones (i.e., expert-based and performance-based) will be analysed in the following sections. Table 2 summarises the explored numerical approaches in relation to the geo-environmental hazard(s) involved but still addressing their impact on buildings and not broadly pertaining the built environment. Three major groups have been identified (i.e., landslides, earthquakes and floods), but landslides are also split into three other sub-categories, i.e., slow-moving slides, rock falls and rapid flow-type slides. This last division was adopted based on relevant researches identified in the course of the literature review.

### 5.1. Expert-based indirect approaches

The first category can be attributed to the methodology proposed by Uzielli [65] for the assessment of building resilience towards slow-moving landslides. Based on the data provided by the Ancona municipality the researchers devised a posterior vulnerability model in order to establish the degree of loss experienced by the buildings. The map of soil displacements in different directions was instead obtained drawing on a dataset of past ground displacements by means of interpolation. Notably, given the slow nature of this phenomenon, the geometric component of soil displacement has been considered more influencing than the kinetic one, which should have been taken into consideration in case of events lasting for a shorter interval of time and presenting a more consistent speed. As a consequence, the analysed buildings have been supposed to undergo rigid shifts over time which do not exceed the ones that affect the underlying soil.

Resilience is obtained subjectively by assigning weighting parameters for structural typology, type of foundations and year of construction and then implementing relevance factors for each of the mentioned indicators, meaning which is the specific “weight” (i.e., numerical relevance) of it for the overall value of resilience. The authors drew on subjective consultations both to technicians of the Ancona municipality and experts in order to determine the relevance factors, and embedding this way a subjectivity factor leading to a higher margin of error. The approach described herein does not take into account the multiplicity of resilience indicators which would be meaningful for a more-in-depth analysis and the dataset of analysed buildings is quite scarce. Despite that, the backbone of the methodology can reveal its efficiency for quick estimations of resilience. Eq. (1) shows the formulation of resilience devised by Uzielli et al., in which  $R$  represents resilience,  $\delta_i$  is a binary variable and  $I_i$  represents a resilience indicator varying according to the considered building feature (year of construction, structural and foundation typology). The expression between the described variables represents  $w_j$  which summarizes the weights assigned to the specific  $j$ -th resilience indicator based on the relevance coefficient  $\varphi_j$  which values are included between 0 and 1. The relevance coefficient and the weighting factor are particularly useful since they easily lead to a numerical assessment of resilience through the combination of the several indicators (i.e., construction age, structural and foundation typology). Consequently, it is straightforward to acknowledge that based on the indicators' classification provided by the authors, deep foundations, retrofitted buildings and more recent constructions are recognized to be the most resilient. Furthermore, the relevance coefficient is attributed higher values for the structural typology, secondary to foundation category and eventually to building age.





Fig. 8. Schematic of the methodology comparison between the expert-based indirect approach (a) and the direct engineering-based approach (b). [source: authors]

Table 2  
Classification of quantitative approaches according to the disruption type in relation to buildings. [source: authors]

Category	Ref.	Landslides			Earthquakes	Floods
		Slow-moving slides	Rock falls	Rapid flow-type slides		
Expert-based approaches	Uzielli et al. [65]	x				
	Kaynia et al. [49]	x				
	Karamouz and Zahmatkesh [71]					x
	Field et al. [68]	x	x	x	x	x
Performance-based approaches	Barberis et al. [63]				x	
	Mavrouli et al. [61]	x	x	x		
	Biondini et al. [8]				x	
	Haugen and Kaynia [111]			x		
	Kircher et al. [44]				x	x
	Cimellaro et al. [53]				x	

$$R = \sum_{j=1}^n (\delta_j \cdot \frac{\varphi_j}{\sum_{j=1}^n \varphi_j} \cdot I_j) \tag{1}$$

A similar approach has been carried out by Kaynia et al. [49] with regard to the vulnerability of a landslides prone urban area. Conversely from what has been done by the previous approach [65] adopting the geometric aspect as dominant, Kaynia considered the kinetic one as a parameter representing the landslide intensity. However, similarly to Uzielli's approach coefficients are subjectively attributed to different structural typologies and maintenance conditions. The proposed methodology takes into account also social vulnerability factors, such as the diverse susceptibility of people according to their age and evaluating on a numerical basis the vulnerability of people in structures, hence the hazard for humans being in buildings affected by landslides. It must be noted that the present approach is limited to vulnerability assessment, without any specific evaluation of resilience, whereas the previous one [65] has been able to achieve a relatively precise level of quantification of both resilience and vulnerability, taking also into account a higher number of building-related indicators. With respect to the described methodology it is relevant to highlight the different structural classifications for buildings respect to the one employed by Uzielli. This factor allows to acknowledge the site-specificity as an essential need for characterizing buildings given the different technological background and material supplies. In essence, the availability of construction raw materials changes according to the location, and this leads to the need of taking into account different structural classification of existing buildings.

A parametric and expert-based methodology has been developed by Karamouz in order to quantify vulnerability and resilience of flood-prone coastal areas in the aftermath of a flood event for a more efficient resource allocation [71]. Conversely to the previously described approaches, this strategy takes into account an expert-based assessment and normalized weighting of relevant indicators for floods in terms of resilience and vulnerability listed in advance. The authors root their

resilience formulation on the “four Rs” (i.e., resourcefulness, redundancy, robustness and rapidity) devised by Bruneau [42] and contextualize them in different domains of society. In this context [71] defined the “four Rs” as resiliency terms, whereas within the governing factors (i.e., resilience indicators, I) are included for instance the coastal length and the likelihood of flooding on century-period base.

