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Building-level physical vulnerability in Europe: Exterior vs interior indicators and GIS–BIM approaches for multiple-hazard risks — A systematic review☆

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A R T I C L E I N F O

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A B S T R A C T

This paper presents a systematic literature review of building-level physical vulnerability indicators in Europe, with a specific focus on the distinction between exterior and interior indicators and on the role of Building Information Modelling (BIM) and Geographic Information Systems (GIS) in assessment workflows. This study identifies existing gaps in the literature in regard to (i) the systematic integration of interior and exterior vulnerability indicators, (ii) pragmatic interoperability between GIS and BIM in assessment workflows, and (iii) more transparent weighting and validation procedures to improve transferability and comparability across different hazards and contexts. Across 26 peer-reviewed scientific publications (2000–2025), we extracted 121 indicators and analysed their use by hazard type, indicator location (interior/exterior), digital tools (GIS/BIM), weighting, and validation process. Most assessments rely on exterior indicators (e.g., material, number of floors, roof type, openings), while only three of the included studies explicitly incorporate interior indicators. GIS is widely used for data collection, mapping, and spatial analysis of vulnerable buildings. At the same time, BIM has so far been rarely leveraged despite its potential to capture interior characteristics and component-level detail needed for robust building-level assessments. The hazards most frequently addressed are landslides, floods, and dynamic flooding, whereas heatwaves – despite their high historic mortality rates in Europe – remain underrepresented. Indicator weighting approaches vary (expert-

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based, statistical, multi-criteria), and empirical validation is limited. These identified gaps show potential future research directions.

1. Introduction

As the impacts of climate change intensify, buildings across Europe are increasingly exposed to a wide range of natural hazards, including floods, heatwaves, landslides, and storms (Forzieri et al., 2016; Navarro et al., 2023). How to assess and improve resilience to natural hazards and climate-change-induced disasters in existing building stock and future constructions has become a shared concern for building owners, public authorities for disaster risk reduction, urban planners, engineers, and architects (Kochskämper et al., 2025; Kohler, 2018; Lak et al., 2020; Quigley et al., 2018). Enhancing the physical resilience of the built environment requires a deep understanding of its physical vulnerability, considering both the environmental context and the building's characteristics. Systematically identifying buildings' vulnerability is a key step in developing and prioritising effective, tailored risk adaptation strategies, as it influences occupants' vulnerability within buildings.

Several frameworks for vulnerability and resilience assessment in the built environment already exist (Büyüközkan et al., 2022; Cerè et al., 2017; Desouza and Flanery, 2013; Godschalk, 2003; Meerow et al., 2016; Saja et al., 2019; The Rockefeller Foundation and Arup, 2016). However, most frameworks operate at the neighbourhood or city-quarter scale and do not provide adequate solutions for assessing vulnerability at the individual building level (de Ruiter et al., 2017; Moreira et al., 2021). Yet it is precisely at this scale where architects, engineers, building owners, asset managers, and public authorities must make decisions, often within budget constraints or competing priorities. For this reason, identifying vulnerabilities of buildings in hazard-prone areas is essential to guide targeted actions and investments. A common approach of physical vulnerability assessments is the use of vulnerability indicators, either as a part of vulnerability indices or vulnerability curves (de Ruiter et al., 2017; Papathoma-Köhle et al., 2019b). Granger et al. (1999) proposed a first set of indicators, later adopted and expanded into quantifiable indicator sets (e.g., Papathoma et al., 2003).

Traditional vulnerability assessments mainly evaluate exterior characteristics of buildings. However, the influence of interior characteristics, such as the positioning of circuit breaker panels and their exposure to hazards like flooding, is often overlooked. This systematic review seeks to fill this knowledge gap by focusing on the treatment of interior building characteristics as vulnerability indicators in the literature (D'Amico et al., 2016; de Ruiter et al., 2017; Malgwi et al., 2020). Such characteristics can intensify possible losses and pose serious risks to occupants. For example, a flooded circuit breaker panel can increase damage cost for reconstruction, while sudden power loss may threaten those dependent on electrical devices.

Currently interior building characteristics cannot be detected through exterior assessments or remote sensing. They are generally not publicly available and cannot be captured using standard geospatial datasets. The use of Building Information Modelling (BIM) can potentially bridge the gap between exterior and interior vulnerability indicators (Khanmohammadi et al., 2020; Marmo et al., 2023; Zou et al., 2017).

