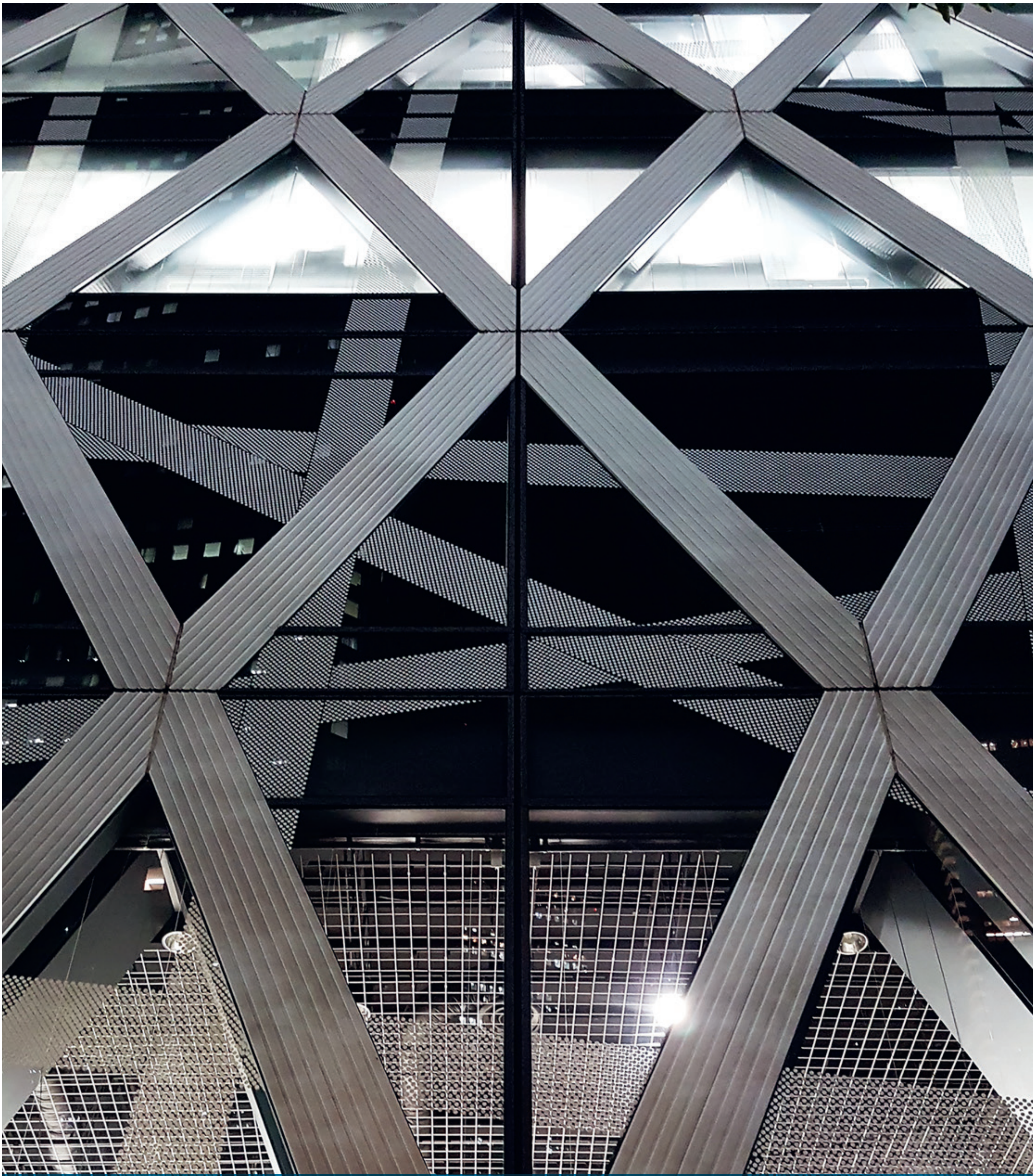

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IDENTIFYING BUILDING RISK: THE POTENTIAL CONSEQUENCES OF THE VULNERABILITY OF BUILDING ENVELOPES' TECHNICAL ELEMENTS

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Abstract

The building envelope serves as the interface with the external environment. Its technical elements (e.g., cornices, balconies, and finishings) are highly vulnerable to damage from external hazards due to their technological characteristics and state of preservation. Such phenomena can lead to potential detachments and falls of these elements onto surrounding areas, posing significant risks to exposed agents and transforming them from "factors at risk" to "risk factors" for urban systems. This paper seeks to formalise the concept of Building Risk, which is defined as the probability that a hazardous event, stemming from the vulnerability of the technical elements of the building envelope, can have detrimental effects on urban systems. A scientific literature survey was conducted to analyse how existing studies have addressed these issues. The results indicate strong interest in the impacts of external hazards on buildings and urban systems, revealing significant gaps in modelling the cascading effects arising from the building envelope vulnerability. Assessing this vulnerability and its impacts is crucial to ensure urban system safety and to fully understand the multi-risk dimensions to which these systems are exposed. The proposed topics aim to inform the implementation of risk reduction measures and the design of low-vulnerability technological solutions tailored to contexts' specific hazards. Future implications include the renewal of risk management strategies to enhance urban system safety.

Keywords

Building risk, Building envelope, Vulnerability, Urban system, Multi-risk.

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1. INTRODUCTION

The frequency and intensity of hazards and the severity of their impacts have increased significantly worldwide over the past two decades, amplified considerably by Climate Change and other risk drivers [1]. Many disaster management and mitigation policies concerning buildings and urban systems to date have focused on reducing the loss of life, property, and services in single disaster risk scenarios [2]. The increasing emergence of complex risk scenarios has revealed the necessity to adopt and implement comprehensive and long-term multi-risk approaches as the basis for Disaster Risk Reduction [1]. These approaches emphasise the urgency of establishing cross-sectoral frameworks to improve the understanding of risks in all dimensions, characteristics, and interactions, as well as developing renewed governance measures [2]. By extending conventional risk reduction and disaster management strategies, these measures aim at the broader goal of building resilient systems employing systemic and coherent multi-risk management strategies [3, 4].

The Horizon Europe Programme [5] and the 2030 Agenda (Goals 1, 11, 13) [6] include the adoption of new emergency management procedures among the global challenges aimed at making human settlements safer. The challenges announced in Cluster 3 of Horizon Pillar 2 promote strategies to improve cities' safety against natural and man-made disasters by identifying priority actions based on an enhanced understanding of risks and strengthening management strategies [5]. By referring to global guidelines, the program analyses disaster risks (Sendai Framework for Disaster Risk Reduction [4]), including chemical (Seveso Directive [7]), climate (Paris Agreement [8]), and hydrogeological (EU Floods Directive [9]). The Key Research and Innovation Orientations outline the necessity to develop integrated approaches that, while addressing short-term safety needs, must foster a proactive culture to deal with long-term risk scenarios [5]. The National Programme for Research 2021-2027 aligns with these themes, as described in section 5.3.1, where it proposes prioritising research on understanding, monitoring, and developing multi-risk strategies against natural and man-made disasters [10].