Eq. (2) represents the formulation for assessing resilience developed by [71], including the summation of the four Bruneau's R<sub>i</sub>s features, each one assessed through the expression included in the first summation evaluated between 1 and 4. The overall system's resiliency is obtained through the value  $\sum_{n=1}^{N_{Ri}} \bar{a}_n(v_{obs}) \times w_{I,c}$  in which  $w_{I,c}$  consists in the weighting factor relatively to the I-th resilience indicator and in relation to the criterion c. The summation is evaluated between 1 one and the total amount of resilience indicators N<sub>I</sub> for each of the R<sub>i</sub>-th terms, since the four main features of resilience might differ in terms of the included resilience indicators I. The value resulting from  $\bar{a}_n(v_{obs})$  is functional to obtain nondimensional values for each of the observed valued ( $v_{obs}$ ) relatively for the various indicators I. The ratio between the amount of indicators for each of the R<sub>i</sub>-th features (i.e., N<sub>I</sub>) and the total number of factors (i.e., N<sub>R</sub>) determines the specific incidence of each of the four resiliency terms on the whole value.

Moreover, the formulation for resilience devised in Eq. (2) recalls on a mathematical level the one devised by Uzielli in Eq. (1). The overall structures of these two equations are conceptually similar and the procedure behind them are also comparable. In fact, both approaches start from the indicator-weighting phase and then quantify resilience as the weighted summation of the diverse governing indicators. The main difference lies in the diverse connection between resilience and building-related features employed in the two researches. Uzielli's approach directly relates the two categories leading to a more straightforward calculation, while Karamouz first links the indicators to the “four Rs” proceeding then with the overall numerical resilience assessment. To this regard, it can be observed that the weighting procedure devised by Karamouz involves a multicriteria decision making

(MCDM) approach, whereas Uzielli's methodology is slightly more fragmented. Conversely, Uzielli's methodology turns out to be more building-specific while Karamouz presents a broader approach which does not explicitly take into account meaningful features strictly related to the building environment.

$$R = \sum_{i=1}^4 \frac{1}{2} \times \left[ \sum_{n=1}^{N_i} \bar{d}_n \left( v_{obs} \times w_{i,c} + \frac{N_i}{N_R} \right) \right] \quad i \in [1, 2, 3 \text{ and } 4] \quad (2)$$

A noteworthy tool for assessing resilience on an urban scale has been developed by [68], drawing on a risk-based approach and taking into account a multiplicity of hazard-related categories (e.g., health, infrastructure, natural, technology), each one including six sub-categories related to more specific threats. Resilience is then evaluated dividing its main aspects in three themes, identified in: 1) society and community, 2) governance and economy and 3) environment and infrastructure. Resilience is then numerically evaluated by summing together the value calculated for the mitigation aspect with the one related to adaptive capacity. The calculation of resilience passes into six stages involving a first understanding of the possible hazardous situation, followed by a second stage of refinement of the most likely and relevant stresses in order to prioritise the risks. As a consequence, the next two stages of the process involve the determination respectively of the resilience demand and capacity by taking into account meaningful properties, such as redundancy, adaptive capacity or exposure. The ratio between the resilience capacity and its demand provides the resilience rating, measuring effectively the enhancements achieved through the mitigation interventions. The last phase of the methodology aims to assess the opportunity for further improvements, by subtracting the resilience capacity to its demand.

Similarly to Karamouz [71], resilience is achieved combining its different features, even if in the current approach a significant contribution consists in calculating the ratio between the mitigated condition of the system and the original one. Field [68] achieved a meaningful tool embracing several fundamental aspects on an urban scale, but there is still margin for more-in-depth measurements of resilience, especially addressing the built environment.

All in all the expert-based methodologies link the disaster-related features in a scattered and subjective way, connecting the building characteristics to their resilience capacity [65] or focusing on the hazardous event itself and the vulnerability of the built environment, but considered in a superficial manner [71]. The result is a granular and disjointed risk assessment which, alone, is not sufficient for a thorough resilience representation. Although, it must be said that semi-statistical based approaches such as the one proposed by Uzielli [65] are particularly useful while dealing with a significant amount of buildings (e.g., city or regional scale), hence for a less in-depth analysis but from a higher perspective.

### 5.1.1. Performance-based direct approaches

The approaches described in this section rely on the employment of finer methodologies (e.g., fragility curves), resulting in a continuous model instead of a discrete and fragmented analysis such as the one achieved through expert-based indirect methodologies [61].

To this regard a comprehensive methodology has been devised by Mavrouli, who numerically evaluated the vulnerability of RC buildings to landslides of three diverse typologies (slow-moving landslides, rapid flow-type slides, rockfalls) using an RC structure model subjected to slope instability and then impacted by rapid-flow type slide and rockfalls [61]. Their approach takes into account essential variables for an engineering-based analysis, such as the type of foundation or soil condition. In addition, a fundamental characterization of the structure materials is provided in terms of characteristic concrete and steel strength, but also the percentage of longitudinal steel reinforcement for columns and beams. The employment of the steel strain as an indicator of damage leads to acknowledge the damage process and eventually the

ductile failure of structural components.

Cimellaro led research team developed a resilience formulation pertaining hospital-type buildings combining the merely structural behaviour with a cost-based and organizational analysis [53] through the tools developed earlier [45]. The contribution to resilience provided by structural performance is evaluated by means of fragility curves, which can relate the probability of exceeding a specific threshold of damage to a certain seismic response parameter [44,112]. After examining four possible retrofitting solutions the authors provided for each one economic and structural breakdowns allowing a comparison amongst them in terms of performance and convenience. The research provides a meaningful tool for healthcare facilities, but an effective methodology should be able to encounter the needs of different building types.

With regard to the merely engineered methodologies, a relevant approach that can be highlighted is the one addressing the development of fragility curves specifically derived for recovery processes and resilience analysis, named Restoration Fragility Functions (RFF) [63]. Their featuring element is being conditional on the Damage State (DS) and the event's intensity (I), while traditional fragility curves relies just on this last variable. By means of a performance based design (PBD) approach, hence considering three DSs (i.e. fully operational, moderate damage and sever damage conditions) the respective restoration functions are developed showing that to an increase in seismic intensity and lower functionality correspond longer recovery times. Resilience and fragility are hence interconnected similarly to what concerns the structural behaviour. To this regard, the more brittle is the failure, the less a structure can be defined as resilient.

Biondini and colleagues achieved an earthquake-relevant and explicit formulation of the system performance represented in Eq. (3) by the ratio between the seismic acceleration bearing abilities of the structure at a considered time ( $a_g(t)$ ) and the initial value of it ( $a_{g,0}$ ) [8]. By taking into account functionality losses occurring in the long run the authors provide a noteworthy contribution to the body of research related to the resilience numerical assessment.

$$Q(t) = \frac{a_g(t)}{a_{g,0}} \quad (3)$$

HAZUS [44] multi-hazard damage assessment methodology enables the evaluation of earthquake-related geo-environmental hazards such as landslides or inundations as an indirect aftereffect of the primary seismic event. Currently no models specifically addressing landslides have been developed among the HAZUS methodology, which consists of three main hazard frameworks specifically related to earthquakes, extreme wind conditions and floods. Resilience is taken into account in a non-explicit way evaluating capacity curves relating the structural inelastic response in terms of spectral displacement to the spectral seismic acceleration and hence resembling the steel tensile test diagram. The methodology devised by HAZUS [44] implies the overlapping of the building capacity curves with the demand spectrum in order to then derive the fragility curves for each damage state and the consequent discrete probability of occurrence.

Notably, the stages involved in this methodology are similar to the ones described for the steel tensile test, encountering first a linear and elastic stage followed by a yielding point after which damage increases with physical displacement even if the seismic force remains constant [44]. Clearly, the complexity of the seismic solicitations in the context of a construction leads to the substitution of stress and strain respectively with spectral acceleration and displacement. Structural displacement is a relevant feature, since its relationship with the stressing parameter establishes the entity of the ductile behaviour, which is the desired performance of a building in case of hazard. As a matter of fact, ductility consists in the ability of withstanding significant deformations before reaching the failure, hence allowing occupants of being warned about the damage or even collapse. Conversely to ductility, fragility represents an unlikely property since the failure occurs in a brittle and

unpredictable way after low values of strain. To this regard, “brittleness” (i.e., fragility) can be effectively identified as the opposite of resilience, in the sense that a system not able to flexibly adapt to disturbances will reach failure [81].

Structurally speaking thus, it can be inferred that resilience and ductility are in a way related but still they differ. PBD and semi-probabilistic approaches to building design have been structured in order to include a component of uncertainty provided by the probability of occurrence of an event (e.g., earthquake) in a certain period of time. Moreover, in countries like Italy there has been a shift from building regulations relying on elastic abilities of structural materials [113] to more sophisticated ones using plastic capacities and hence aiming to achieve a ductile behaviour [19]. Thus, building now are designed to perform with an adaptive behavior rather than relying on their capacity of “bouncing back” elastically. On the other hand, resilience is a broader concept, encompassing not just the design, but also what is entailed before, during and after, including disruptive conditions. As a consequence, in light of this conceptualization of resilience in relation to the built environment, an effective resilience planning and framing needs to take into account all the features highlighted above. In light of the foregoing, one meaningful issue to solve is how could it be possible to embed resilience in a long-term perspective design of buildings, in order to make it concretely applicable and tailored to the changing needs of a building?

All in all, the herein described methodologies clearly differ from the expert-based category ones, the latter being suitable for a less specific analysis addressing a larger building dataset, whereas the current typology fits better the purpose of a restricted context (e.g., standalone building or aggregate of constructions) hence needing a much finer analysis. However, the methods described in this section are able to achieve a more comprehensive analysis, connecting a significant amount of parameters but showing the potential for improvement with the implementation of evidence-based techniques.