In developing a multi-risk approach, the above-mentioned programs primarily address disaster risks perceived as exceptional and potentially catastrophic. These can be classified as "Intensive risks", defined as high-intensity and low-frequency events caused by major hazards, distinguished from "Extensive risks", which are defined instead by low-intensity and high-frequency events, usually associated with weather-related and/or highly localised hazards [11, 12]. For the purpose of this paper, these definitions were deemed functional to express the proposed topic, particularly in the way they classify risks according to relevant events' characteristics.

Although the classification of Extensive risks identifies persistent events, the focus of both definitions remains on external hazards directly impacting buildings and urban systems [3]. In contrast, a comprehensive analysis of the cascading risks that buildings themselves generate for the urban system is often overlooked. The multi-risk concept encompasses the complex assessment of multiple hazards, which can trigger chains of hazardous events across different spatial and temporal scales [13]. Unlike simpler multi-hazard perspectives, multi-risk assessment accounts for the interdependencies between hazards and risks, addressing their interactions and combined effects on other risk factors, such as triggered events, cascade effects, and amplified vulnerability in successive hazards [13, 14]. In these scenarios, the multi-risk dimension emerges from multiple hazards threatening the same elements at risk either non-simultaneously, simultaneously, or in rapid succession, whether independently and through impact chains [2, 4, 13, 14].

Based on the above considerations, multi-risk approaches must comprehensively analyse and evaluate cascading effects stemming from building vulnerability. The hazard posed by the vulnerability of building envelopes' technical elements and their cascading impact on surrounding areas is often overlooked in the described context. This contribution seeks to expand on and address this gap by introducing the concept of Building Risk (R_b).

1.1. RESEARCH CONTEXT AND RELEVANCE OF THE TOPIC

As the boundary between the building and its context, the building envelope plays a critical role in protecting the building from external actions and directly interacts with other elements of the urban system. This system consists of two main components: the social component, representing the population, and the infrastructural component, which includes, among others, buildings, networks, and essential services [15].

In this study, the building is conceptualised as a complex system of technical elements, following the systematic classification of the Italian national standard UNI 8290 [16]. The UNI8290 categorises buildings into four levels, based on the functions and interrelationships of individual elements: *Classi di Unità Tecnologiche* (Classes of Technological Units); *Unità Tecnologiche* (Technological Units); *Classi di Elementi Tecnici* (Classes of Technical Elements); *Elementi Tecnici* (Technical Elements). This classification recognises the non-hierarchical interconnection between elements and their role in achieving overall building performance, moving beyond the typical distinction between "structural" and "non-structural" elements. Unlike other classification systems, such as FEMA's (Federal Emergency Management Agency) hazard-specific classification [17], the UNI8290 offers a comprehensive approach that aligns more closely with the framework of the proposed research by providing a functional breakdown of building subsystems, essential for understanding, assessing, and ensuring efficiency in the entire building process. Following the UNI8290, the building envelope comprises the set of Classes of Technological Units' *Chiusura* (building closure elements) and *Partizione esterna* (external partition elements) [16]. These two classes include all the Technical Elements that define the building envelope, ensuring the separation between internal and external spaces and shaping the areas connected to the building system [16]. Therefore, these Technical Elements represent key factors in assessing the interactions between the envelope itself and other urban system components.

These elements (e.g., cornices, balconies, chimneys, cladding) are particularly vulnerable to the direct impact of external hazards and are traditionally identified as "factors at risk". These impacts determine a more or less severe decay in technical elements' performance. This decay leads to progressive deterioration, resulting in phenomena such as degradation and detachment, which pose continuous threats to urban systems in terms of potential falls and/or obstruction of escape routes (Fig. 1). In this sense, the technical elements of the building envelope become an additional hazard factor for urban systems, shifting from being "factors at risk" to becoming "risk factors" themselves.

These phenomena are widespread in many urban areas, particularly affecting buildings over fifty years old, which form a substantial part of today's cities. In addition, recent years have shown that climate change exacerbates the degradation of technical elements of the building envelope, increasing its vulnerability to both Extensive and Intensive hazards [18]. As a result, the widespread risk of collapse from damaged building envelopes poses significant safety consequences for urban systems, regardless of the occurrence of exceptional conditions typical of intensive hazards, identifying in these elements an additional risk factor beyond codified ones.

Intensive hazards typically cause immediate and substantial damage to both the technical elements of the "building envelope" and the "load-bearing structure" [16]. Conversely, Extensive hazards have a persistent, cumulative effect over time, which is less evident on the load-bearing structure, but they cause gradual and equally significant damage to the technical elements of the envelope in relation to the exposure of urban systems [19–21]. While scientific literature regarding risk assessment to the built environment extensively covers risks to the "load-bearing structure" [16], particularly regarding Intensive hazards, a multi-risk approach requires deeper analysis of how these hazards affect other Classes of technological units, especially the particularly vulnerable elements of the "building envelope" [16].

Regarding Extensive risks, a further critical issue arises. Recurrent and persistent actions are common in urbanised contexts and continuously affect the building envelope under normal operating conditions [19–21]. Even without Intensive hazards, technical elements are still highly vulnerable to these continuous actions. Al-

Fig. 1. *Examples of damaged cornices, balconies, plasters, and decorations.*

though research has focused on the reduction of energy performance due to the impact of Extensive risks, the cumulative effects on other vulnerability dimensions are often neglected. The widespread degradation of these elements and the rising frequency of hazardous events from their collapse highlight the need to expand studies on their vulnerability, assessing the impact of Extensive hazards in terms of urban systems safety as well [22–25].

Despite the intuitive nature of R_b, its assessment is not often explored in the scientific literature [19] and is inadequately addressed in international development and planning policies, and a proper definition of such risk does not emerge from the current state of the art. Furthermore, existing studies on building envelope technical elements are limited, failing to provide a full understanding of hazards' impact in relation to their vulnerabilities.

The experience gained by the research group in the field of risk management, particularly in supporting Public Administration in the Phlegraean area, has revealed that the persistence of Extensive hazards affects citizen safety as significantly as disaster events [20]. Indeed, in the specific context of the Phlegraean area, the low-intensity and high-frequency solicitations typical of the Bradyseismic phenomena add up to other extensive hazards typical of current conditions in urbanised contexts, such as those related to weather phenomena or interference of infrastructures. These hazards, acting as constant triggering events, continuously contribute to increasing the vulnerability of technical elements of the building envelope. These ongoing triggers together amplify their degradation, generating cascading effects due to the subsequent fall of these elements onto surrounding areas, which, in turn, configure a Building Risk scenario for the urban system.