## 6. Holistic perspective to resilience research

Resilience is a multi-disciplinary and complex concept; hence its analysis and formulation cannot leave aside some related notions such as vulnerability, adaptive capacity and recoverability, especially concerning the built environment issue in face of disruptions. Furthermore, as one of the objectives of this research involves the identification of a high-level conceptual framework underpinned by mathematical formulations for the built environment resilience, it is of primary relevance to acknowledge the existing relationship between the different concepts. The analysis of the connected literature will allow explaining the approach adopted in the present research, hence the interrelation amongst the aforementioned concepts.

### 6.1. Vulnerability

According to the Oxford Dictionary, the concept of being vulnerable to potential threats is broadly defined as “the quality or state of being exposed to the possibility of being attacked or harmed, wither physically or emotionally”, while in the literature it has been identified in relation to natural disruptions as “the characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard” [114].

Generally, most of the definitions addressing vulnerability have in common a negative meaning which is connected to susceptibility and likelihood of being damaged [115], leading in some cases with its identification as an antonym of resilience [38,116]. Similarly, the IPCC Third Assessment Report (TAR) has devised vulnerability as the likelihood of a system to be unable to deal with extreme events and being a function of specific features related to the event to which the system is exposed to [117]. Manyena partially followed this path, depicting

vulnerability as the representation of the potential susceptibility of a system to extreme events, but also identifying it with a lack of disaster resilience [72]. Vulnerability thus addresses to a pre-disruption state of the system, in which possible conditions that can bring to disaster can develop and eventually lead to a threatening situation [48].

As a matter of fact, a system can be vulnerable to threats even finding itself in stable conditions and increasing its likelihood of being damaged while starting to undergo a disruption [118]. This interpretation is in contrast with the one that assumes vulnerability as a state of the system which has already been affected by disturbances, but just before exhibiting its recovery capabilities, hence including vulnerability in the whole resilience process [57].

The debate about the existence and typology of a possible correlation that links resilience and vulnerability has raised several opinions [72,76,116], and a clear summary of all these views has been devised by Manyena, who identifies two main standpoints: the first one considers resilience and vulnerability as separate entities, whereas the other one sees them as related [72]. Folke and colleagues [116] underpinned that a lack of resilience coincides with a strong influence of vulnerability, defining one as the ‘flip side’ of the other, and including resilience as a property of vulnerability together with exposure and sensitivity, but this view has been criticized as leading to a “circular reasoning” [72,76]. The position adopted by Folke and colleagues has been partially shared by Gallopín. In fact, as it can be acknowledged from Fig. 9, Gallopín considered exposure as a feature of vulnerability as well as system's sensitivity and response to threats. The author also argues that vulnerability addresses to structural changes of the system, whereas resilience deals with modifications in its state conditions [118], hence in this sense both Folke and Gallopín share the view according to which resilience should be a subset of vulnerability.

From the overview of the definitions provided, a robust interrelation amongst vulnerability and disruptive events can be underpinned, as well as with resilience itself and the system's ability to recover from damages [115,118]. Since the present paper deals with resilience contextualized in the built environment, exposure is also considered as a relevant parameter to be embedded in the framework, as well as sensitivity and response capacity. Clearly, the diverse exposure of construction (e.g. geo-morphological features of the location) can influence their vulnerability in face of hazardous conditions (e.g. wind, snow, earthquakes) and consists in one of the first issues that needs to be taken into account according to building regulations in the design process [19,22]. Narrowing the attention to the built environment domain, it is needed to distinguish between new and existing building and resilience needs to address both of them, even if differently. As far as new constructions are concerned, vulnerability is not measured since the building can't be vulnerable to something if it has not still been realized, and once built is supposed to be resistant to the threats for which it has been designed. However, even building regulations might include uncertainties that make buildings and infrastructures vulnerable to rare events or unforeseen disruptions.

On the other hand, with regard to existing constructions the issue is different, since vulnerability can be effectively quantified [65,119,120]. In particular, the vulnerability of the existing building stock consists in the only parameter on which actions are possible in order to reduce the

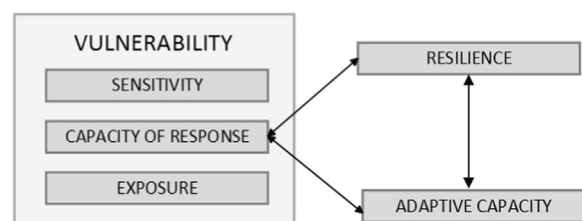


Fig. 9. Linkages between vulnerability and resilience-related features [adapted from [118]].

likelihood of damages. The reason for comes from the definition of risk, consisting in the combination between hazard, exposure and vulnerability. The only variable on which interventions are allowed is hence the latter, being the first two factors functions of geographical and geological aspects [120].

Vulnerability in relation to the built environment expresses the existing correlation amongst the intensity of an event and the expected damage. As a consequence, it can be underpinned that the vulnerability curve is different for each system and varies also with the extent of the system, so if it addresses to a single building or a urban scale [121].

Vulnerability in the context of urban systems does not consist in a linear function. In fact, a slight damage can be absorbed elastically, but when exceeding a certain threshold the system enters a critical phase in which the level of loss can increase despite the constant solicitation [122]. If that happens, in case of further amounts of stress the system can collapse without any chance of recovery [122].

It must be said that in light of the new evolutionary approach to resilience, a proactive and real-time identification of potential vulnerabilities of a system represents a positive factor, allowing to detect possible failures and weak points that could lead to critical loss of performance.