1.2. PAPER'S CONTRIBUTION

Based on the considerations discussed, it is evident that the vulnerability of the technical elements of the building envelope plays a crucial role in response to external hazards at the building scale and in determining the cascading effects at the urban scale. The topic addressed highlights the need to comprehend and identify R_b as an additional rate within a multi-risk approach, focusing not only on the impact of external hazards on the built environment but also on the cascading effects generated on urban systems by buildings and their components during their service life.

This contribution aims to conceptualise and formalise R_b, along with its characteristic parameters, providing a preliminary definition of it, aligned with the hierarchical process of risk management techniques, which begins with risk identification, followed by analysis, evaluation, and mitigation [13].

2. METHODOLOGY

To achieve the expected result, this contribution: conducts a bibliometric survey on buildings and urban systems risks (§2.1); analyses key concepts underpinning risk scenarios for the built environment (§2.2); and identifies R_b by defining its characteristic parameters (§2.3).

The first phase involves analysing existing scientific frameworks on risks related to buildings and urban systems, within which R_b can be identified along with its parameters, to understand the focus of these studies and confirm the gaps noted in multi-risk management frameworks. The second phase applies a comparative analysis of risk scenarios for the built environment, examining the differences and similarities between risk parameters and their characteristics, as well as the main factors useful for their assessment. In this phase, the aim is to outline common concepts underlying recognised risk theories to support the identification of R_b and its characteristic parameters. The third phase, building on the previous analyses, develops a methodological framework to formalise R_b characteristic parameters by conceptualising the distinctive type of hazard determined by the technical elements of the building envelope due to their vulnerability and how it can determine, in turn, cascading effects on the urban system.

2.1. BIBLIOMETRIC DATA PROCESSING

Data collection was conducted using Elsevier's Scopus database, chosen for its efficiency, expert curation, and regular updates, making it suitable for analysing peer-reviewed literature across diverse disciplines. The initial search focused on the keywords "urban risk" and "building risk". The results were refined by narrowing the search to articles published between 2013 and 2023 and within the subject areas of Environmental Sciences; Engineering; Earth and Planetary Sciences; Energy; Social Sciences; Business Management and Accounting; Computer Science; Economics, Econometrics and Finance; Multidisciplinary. These areas were considered most relevant, and the chosen time range ensured data stability. The first query ("urban risk" AND "urban" AND "risk") yielded 38,354 documents with 57,193 interactions across the subject areas, while the second ("building risk" AND "building" AND "risk") returned 36,215 documents with 55,994 interactions (data exported as of 20 February 2023). The lexical analysis reveals a steady increase in the number of articles over the period analysed (Tab. 1), underscoring the growing relevance of these topics.

Figure 2 shows the distribution and incidence of resulting documents across the scientific area considered. The pie chart in Figure 2a illustrates a predominant presence of these terms in the scientific fields of Environmental Science (33.1%), Social science (22.5%), Engineering (14.5%), and Earth and planetary sciences (11.1%). This suggests that urban system risks are addressed across diverse sectors, particularly focusing on environmental and social aspects. The literature widely discusses the topic, especially in relation to climate change, sustainability, and risk perception and communication, highlighting the cultural component inherent in risks in urban systems. The pie chart in Figure 2b shows a similar distribution for these terms but with a notable increase in Engineering (28.9%), reflecting a growing focus on risk management for the built environment and urban systems.

Further studies were conducted to understand whether the observed increase reflects a deeper focus on risks within the specific framework of the built environment. Data from the Scopus survey were exported and processed using two open-source text-mining and keyword co-occurrence tools, Bibliometrix [26] and VOSviewer [27]. These tools were used to identify the most frequent keywords in the relevant subject areas and to analyse the co-occurrences between these terms and topics. This re-

Queries	Year of reference										
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
"urban risk" AND "urban" AND "risk"	*2223*	*2470*	*2555*	*2867*	*3046*	*3643*	*4237*	*4840*	*5560*	*6002*	*911*
"building risk" AND "building" AND "risk"	*2317*	*2506*	*2586*	*2915*	*3133*	*3531*	*4082*	*4363*	*4793*	*5290*	*699*

Tab. 1. *Number of documents per year for each of the queries used in the bibliometric search. Source: data retrieved from Elsevier online database.*

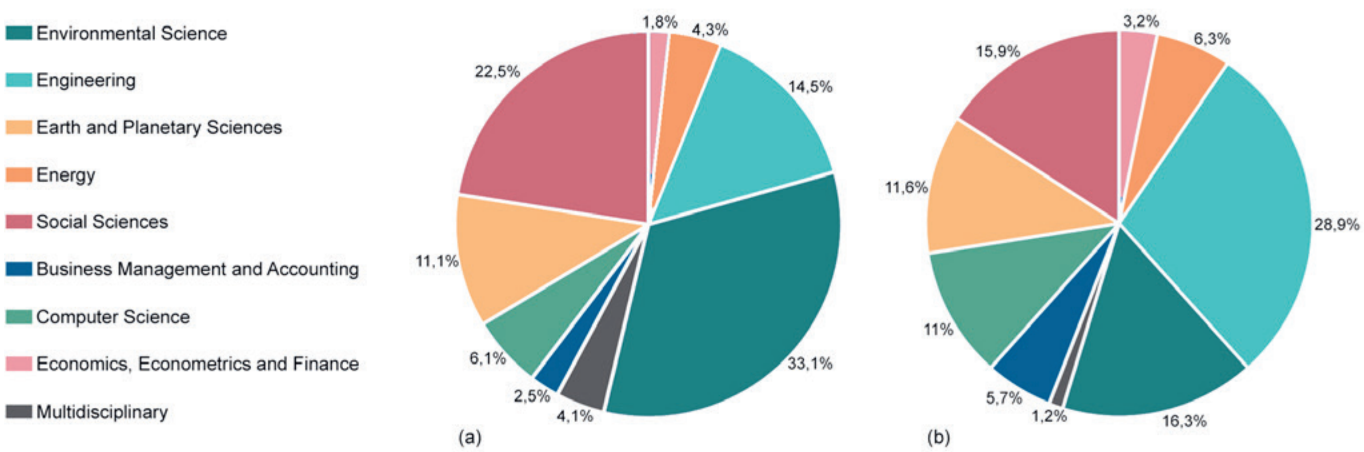

Fig. 2. *Distribution and incidence of documents' number by subject area. (a) Incidence of documents' number by subject area for the queries "urban risk" AND "urban" AND "risk". (b) Incidence of documents' number by subject area for the queries "building risk" AND "building" AND "risk". Source: data retrieved from Elsevier online database.*

sulting keyword index helps to identify the most recurrent themes in current scientific literature concerning the impact of codified risks on buildings, performance loss, and consequences for urban systems.

The Bibliometrix R package employs various bibliometric analysis methods to conduct scientific literature mapping analyses, offering intuitive data visualisations and mappings of scientific literature [26]. Due to limited data processing capacity, 2000 documents per year were selected using the "relevance" filter, resulting in 20,699 articles (data exported as of 20 February 2023). After loading the data into Bibliometrix, an additional filter limited the study to the following specific Document Types: article, book, book chapter, conference paper, review, short survey. A recurrence analysis of the Most Relevant Words among the Author's Keywords was performed for each of these scientific products. A synonym filter was applied to group inhomogeneous data and exclude keywords unrelated to the survey to avoid scattering the data derived from Scopus. The results are summarised in the recurrence plots shown in Figure 3.

Figure 3a illustrates the frequency of each Author's Keyword over the selected period, providing a breakdown of the Most Relevant Keywords. Cumulative occurrences up to 2023 highlight the prominence of topics such as risk assessment (802 occurrences) and risk management (523 occurrences). The results support the evidence that scientific research is currently shifting its focus from disaster risk reduction (61 occurrences) and disaster risk management (58 occurrences) to risk analysis (265 occurrences) and proactive assessment and management approaches, emphasising resilience. This trend reflects a growing focus on overarching governance policies. The graph in Figure 3 also reveals a strong connection between this approach applied to the built environment (616 occurrences) and policies connected to climate change (526 occurrences) and energy efficiency (516 occurrences), demonstrating that the focus of research is trending towards concepts of resilience (490 occurrences) and vulnerability (487 occurrences). The similar cumulative recurrence values of these concepts reinforce the relevance of the topics proposed.

Figure 3b shows the cumulative recurrence rate variation for each Author's Keyword over the reference period, indicating a steady increase in interest related to climate change, resilience, risk assessment, etc., throughout

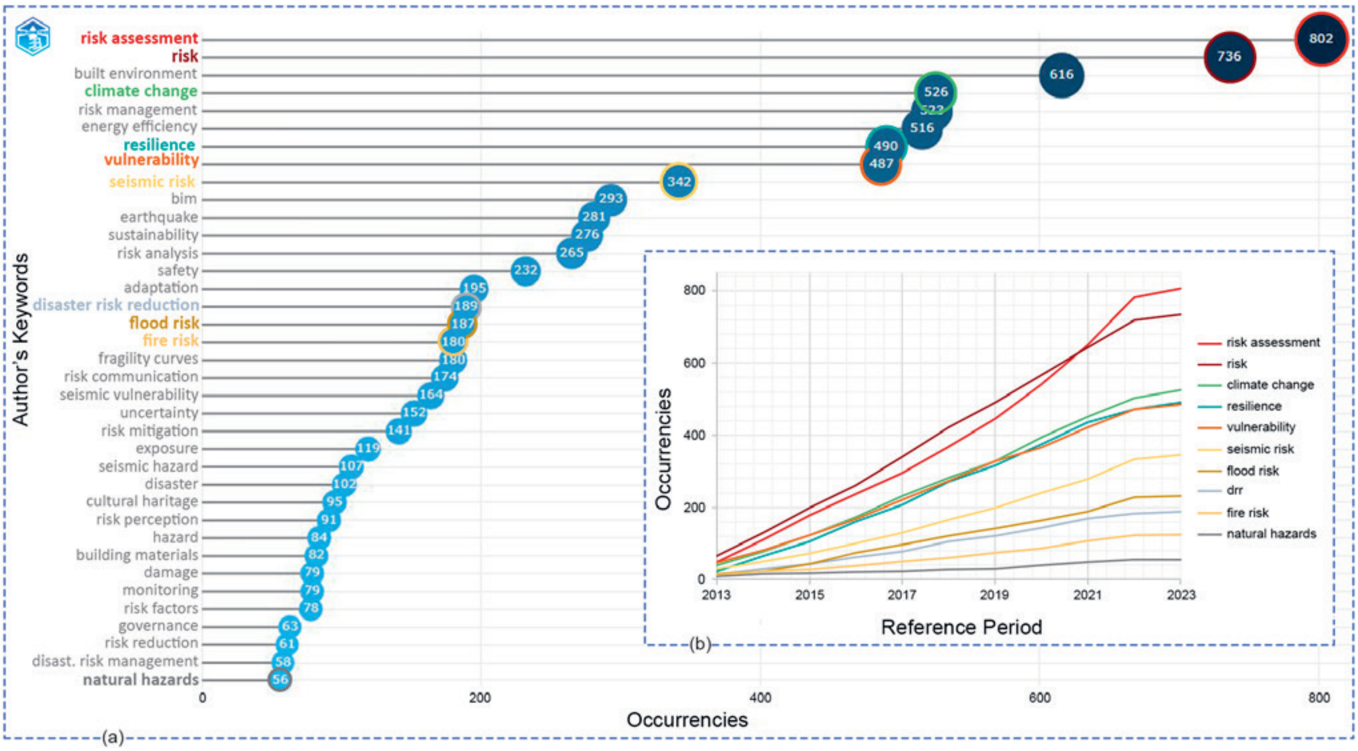

Fig. 3. *Results of the recurrence analyses of the Most Relevant Words among the Author's Keywords. (a) Total number of occurrences for each Author's Keyword over the reference period. (b) Variation in the cumulative number of occurrences for each Author's Keyword over the reference period. Source: adapted from Bibliometrix [26].*

the years. This trend can be attributed to the adoption of a multi-risk approach influenced by the ongoing climate crisis.

Figure 3 further highlights that current scientific studies focus primarily on Intensive risks directly affecting buildings and urban systems (seismic risk (342 recurrences), flood risk (187 recurrences), fire risk (180 recurrences, etc.). However, these studies do not adequately consider the cascading impact buildings generate on urban systems. Despite using the query “building risk”, a prominent correlation between risks, buildings, and the technical elements that constitute the building envelope does not emerge with sufficient impact.

To better understand this evidence, the search was refined with the two more specific keywords “building” AND “risk” AND “element” and “building envelope risk”. In order to identify the interconnections between the most recurrent themes associated with these keywords and the contexts in which they are used, an analysis was carried out using the VOSviewer software tool, which enables the determination of co-occurrences between keywords providing network maps and visualisations (Fig. 4) [27].

Figure 4a confirms that the studies concerning the technical elements of buildings are sector-specific, showing stronger correlations with Intensive natural hazards (seismic risk, flood, landslide) and topics related to climate change and energy performance (including sustainability, building materials, and energy efficiency). Despite including the keyword “element”, terms such as concrete and masonry, which pertain to the Classes of technological units of the “Load-bearing structure”, appear with significant frequency. There are only weak correlations between “non-structural elements” and seismic risk topics, confirming the rigid decomposition of the building into structural and non-structural elements, which does not fully capture the complexity of the building system. Additionally, it shows a lack of comprehensive studies addressing the technical elements of buildings, the risks they are exposed to, and their cascading impacts.