### 6.2. Recoverability (or restorative capacity)

The time that a disrupted system needs to restore its performance has been identified as recoverability (or restorative capacity) [42] and also addresses to the rapidity concept [60]. In fact, recoverability is often defined coupled to the recovery time, which corresponds to the period needed to achieve an equal or better level of performance compared to the one that the system owned previous to the disruption [52]. Though, rapidity and recovery time must not be identified as the same parameters, since the latter is needed to obtain the system performance function, whereas the first one is the derived from the functionality of the system [52]. Recoverability applied to buildings relies on several variables (e.g. cost, time, construction choices) and consists in a complex process to be defined. Some efforts have been done in order to determine the recoverability on a probabilistic level by [63] and with a more comprehensive methodology providing four different strategies of recovery after disruption by [53].

### 6.3. Adaptive capacity

Adaptive capacity, according to the literature, can represent the ability of a system to undergo changes and readjust itself in case of disruptions [60], but it is also depicted as an intrinsic feature of the social component in a SESs and can influence resilience and its properties [40]. Two diverse components of adaptive capacity have been identified in the literature and the first addresses to the ability of a system to preserve its features towards a disruption. Besides, the capacity of a system to enhance its conditions in absence of changes or an increase in the amount of environments to which it is able to adapt represents another relevant feature [118].

In line with the “basin of attraction” theory Folke and colleagues define adaptability in the socio-ecological domain as the capacity of a system to modify its mechanism of response to both external and internal stimulus, but still without exiting the stability domain [54]. They also devise the adaptive capacity of a system as a part of resilience, being thus in agreement with Gallopín’s work. An effective overview of the relationships existing amongst vulnerability, resilience and adaptive capacity has been provided by Cutter and colleagues [48], showing how broad and diverse are the positions of the literature towards these issues.

All in all, the body of literature about resilience and its connected issues is broad and there is a urgency for developing a concrete and shared metric of resilience which should also be proved to be effective in real conditions [48]. This research will embrace the approach

proposed by Gallopín, hence including resilience as a sub function of vulnerability [118], and adaptive capacity as a subset of the latter.

## 7. Conceptual framework for built environment resilience and directions for future research

Based on the extensive and critical review of the resilience literature presented earlier, a conceptual framework supported by a mathematical formulation is presented with a view to factor in the essential concepts behind the diverse existing work in a reasonable and accessible manner and providing insights and opportunities for future research.

A special focus goes to the qualitative and quantitative approaches for the modelling and enhancement of building resilience throughout the paper. The review highlighted that the majority of the qualitative approaches assessing resilience towards hazardous events for the built environment have been developed adopting an organizational and managerial perspective. Conversely, quantitative approaches are hazard-specific and target defined building typologies leading to a more accurate evaluation but still to an overall fragmented perspective. Thus, a significant gap can be identified in relation to a more comprehensive resilience formulation targeting technical aspects for the built environment in face of geo-environmental hazards. More specifically, the present section will provide a preliminary framework devised in order to enhance resilience towards geo-environmental hazards and an application in the context of buildings in relation to seismic activity. In order to aid and achieve clarity in relation to the formulation of our conceptual network, the following glossary of terms is given:

- **Built Environment (BE) Intrinsic Characteristics:** The inherent features of the built environment both related to structural and non-structural components, taking into account also their status variables over the construction lifespan.
- **Geo-environmental Hazard:** A natural or human-induced geo-environmental event (e.g. earthquakes, landslides, volcanic activity, tsunamis, erosion and flooding) which has the potential to create losses.
- **Geo-environmental Disaster:** A destruction of functioning to a community caused by a geo-environmental hazard.
- **BE Resilience:** The intrinsic ability of the built environment to react positively before, during and after the presence of the adversely exogenous input (e.g., landslides), i.e., the ability to absorb external disturbances, in order to maintain the system's original states or reach a new set of steady states for serving its normal functionalities.
- **BE Vulnerability:** The degree to which the built environment is affected adversely to the occurrence of a hazardous event.
- **BE Risk:** The actual exposure of the built environment to a geo-environmental hazard.

### 7.1. Proposed resilience of the built environment framework

Fig. 9 illustrates a proposed conceptual framework, informed by the above critical review of resilience literature, applied to the built environment domain, including buildings (domestic, public and industrial) and infrastructures. The proposed framework is generic in nature and can be adapted to other sectors such as social and ecological contexts. The framework aims to capture a range of different considerations arising from the built environment and the outside natural, social and disaster dimensions in which buildings and infrastructures operate. Given the built environment focus of the research, we then present its resilience to various geo-environmental disasters including earthquakes, landslides, volcano, tsunamis, and flooding, but within the context of a wider natural and social environment. In general, the conceptual framework can be articulated from the related resilience, vulnerability and risk forming processes (Fig 10).