Figure 4b reveals similar considerations, showing that risks to the building envelope and its technical elements are mostly related to climate change and are strongly connected to energy efficiency issues, with no clear connections to risks associated with urban systems. Although there is a correlation with “durability”, it mainly pertains to energy performance and retrofitting, while terms such as maintenance, monitoring, and other aspects of envelope performance, vulnerability, or safety are absent.

This indicates that, despite the intuitive correlation between risks directly impacting buildings’ technical el-

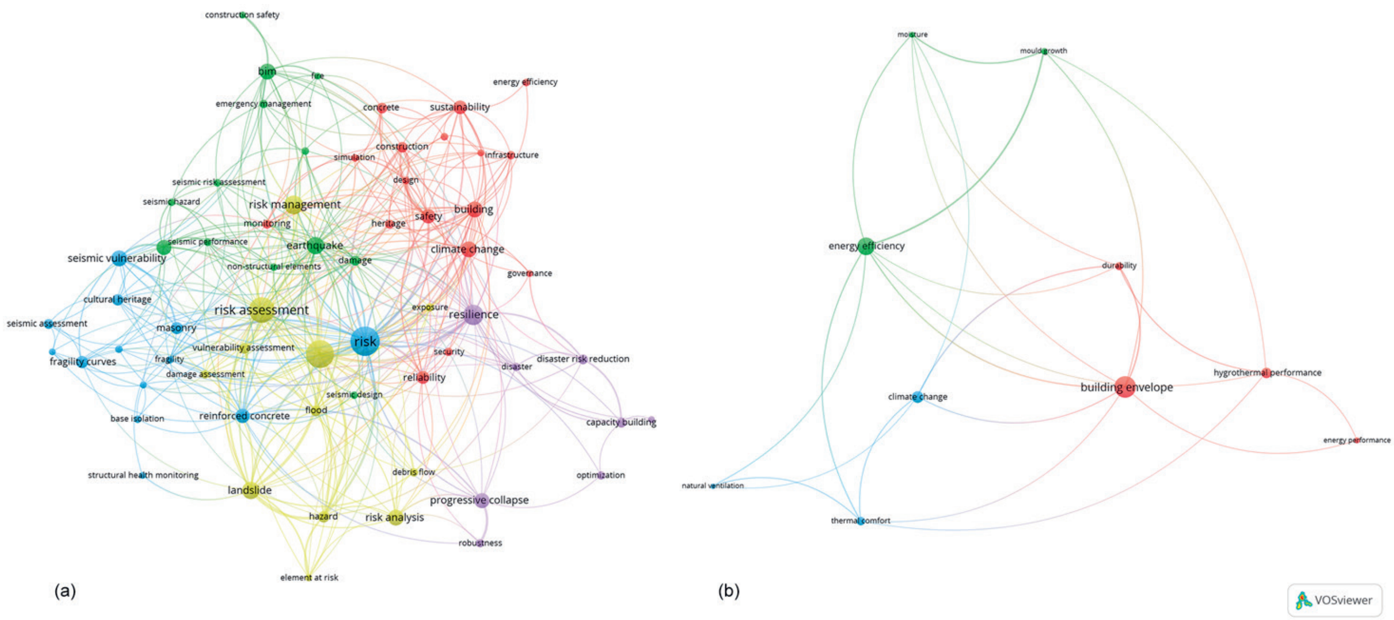

Fig. 4. *Network visualisation map of co-occurrence connections between keywords. (a) Co-occurrence of keywords associated with the queries “building” AND “element” AND “risk”. (b) Co-occurrence of keywords associated with the query “building envelope risk”. Source: adapted from VOSviewer [27].*

ements and those they pose in turn to urban systems, the focus of scientific research remains too distant from a systemic analysis of these interconnections. This gap in the existing scientific literature hinders the integration of these risks into multi-risk analyses, preventing a comprehensive understanding and management of the system of risks affecting urban systems.

2.2. RISK PARAMETERS IDENTIFICATION AND ANALYSIS

Due to the probabilistic nature of the concept of risk, the definition of such scenarios varies depending on the contexts and disciplinary fields considered. It is possible to trace recurring archetypal concepts based on an analysis of the main concepts underlying these scenarios within the State of the Art.

In scientific literature and regulatory frameworks, risk (*R*) is conventionally defined as the probability (*P*) that a Hazardous Event [11, 13] will cause harmful effects (*D*) on population, settlements, and infrastructure within a specific area and over a specific period. This relationship considers the interaction between the hazard (*H*) affecting a given context, the exposure (*E*) of elements subjected to it, and their vulnerability (*V*) [11, 28] and can be expressed by the equation $R = H x V x E$, where the magnitude of the expected damage (*D*) is a function of the parameters V and E. Therefore, defining these three parameters is essential to accurately identifying a specific risk.

The hazard (*H*) refers to the probability of an event occurring within a specific period, in a certain area and with a certain intensity [13, 28]. In seismic risk assessment, the hazardous event may threaten people's safety depending on the presence and density of affected buildings. In contrast, hydrogeological risk manifests as threats regardless of the presence of buildings [29].

Damage is the consequence resulting from the occurrence of a Hazardous Event [29]. Its magnitude depends on the hazard itself and the vulnerability and exposure of elements at risk. For seismic risk, sparse urban areas with high-hazard levels may result in a near-zero level of risk, while heavily urbanised low-hazard areas may result in higher levels of risk. In hydrogeological scenarios, events like floods may pose higher risks if they impact infrastructure systems and lower risks if they affect agricultural systems [29, 30].

The commonly used definition of vulnerability of an element at risk describes its susceptibility to damage or alteration caused by the actions induced by a hazardous event of a certain intensity or by physical, social, economic, and environmental factors that may amplify the impact [11, 13, 29]. Vulnerability can be classified into different types (physical, economic, social, etc.), and its assessment varies depending on the specific nature of the analysed risk and the characteristics of the associated phenomena. The parameters considered in the assessment should be those relevant to understanding the susceptibility of exposed elements. For instance, in seismic risk assessment, the vulnerability of structures is evaluated through their fragility and capacity to withstand and respond to seismic events. When dealing with environmental risk assessment, parameters connected to the chemical and physical compatibility of materials with their environment are also of paramount importance.

Exposure can be expressed in two forms: physical exposure, which refers to the quantity and value of exposed elements that may suffer damage, alteration, or destruction as a result of a hazardous event, and functional exposure, pertaining to the functions that may be wholly or partially disrupted by the hazardous event [13, 28, 29].

2.3. R_B PARAMETERS IDENTIFICATION AND ANALYSIS

Building upon the gaps that emerged from the bibliometric analysis and adapting the themes exposed in section 2.2, R_b is conceptualised along with an identification of its characteristic parameters.