First of all, the framework starts with a set of intrinsic characteristics that define a particular built environment including the structural

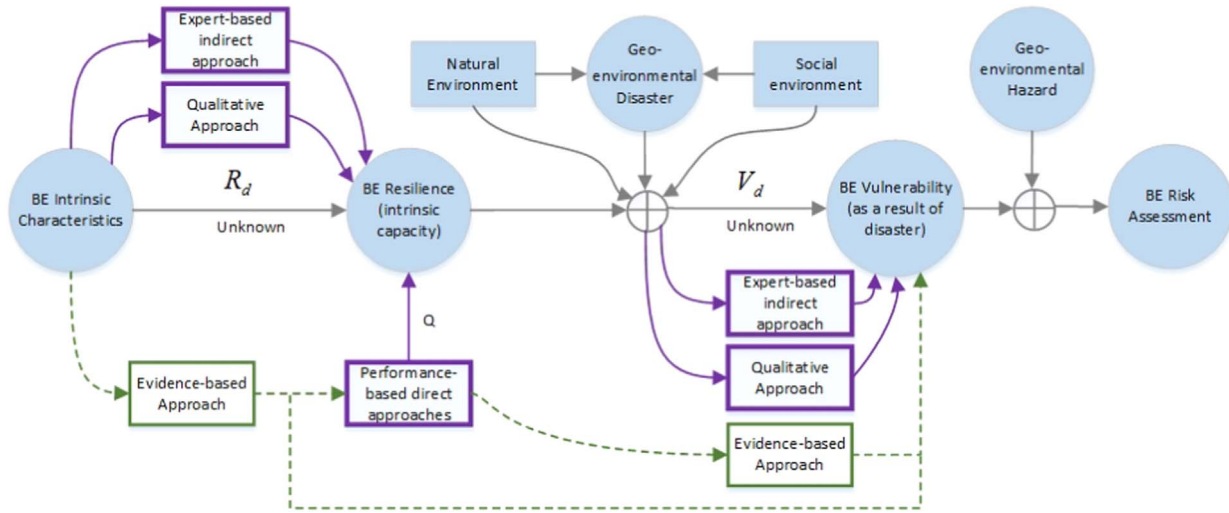


Fig. 10. Conceptual framework for built environment resilience related research. [source: authors]

components (e.g., wooden, masonry and concrete/steel frame) and non-structural components (e.g., HVAC, electrical and plumbing systems). The design, operation and maintenance of these components together with other characteristics of the construction including its type, foundation and age will determine its resilience to various geo-environmental disasters. It should be noted that when we present resilience in this paper, it is usually accompanied with a “target object” defining the specific threats; so for example we have a construction which can be flood resilient, earthquake resilient and/or landslide resilient. Otherwise, speaking of resilience alone would refer to the general resilience of the construction to any kind of geo-environmental threats. Based on that, a generic resilience model is formulated as:

$$Resilience = R_d(T, A, F, S_c, S_s, N_c, N_s, U_r), \quad (4)$$

where  $R_d$  represents the function of resilience level with respect to a particular geo-environmental disaster,  $T$  is the construction type,  $A$  is the construction age,  $F$  is the construction foundation,  $S_c$  and  $N_c$  are the set of structural and non-structural components of the construction,  $S_s$  and  $N_s$  are the set of standards and statuses of the design, operation and maintenance for structural and non-structural components, and  $U_r$  refers to any unquantified resilience indicators that are formulated as the uncertainty to the resilience model.

A detailed classification between structural and non-structural components of buildings can be found in [123]. For example, there are design, operation and maintenance standards for the emergency lighting to be functioning after the earthquake for owner's safety purposes [123]. In this regard, the performance of non-structural components that are essential to the functioning of critical infrastructure, such as electricity/food production/distribution, telecommunication, water supply, transportation and public health systems, should be guaranteed with high design, operation and maintenance standards following geo-environmental disasters. It may also be worth mentioning that as varied from region to region, different costs can be incurred for the actual implementation of a building standard. Notably, given this general resilience model, it should be recognised that different specific resilience models and associated important indicators can be resulted with respect to different disasters, as a distinct disaster poses different impacts and thus requirements on those indicators in order to get the construction resilient.

Moreover, as indicated in the above resilience model, the larger the degree of uncertainty involved in determining indicators, the less the model's capability of capturing such resilience. Based on that, the actual model accuracy will also depend on how the model is obtained and expressed. For example, a subjective but quantitative approach as

presented in [65] only takes structural typology, building age and foundation type into consideration and expresses the resilience model in the form of weighted summation on these indicators. Given our framework, it is easy to conceptualise a variety of existing fragmented forms of models as discussed previously, generally each considering a different set of indicators without a holistic and systematic view and sufficient justification and verification of their underlying methodologies. The research question then arises in how to qualitatively or quantitatively identify the exact resilience indicators and express the resilience formulation with respect to the specific type of geo-environmental disaster in a convincing way. Furthermore, it is worth mentioning that the output of the proposed resilience model should not be only limited to continuous numerical values (for example, a normalised value between 0 and 1), but can also be linguistically understandable or fuzzy concepts (for example, a label from a predefined set of classified resilience labels including very high, high, medium, low and very low).

In relation to the resilience study, a related concept of vulnerability defined as the extent of damage to the built environment due to geo-environmental disasters can now briefly discussed. Overall, if a construction is more resilient in terms of addressing a specific threat, it would be less vulnerable but the real complexity is also dependent on the surrounding environment. The corresponding vulnerability model can therefore be formulated as:

$$Vulnerability = V_d(R_d, G_d, N_e, S_e, U_v), \quad (5)$$

where  $V_d$  represents the function of vulnerability level usually as a result of a particular geo-environmental disaster,  $G_d$  describes the contributing disaster to the disruption,  $N_e$  describes the natural environment,  $S_e$  describes the social environment, and  $U_v$  refers to any unquantified vulnerability indicators formulated as the uncertainty to the model. Here, a natural environment is comprised of any naturally appearing entities including climate, weather, water, natural resources and soil texture, while a social environment defines human interactions, gender/ethnic background, work and education, and economic activities. It is then foreseen that different natural, social or disaster considerations can lead to different degree of vulnerability for a given construction. Such vulnerability can then be combined further with the geo-environmental hazard information to perform risk assessment [65].

As summarised in [48], different forms of frameworks describing the relationships between vulnerability, resilience and adaptive capacity have been discussed in the literature. Given our proposed framework and associated formulations, we can easily consider the adaptive capacity as part of the resilience in terms of the system ability (stemmed

from the design, operation and maintenance of either the structural or non-structural components) to adjust positively in response to an exterior change or disturbance. On the other hand, improving resilience is regarded as one intrinsic ingredient to reduce the vulnerability which also factors the specific quantification of a disaster and natural and social environments. The aim of the proposed framework is to provide a holistic and systematic view on the resilience and vulnerability aspects of the built environment, while examples of categories of indicators listed above are no means of exhaustive. In a broader sense, built environment resilience and vulnerability with respect to different threats can certainly be attributed to the distinct (degree of) involvement of indicators and also distinct models designed to describe the underlying mechanism. It is thus imperative to identify and reach a consensus on the detailed key indicators (together with their interactions) of resilience and vulnerability for the major geo-environmental disasters, or at least the unified approach leading to such identification (in cases that they are context specific, for example, in terms of regional differences). Regarding a particular threat, the model also needs to consider certain extent of uncertainties arising from the absence of less important or recognised indicators, which therefore lead to model errors or residuals. In addition, model errors can also be found in the qualitative approach regarding subjective reasoning and the quantitative approach regarding monitoring, and model structure and parameter determination.

## 7.2. Resilience research future directions

Built environment resilience requires a comprehensive programme of research spanning several interrelated disciplines. In that respect, four key strategic areas requiring further research are identified and briefly discussed below, namely: (a) risk based cost optimal resilient design and standards of buildings and infrastructures, (b) model based evaluation and optimisation of buildings and infrastructures, (c) integrated risk modelling, inference and forecasting, and (d) heterogeneous disaster data acquisition, integration, security and management.

### 7.2.1. Risk based optimal resilient design and standards of buildings and infrastructures

Current approaches to building design demand that buildings meet several serviceability performance criteria related to each of their constituent systems [124,125]. Serviceability requirements are formulated in the form of range values (upper and lower limit) to be satisfied. When serviceability requirements are outside the range of these specified values, undesired conditions can be induced which can cause stress and potential harm to the building and its occupants. However, many model parameters are subject to variation and change over the projected building lifecycle.

From a wider scale, urban concentration of populations, as well as intense social interactions and economic activity, characterise our modern cities. It is essential to (a) understand how disasters propagate from buildings through cities and disrupt physical, socio-cultural and economic city systems, (b) how can the impact of these disasters be reduced and managed? (c) how can cities become more resilient? Research suggest that most resilience-related initiatives focus on a building/block of buildings level and do not address the complexity of urban environments that depend on the interaction between social, economic and technical systems.

### 7.2.2. Model based evaluation and optimisation of buildings and infrastructures

Building data analytics is often aimed at energy benchmarking and environmental (indoor occupant comfort, air quality) performance monitoring, which if combined with structural monitoring, can provide useful data about whole-building resilience. Live datasets from current building monitoring are at best sporadic, often comprising an ad-hoc combination of off-the-shelf building management systems (BMS) and

distributed data metering equipment combined using traditional database (SQL) solutions. The ad-hoc combination presents many challenges for extracting meaningful relationship between datasets, due to the variations in information exchange protocols across systems – resulting in distributed (often inconsistent or corrupted) data.

Moreover, the complex interplay between the variables that underpin building systems behaviour precludes a simple set of rules or guidelines and necessitates the development of more complex data rich models which (a) better inform designers about the lifecycle trade-offs that can be made between different systems of a building and (b) devise appropriate response strategies to unexpected solicitations. In that respect, a systems thinking perspective is essential as it provides a foundation for building systems modelling necessary to understand how the different components within a building interact, the involved variables, their dependencies, and the dynamic forces that affect their performance. There is an urgent need to develop cost-effective methods, tools and guidelines for acquiring, integrating, secure management and streaming of distributed heterogeneous data on disaster risks and impact on buildings.

### 7.2.3. Integrated risk modelling, inference and forecasting

Existing approaches to built environment risk modelling lack a holistic understanding of disaster risks, their boundary conditions and impact on building standards. It is important to “analyse together” geo-environmental data, building performance and socio-economic activities with the objective of inferring (hidden) correlations that are not directly observable and inferring knowledge about their interdependencies. Integrated risk modelling, inference and forecasting should make use of fused and streamed data from heterogeneous sources to infer knowledge of impact (losses due to a disaster), risk (probability of a disaster event) and performance of building systems (damage, degradation) on geospatial and temporal scales.