The panel in Figure 5 provides a synoptic overview of the concepts underlying R_b.

Figure 5a illustrates the building as an elementary particle of the urban system, and some of the most vulnerable technical elements of its envelope are pointed out. Figure 5b identifies two hypothetical multi-risk scenarios for the urban system and its buildings. Scenario A depicts a multi-risk storyline where the urban system and its buildings are exposed to both Intensive (R_{int}) and Extensive

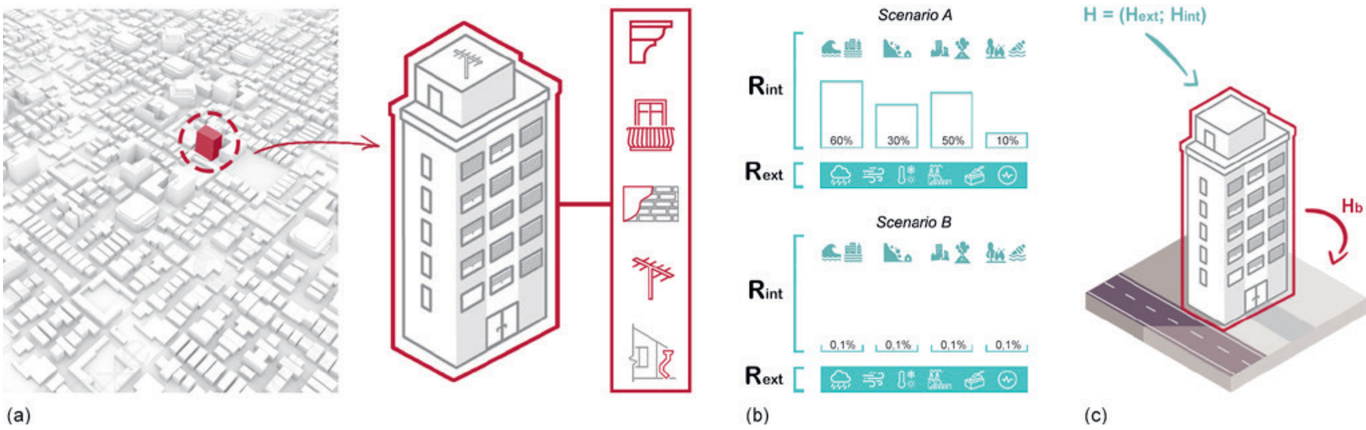

Fig. 5. *Synoptic overview of the concepts underlying R_b.*

(R_{ext}) hazards, which can either combine with each other or trigger subsequent cascading effects [13, 14]. Scenario B identifies a multi-risk storyline where the urban system and its buildings are predominantly exposed to Extensive hazards (R_{ext}). Extensive hazards in this context include, for instance, those related to Climate Change (e.g., sudden heavy rainfalls, heat waves, wind loads), solicitations typical of highly urbanised contexts (e.g., interference with civil infrastructure systems), phenomena of ground deformation and dynamics (bradyseism, landslides, etc.), and environmental conditions [11, 18, 21, 25]. Indeed, regardless of the occurrence of Intensive hazards, Extensive ones act with persistence, continuously exposing the components of the urban system to recurrent stresses during normal operating conditions and determining different combined impacts [13, 14, 21, 22].

At the building scale, in both scenarios, the hazards directly impact the technical elements of building envelopes, configuring them as "factors at risk". The extent of the impact of different hazards on technical elements is related to their susceptibility to damage or alteration caused by the relevant hazard. By building upon the definition expressed in the previous section, the Vulnerability of the Technical Elements (V_{et}) can be therefore defined as the tendency of the technical elements of the building envelope to suffer damage because of external hazards [11, 13, 28, 29]. This vulnerability depends on their characteristics (technical solutions, construction and installation methods, materials, dimensions, etc.) and their state of conservation as a physical factor which can amplify the effect of external stresses [11, 31].

The damage to these elements, proportional to their specific V_{et}, determines a cascading effect for urban systems, turning into hazard factors in terms of potential falls and/or obstruction of escape routes. This hazard, defined as Building Hazard (H_b), can, in fact, be conceptualised at the urban level and is identified as the probability that the fall of a technical element of the building envelope (Hazardous Event) may occur in a specific period, in a certain area and with a certain intensity [3, 11, 13, 28]. In this setting, technical elements shift from being "factors at risk" to being "risk factors" for the urban system (Fig. 5c). It is consequential to establish a relationship between the V_{et} and the H_b, which could be conceptually expressed by the relation $H_b = f(V_{et})$, defining the direct correlation between the V_{et} and the probability of occurrence related to the fall of the technical element considered or portions of it.

The expected damage caused by H_b is related to the safety of exposed elements and depends on both System Vulnerability (V_{syst}) and System Exposure (E_{syst}). V_{syst} can vary based on characteristics such as the type of urban fabric (including regularity, distances between buildings, open spaces, and accessibility) and the ratio of building height to roadway width [13, 28, 30]. While the V_{et} is a "direct vulnerability", definable at the building scale in terms of the failure of the individual technical element, the V_{syst} is an "induced vulnerability", and it is defined at the urban scale, in which the relationships between different elements and subsystems are considered along with the indirect consequences of the V_{et} [29]. The assessment of the E_{syst} might refer to the number of people, or exposed elements in general, living and transiting in a given area, providing a measure of how populated a portion of the urban fabric is. It can depend on, among others, the destination and intensity of use, the value and importance of the building typologies, the level of urbanisation, and the intensity of flow services [3, 13, 28, 29], and its assessment relies on the effect that H_b might have on the exposed elements. It can refer to, for instance,

On the basis of the above considerations, R_b arises transversely to other hazards commonly considered in multi-risk analysis. Within both multi-risk storylines described, it can be seen firstly as a cascading effect triggered by other hazards, configuring itself as an additional Extensive risk rate for urban systems since its impact persistently acts on them and threatens the safety of the exposed population. However, it can also be seen as an amplifying factor that increases, for instance, the vulnerability of an urban system exposed to Intensive hazards such as earthquakes or volcanic eruption, in considering the probability of obstruction of escape routes caused by the falling debris.

3. RESULTS AND DISCUSSION

Based on the studies developed and considering the three characteristic parameters identified and their relationship, an overall definition of R_b is given.

R_b is defined as "the probability that a hazardous event, resulting from the vulnerability of the technical elements of the building envelope, can cause harmful effects on urban systems" and it can be expressed as a function of the following parameters (Eq.1): the hazard associated with the vulnerability of the technical element, (H_b); the Exposure of the components in the affected urban system, (E_{syst}); the vulnerability of the affected urban system, (V_{syst}).

$$R_b = H_b \times V_{syst} \times E_{syst} \quad (1)$$

The analytical description of each parameter is still under study, in accordance with the preliminary phases of the present research and in line with the aim of the paper, deferring actual methods for its quantification to future discussions. However, a theoretical application of these concepts and some practical examples of potential methods to be used for the Rb assessment retrieved from the existing literature are provided.