Decisions on resilience design interventions and standards often rely on an estimate of cost and associated benefits. Existing methods for assessing cost of resilience measures do not factor in the following costs: pre-construction or non-construction, construction, ancillary, operation and maintenance, and cost of disruption due to a disaster event. There is a lack of resilience characterisation techniques and methods that consider various scales from micro (building/infrastructure) and macro (district/city/region) taking into account nonlinear and continuously changing governing variables and their boundary conditions.

### 7.2.4. Heterogeneous disaster data acquisition, integration, security and management

One of the key challenges in disaster management, response and resilience is related to the lack of availability of data to the built environment stakeholders for upstream processing, analysis and informed decision-making. There is an urgent need for the development of geo-environmental big data acquisition techniques focusing on various disaster related events, such as: soil displacement to monitor earthquakes and their effects [126–128], floods monitored by hydrological and meteorological sensor networks, and volcanic activities utilising data collected in real time by specialised seismic sensor networks.

## 8. Conclusion

The paper aimed at exploring different conceptualisations of resilience in relation to geo-environmental disruptive events, through the critical analysis of both qualitative and numerical methods from an engineering point of view. Despite the meaningful research that has been carried out in this regard, evident gaps have been pointed out in relation to the lack of a holistic viewpoint towards a finer resilience assessment.

Two major mainstreams in the attempt of framing resilience have been identified, i.e., qualitative and quantitative approaches. It has been observed that a non-numerical analysis leads to an interpretive

qualification of resilience, clearly not suitable for engineering purposes being far too broad and general. Conversely, the reviewed quantitative approaches revealed their application in a wide variety of real-world specific contexts (e.g. building-scale analysis); however, without an integrated methodology.

The numerical (i.e., quantitative) methodologies have been then split into two more categories. The first has been identified in multi-hazard approaches, involving broad-scale networks without any particular focus either on buildings or infrastructures. In contrast to that, a series of more focused methodologies have been identified as dealing with a building-scale analysis or targeting specific areas (e.g., urban scale) and their resilience in relation to a single typology of disruption. The second category has been deeply analysed considering several researches, highlighting their pros and cons in light of the differentiation amongst subjective (i.e., expert-based) approaches and performance based methodologies.

A general agreement in relation to how concretely pursue resilience has not been achieved yet, which is not surprising considering the extent of the concept in different domains. Yet, it would be expected some sort of consensus at least within the same domain of analysis (e.g., building engineering, biology, sociology) in terms of *how* to pursue resilience. In this sense, resilience should be defined within clearly delimited areas and hence being context-specific, in order to be precise enough to be numerical (hence, objective), but without losing the overall picture (hence, being holistic). To achieve that is necessary identifying which are the vulnerable objects that resilience must address and establish a set of potential disruptions suitable to be embedded in the same category (e.g., geo-environmental hazards, human-triggered disruptions, and health related hazards). Consequently the framework for resilience adopted in the context of that category would be able to address simultaneously different threats with little effort in adapting the parameters. As such, in our framework we identified the building stock and clearly chose geo-environmental disruptions and not just earthquakes or floods for defining. Similarly, we did not include for instance human-triggered disruptions (e.g., blasts employed for building demolitions) because they would involve a different approach and hence, they can be targeted as part of a different research. On a broader level, a significant advantage of adopting a more horizontal distribution of the tasks in the resilience planning would entail more fluid processes, in contrast with the purely vertical approaches that have been embodied in recent times.

Specifically in relation to the building engineering domain and referring to quantitative resilience assessments, the literature review highlighted a strong contrast between extremely broad analysis and limited-scale methodologies (i.e., multi-hazard approaches versus single-hazard ones, such as devised in Section 5). Future research should focus on finding a pragmatic, real-time and concretely useful framing of resilience, able to encompass holistically a range of hazards relying on meaningful parameters that can be adjusted according to the addressed disruption. Opportunities for future work could embed the following directions:

- Pragmatic/useful in practice;
- Flexible/adjustable according to the analysed disruption(s);
- Inclusive/holistic;
- Embed pragmatic emergency planning strategies;
- Context specific.

Furthermore, resilience has been contextualised also referring to more high-level concepts, such as vulnerability, adaptive capacity and recoverability. This is motivated by the need of acknowledging the correlation underpinning these concepts, in order to devise a preliminary conceptualisation of resilience as a sub-function of vulnerability. In that regard, the detailed identification of the specific resilience indicators was out of the scope of the present paper.

With respect to future work opportunities, they will involve the

definition of a relevant set of meaningful indicators regarding resilience to geo-environmental hazards. A Delphi-based methodology will be adopted. The first stage will involve the setting-up of a panel of expert, selected based on four main determining factors: (a) knowledge and experience in relation to the field; (b) determination in being involved in the process; (c) availability of suitable time for participation; (d) incisive communication abilities [129]. As deeply devised in [130], the identification of the panel of experts will start determining relevant personalities with adequate expertise, knowledge and experience. Experts will be drawn from (a) several fields to provide a broad coverage of resilience research [131] and (b) different countries, in order to cover a wider range of perspectives in relation to building-related hazard conditions and also geographical domains to have access to more holistic dataset of possible scenarios. This research will be reported in follow-on publications.

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