A technical element of the building envelope situated in an Extensive risk scenario is considered, such as a reinforced concrete balcony in a densely urbanised area. This element is regularly exposed to external actions due to operational conditions (e.g., mechanical stress and fatigue) and environmental factors. Depending on its technological characteristics, such an element and its components (such as front edges, soffits, balustrades, etc.) can be more or less vulnerable to the direct impact of external actions, configuring them as "factors at risk". For instance, water infiltration, exacerbated by increased rainfall and CO_2 pollution, triggers oxidation in the reinforcement, especially at the front edge. This causes volumetric expansion and detachment of cover layers, often resulting in the "expulsion" of the front edge. Such deterioration creates an additional "risk factor" for the urban system, exposing it continuously to its potential fall into surrounding areas. This exemplifies how external hazards affecting building envelope technical elements can trigger significant cascading effects on urban systems.

The V_{et}, as described in section 2.3, can be expressed as a scale of a-dimensional values and comprises two rates: an intrinsic rate related to the technological characteristics of the element and a second rate related to its state of preservation. The intrinsic rate reflects the susceptibility of the technical element to damage from external actions. It can be defined on the basis of comparison criteria among different construction technologies and their response to external action in terms of degradation and damage. The second factor acts as an amplifying coefficient, linked to the state of preservation of the element, to be multiplied by the intrinsic rate to obtain the final V_{et}. For instance, considering two balconies of two different construction technologies, one in masonry and one in reinforced concrete, at an equal state of preservation, it can be argued that, with respect to seismic solicitations, the masonry balcony would exhibit higher vulnerability to seismic forces than the reinforced concrete balcony.

The H_b is also an a-dimensional factor, directly correlated with V_{et} (e.g., as vulnerability increases, so does the probability that the element will experience significant degradation levels leading to its collapse), to be combined with both the height and the mass of the element to obtain a potential magnitude of the relevant hazard posed [32, 33].

The extent of damage caused by elements' fall varies based on the urban system's V_{syst} and the E_{syst}. V_{syst} can be evaluated in terms of the compactness or dispersion of the urban fabric, for example through metrics such as Building density, expressed in m^3/m^2, which indicates the volume of built-up spaces relative to land area; the number of buildings per km^2 combined with the ratio of building height to street width; the Territorial coverage ratio, expressed in m^2/m^2, representing the proportion of area covered by buildings; and urban form and the network topology [20, 28, 34]. Always relying on existing assessment methods, E_{syst} can be quantified using Residential density, expressed in inhabitants per km^2, the Crowding index, expressed in the number of persons per dwelling, combined with the Index of productive activities, expressed in number of productive units per km^2 [20, 29].

By building upon the examples provided, in evaluating the safety of people exposed, it can be conceptually presented that balconies at significant heights above street level in urban fabrics with high building density and facing crowded streets pose a significantly higher risk compared to those at lower heights in less densely constructed and less crowded areas. The topic of the hazard posed by the technical elements of the building envelope to people was addressed by a few previous studies [21, 32, 33]. These works, however, focused mainly on the lack of maintenance without considering the vulnerability of technical elements to specific hazards. On the contrary, this paper suggests that the probability of building technical elements that collapse is closely related to this vulnerability and must be assessed in a multi-risk approach.

At this stage, Building Risk can be assessed in various ways depending on the type of harmful effect to be assessed and the urban system component considered as the exposed agent. For instance, when considering the physical component of the population, R_b evaluates the number of people potentially affected by a fall and the relevant extent of damage caused. When considering the functional component, R_b can evaluate the percentage of obstructed escape routes due to fallen debris, indirectly affecting peoples' safety during catastrophic events [35]. These examples illustrate how Building Risk contributes within the multi-risk approaches: in the first case, it can be seen as a cascading effect triggered by other hazards; while in the second case, combined with other hazards, it can be seen as a factor amplifying vulnerability, especially during events such as earthquakes or volcanic eruptions.

4. CONCLUSIONS

The observations presented in this contribution are based on scientific literature surveys, along with an analysis of risk scenario definitions for the built environment and urban systems. The literature reveals a growing interest in multi-risk management strategies and resilience, particularly regarding the direct impacts of risks on buildings and urban systems. However, two critical gaps have been identified: not accounting for the impact of both Intensive and Extensive risks on the technical elements of the building envelope and overlooking the subsequent cascading hazards affecting urban systems. The research team's experience in risk underscores the relevance of the issue, as current policies primarily address Intensive risks while overlooking the need for an effective assessment of the constant impact of technical elements of the envelope on the urban system. The definition of R_b becomes a key factor for a comprehensive multi-risk approach that enables the assessment of this impact. Its identification provides a foundation for more in-depth studies on the vulnerability of technical elements to various hazards. It serves as a preliminary step toward prevention measures and design strategies that propose low-vulnerability technological solutions tailored to the relevant system of hazards. In this sense, both design and maintenance measures serve as risk prevention and mitigation strategies since they become strategies to reduce the vulnerability of technical elements and, at the same time, strategies to mitigate their impacts on the urban system.

The formalisation of R_b as an additional rate in multi-risk scenarios marks a significant advancement in scientific research, especially in multi-hazard and multi-risk modelling. The work is limited to the formal definition of R_b. Practical applications will enable the development of innovative tools and methodologies to support public decision-makers in defining informed multi-risk reduction and management strategies. For instance, they will help identify priority intervention areas and determine proactive early-warning monitoring actions.

The demand for in-depth studies is evident in the topicality of the issues addressed and in the pressing need for research products that are directly applicable and measurable in real contexts. This strengthens the connection between research and practical application in a multi-sectoral and participatory approach, as emphasised by international research and innovation planning instruments. Future research will build on these preliminary studies and definitions to enhance knowledge and deepen all phases of risk management techniques, including the development of operational methods for assessing and evaluating R_b.

Authors contribution

Conceptualization, Writing - Review & Editing, Supervision, Project administration, Funding acquisition, R.C. Methodology, Software, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization, M.F. Conceptualization, Methodology, Software, Investigation, Writing - Original Draft, Writing - Review & Editing, Supervision, V.V.

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References

[1] UNDRR (2020) The human cost of disasters: an overview of the last 20 years 2000-2019. UNDRR Publications, Geneva. https://www.undrr.org/quick/50922. Accessed on October 15, 2025

[2] UNDRR (2021) Strategic Framework 2022-2025. UNDRR Publications, Geneva. https://www.undrr.org/media/49267/download?startDownload=true. Accessed on October 15, 2025

[3] UNDRR (2022) Global Assessment Report on Disaster Risk Reduction. UNDRR Publications, Geneva. https://www.undrr.org/media/79595/download?startDownload=true. Accessed on October 15, 2025

[4] UNDRR (2015) Sendai Framework for Disaster Risk Reduction 2015 - 2030. UNDRR Publications, Geneva. https://www.unisdr.org/files/43291_sendaiframeworkfordrren.pdf. Accessed on October 15, 2025

[5] European Parliament, Council of the European Union (2021) Regulation EU 2021/695 establishing Horizon Europe – the Framework Programme for Research and Innovation. https://eur-lex.europa.eu/eli/reg/2021/695/oj. Accessed on October 15, 2025

[6] United Nations (2015) Transforming our world: The 2030 Agenda for Sustainable Development. https://sustainabledevelopment.un.org/post2015/transformingourworld. Accessed on October 15, 2025

[7] European Parliament, Council of the European Union (2012) Directive 2012/18/EU on the control of major-accident hazards involving dangerous substances. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012L0018. Accessed on October 15, 2025

[8] United Nations (2015, November-December) Paris Agreement - Framework Convention on Climate Change. Report of the Conference of the Parties on its twenty-first session, 4. https://unfccc.int/resource/docs/2015/cop21/eng/10.pdf. Accessed on October 15, 2025

[9] European Commission (2007) Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the Assessment and Management of Flood Risks (Flood Directive). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0970. Accessed on October 15, 2025

[10] Ministero dell'Università e della Ricerca (2020) Programma nazionale per la ricerca 2021-2027. https://www.gea.mur.gov.it/docs/Pnr2021-27.pdf. Accessed on October 15, 2025

[11] United Nations General Assembly (2016) Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction. https://www.preventionweb.net/quick/11605. Accessed on October 15, 2025

[12] UN-ISDR (2015) Global assessment Report on Disaster Risk Reduction. https://www.preventionweb.net/understanding-disaster-risk/key-concepts/intensive-extensive-risk. Accessed on October 15, 2025

[13] European Commission (2010) Risk Assessment and Mapping Guidelines for Disaster Management. Commission Staff Working Paper, Brussels. https://ec.europa.eu/echo/files/about/

COMM_PDF_SEC_2010_1626_F_staff_working_document_en.pdf. Accessed on October 15, 2025

[14] Curt C (2021) Multirisk: What trends in recent works? – A bibliometric analysis. Science of The Total Environment 763:142951. https://doi.org/10.1016/j.scitotenv.2020.142951

[15] European Environment Agency (2015) The European Environment. State and Outlook 2015. European Briefing. https://www.eea.europa.eu/soer/2015/europe/urban-systems. Accessed on October 15, 2025

[16] UNI 8290-1 (1983) Edilizia residenziale. Sistema tecnologico. Analisi dei requisiti

[17] Federal Emergency Management Agency. Department of Homeland Security (2005) Earthquake hazard mitigation for Nonstructural Elements. FEMA 74 Field Manual. https://mitigation.eeri.org/files/FEMA74_FieldManual.pdf. Accessed on October 15, 2025

[18] Barrelas J, Ren Q, Pereira C (2021) Implications of climate change in the implementation of maintenance planning and use of building inspection systems. Journal of Building Engineering 40:102777. https://doi.org/10.1016/j.jobe.2021.102777

[19] Castelluccio R (2018) Il costruito come fattore di rischio. Techne - Journal of Technology for Architecture and Environment 15:225–233. https://doi.org/10.13128/Techne-22110

[20] Castelluccio R (ed) (2017) Studio degli scenari di rischio a supporto del Piano di Protezione Civile del Comune di Pozzuoli. Doppiavoce, Napoli

[21] Moghtadernejad S, Mirza S (2014) Performance of building facades. In: Proceedings of CSCE, 4th International Structural Specialty Conference, 28–31 May. Canadian Society for Civil Engineers, Halifax

[22] Erdly JL, Schwartz TA (eds) (2004) Building façade maintenance, repair and inspection. ASTM International, West Conshohocken, PA

[23] Corsi E (2019) Nella "Città dei crolli" nemica anche l'estate. Roma, Quotidiano d'informazione fondato nel 1862, 19 giugno. https://www.ilroma.net/opinione/nella-%E2%80%9Ccitt%C3%A0-dei-crolli%E2%80%9D-nemica-anche-lestate. Accessed on October 15, 2025

[24] Venezia, grosso pezzo di cornicione cade tra i passanti. La Nuova di Venezia e Mestre June 2, 2023. https://nuovavenezia.gelocal.it/venezia/cronaca/2023/06/02/news/venezia_grosso_pezzo_cornicione_cade_tra_passanti-12837132/. Accessed on September 12, 2023

[25] Silva A, de Brito J (2021) Service life of building envelopes: A critical literature review. Journal of Building Engineering 44:102646. https://doi.org/10.1016/j.jobe.2021.102646

[26] Aria M, Cuccurullo C (2017) Bibliometrix: An R-tool for comprehensive science mapping analysis. Journal of Informetrics 11(4):959–975. https://doi.org/10.1016/j.joi.2017.08.007

[27] van Eck NJ, Waltman L (2017) Citation-based clustering of publications using CitNetExplorer and VOSviewer. Scientometrics 111(2):1053–1070. https://doi.org/10.1007/s11192-017-2300-7

[28] Rausand M (2011) Risk Assessment: Theory, Methods, and Applications. John Wiley & Sons, Hoboken, NJ

[29] Stanganelli M (2003) Prevenzione e mitigazione dei rischi naturali nella pianificazione urbana e territoriale. Giannini, Napoli

[30] UNDRR (2022b) Technical Guidance on Comprehensive Risk Assessment and Planning in the context of climate change. https://www.undrr.org/quick/71077. Accessed on October 15, 2025

[31] Castelluccio R, Di Martire D, Guerriero L, et al (2021) Methods for assessing the vulnerability of non-structural components. Monitoring for risk management. Sustainable Mediterranean Construction 14:156–162

[32] Ruiz F, Aguado A, Serrat C, et al (2019) Condition assessment of building façades based on hazard to people. Structure and Infrastructure Engineering 15(10):1346–1365. http://dx.doi.org/10.1080/15732479.2019.1621907

[33] Ruggiero G, Marmo R, Nicolella MA (2021) Methodological Approach for Assessing the Safety of Historic Buildings' Façades. Sustainability 13:2812. https://doi.org/10.3390/su13052812

[34] Sharifi A (2019) Resilient urban forms: A review of literature on streets and street networks. Building and Environment 147:171–187. https://doi.org/10.1016/j.buildenv.2018.09.040

[35] Bernardini G, Ferreira TM (2022) Combining Structural and Non-structural Risk-reduction Measures to Improve Evacuation Safety in Historical Built Environments. International Journal of Architectural Heritage 16(6):820–838. https://doi.org/10.1080/15583058.2021.2001117