In current research, physical vulnerability indicators for buildings are often considered in relation to a particular hazard, rather than considering the combined effects of multiple hazards on potential building damage. Building owners and key stakeholders in the building sector need to know what vulnerabilities the buildings have across the entire scope of potential hazards, including compounding hazards. Climate change-driven hazards, such as windstorms, heavy rain, and extreme heat, are a particular concern due to their dynamic development and evolving forecast scenarios. Hence, we consider multiple hazards in risk and vulnerability assessments, as underlined in literature (e.g., Gill and Malamud, 2014; Kappes et al., 2012; Tilloy et al., 2019; Ward et al., 2022). The novelty of this study lies within the analysis of the current application of interior indicators, BIM and multiple hazards in physical vulnerability assessments. Beyond compiling existing studies and indicators, this review provides a synthesis of the current state of physical vulnerability assessment at the building level, identifying key trends in indicator selection, identifying opportunities for future research and proposes directions. We systematically explore the current integration of these topics and do not aim to validate or evaluate the effectiveness of the approaches identified.

In order to investigate the outlined research gaps, we analyse European studies on physical vulnerability assessments on building level and extract the used indicators. From this, we compile a comprehensive collection on currently used indicators. The analysis of the building vulnerability indicators is basis for answering the following three key research questions (RQs):

RQ1: Which interior and exterior indicators are currently used in the literature to assess physical building vulnerability?

RQ2: Which indicators are currently collected and evaluated leveraging BIM? What are the advantages of integrating BIM and GIS, and what obstacles exist?

RQ3: Which indicators are currently used in vulnerability analyses for diverse hazards, which weighting methods are adopted, and how do these indicators contribute to the development of multi-hazard assessment framework? Which indicators remain underdeveloped, particularly for future urban risk scenarios?

Guided by these research questions, this study systematically explores current physical vulnerability assessments and the used indicators. It addresses existing gaps in the literature by highlighting the need for (i) the systematic integration of interior and exterior vulnerability indicators, (ii) pragmatic interoperability between GIS and BIM in assessment workflows, and (iii) more transparent weighting and validation procedures to improve transferability and comparability across different hazards and contexts.

This study is structured as follows. Section 2 establishes working definitions as the basis for this study. Section 3 presents the methodological framework used and the scope of analysis. Section 4 outlines the results of the review and interprets these, focusing on interior and exterior indicators, BIM and GIS use, and multiple hazards. Section 5 explores potential advancements and outlooks physical vulnerability assessments. This study concludes by reflecting on the identified gaps in literature, outlining the directions for further research, and highlighting the relevance of indicator-based approaches for strengthening urban planning and architectural design to foster resilience and reduce disaster risks (Section 6).

2. Working definitions

This section aims to clarify terms used in this study and to enhance cross-sectoral understanding of this study. More specifically, we aim to incorporate architectural and risk management perspectives in the terms and their definitions, while adapting their use to this specific review to avoid misunderstandings. The main rationale is to follow the impact pathway of a hazard from the exterior to the interior. Therefore, we apply the following definitions:

a) *exterior indicators*: Based on ISO 13822:2010 and ISO 16818:2008, exterior indicators relate to the site conditions and building envelope. On the one hand, these include characteristics of the direct property surroundings (e.g., height and direction of trees, protective barrier on the premises) as well as building envelope and environmental assets that can be assessed with a walk-around inspection or aerial survey (e.g., height of the lowest opening, roof type, number of floors). They represent the first barrier against natural hazards. Once this barrier is breached, internal building characteristics become relevant to the building's performance during a disaster.
b) *interior indicators*: Based on the Code of Measurement for Cost Planning of the European Committee for Construction Economics (CEEC Code), interior indicators relate to internal finishings (CEEC Code, Section 4) and services installations, special equipment and installations and furniture and fittings (CEEC Code, Section 5). The most common interior indicators are the locations of the heating and electricity central appliances.
c) *direct/indirect indicators, and indicator values*: We adopt the term 'vulnerability indicator', as it is defined by Fuchs et al. (2018), Nardo et al. (2005), OECD (2008) and described by Birkmann (2006, p. 87) as "a variable which is an operational representation of a characteristic or quality of a system able to provide information regarding the susceptibility (…) and resilience of a system to an impact of an albeit ill-defined event linked with a hazard of natural origin". Both the terms 'vulnerability indicators' and 'susceptibility indicators' were used in the reviewed literature. This is also in line with our definition for physical vulnerability (see *e*). Both direct and indirect indicators are considered in this study. Each indicator can assume different manifestations; for example, the 'roofing material' indicator can be either tile, metal sheet, or thatch. For each manifestation, a value can be assigned, typically ranging from 0 to 1 (e.g., tile=0, metal sheet=0,5, thatch=1). In some cases, a weighting factor is added to account for variations in the influence of individual indicators on the overall score.
d) *individual building:* In this study, vulnerability is considered at the level of individual buildings, in relation to buildings themselves and the characteristics in their immediate surroundings, such as trees or walls. To underline the responsibility and sphere of influence of building owners or inhabitants, we limit these aspects to the property boundary. Therefore, assets located outside the property, such as municipal flood protection walls, are not included.
e) *physical vulnerability*: We use vulnerability indicators to describe building characteristics in relation to physical factors. Based on definition of vulnerability by United Nations Office for Disaster Risk Reduction (UNDRR, 2017), this study focuses only on 'susceptibility' and not on 'exposure'. Vulnerability refers to physical, social, economic, and environmental factors that increase the susceptibility of individuals or systems to the impacts of hazards (UNDRR, 2017). In relation to the various factors associated with vulnerability across the physical, social, economic, and environmental dimensions, we focus on the physical factors.
f) *multiple hazards:* We have opted to use 'multiple hazard' in this study instead of 'multi-hazard'. The effects of multiple hazards interact with each other in complex patterns. They can alter amplitude, probability, and even trigger other hazards (Kappes et al., 2012; Lee et al., 2024; Wang et al., 2020; Zscheischler et al., 2020). Therefore, multi-hazard risk assessments pose significant challenges, as the processes leading to altered hazard amplitudes and their numerical values remain poorly researched. Instead, this study uses a simple overlay of single hazards, referred to as 'multi-layer single hazard' approach or 'multiple hazard' in short (Gill et al., 2022).

By referring to (a) and (b) categories, the indicators can be classified as either exterior or interior. Some indicators, however, are context-dependent, as they can relate to both internal and external building aspects. For instance, the 'number of floors/building height' can be considered an interior indicator when referring to occupied floors, but an exterior indicator when describing the building envelope. Similarly, the 'height of openings/ground floor windows or doors' affects interior conditions such as light and ventilation, while from the exterior it influences façade design, exposure, and hazard vulnerability.

3. Methodological framework

The following rationale guided the approach. We defined a sample of studies by conducting a systematic review of scientific publications on physical vulnerability assessments in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement (Page et al., 2021). We then analysed and categorised the approaches, focusing on interior indicators and the use of BIM and GIS in these studies. The approach is described in Section 3.1. We then conducted explorative searches in areas where the systematic search yielded limited results, this is described in Section 3.2.

This review does not aim to provide a bibliometric overview of the topic, as it is specifically designed to address the key research questions through in-depth content analysis. Rather than analysing publication trends, keyword clustering, citation patterns, or authorship networks, this research provides a structured content analysis of existing studies, delving into current approaches and analyses indicators used for vulnerability assessments of buildings. This study is explorative; hence, relationships between variables or indicators are not tested using inferential statistics but are explored through the integration of quantitative findings and qualitative analysis.

3.1. Systematic search approach using PRISMA

More specifically, the authors conducted a systematic search to identify the studies that have contributed to knowledge of physical vulnerability indicators for buildings exposed to natural hazards. To be included in this review, publications must fulfil this set of inclusion criteria:

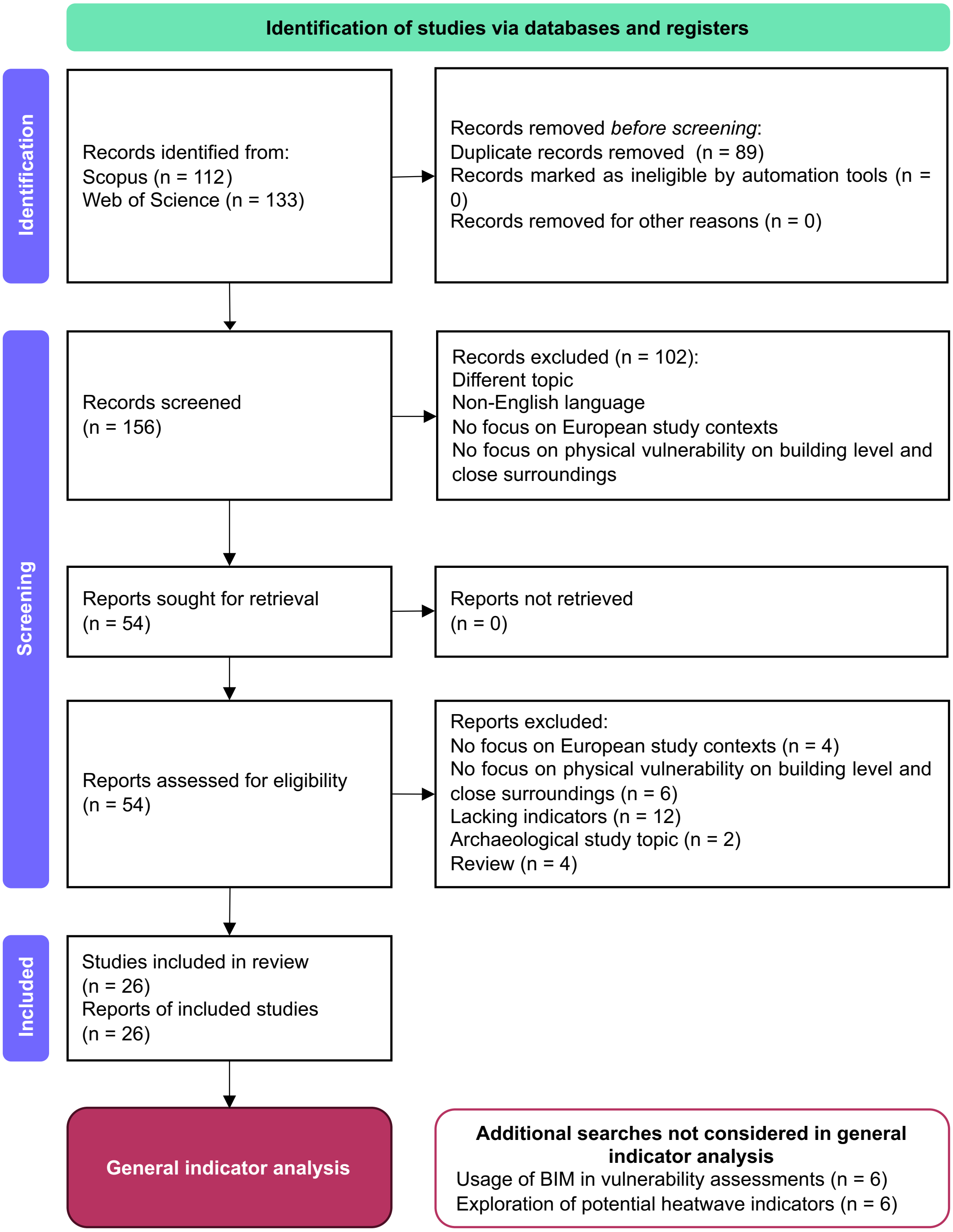

Fig. 1. PRISMA flow diagram adapted from Page et al. (2021).

1. *Publication type:* Scientific journal article. Conference proceedings, book chapters, or any other publications are excluded
2. *Study context:* European countries (according to the geographic definition of Europe), due to their unique historical, cultural, architectural, and legal characteristics
3. *Language:* English
4. *Timeframe:* January 2000–April 2025
5. *Topic:* Focus on physical vulnerability on the building level and the close surroundings to natural hazards
6. *Outcome:* A set of indicators related to building vulnerability assessment and the hazard scenarios

Review articles are considered only if they select indicators for the application within a physical vulnerability assessment, as most reviews collect indicators but typically lack application.

Two common academic databases (Scopus and WoS-Web of Science) were searched on the 15th of April 2025. Based on the outlined rationale, search terms include synonyms of physical vulnerability, natural hazards, and indicators. Considering relevant natural hazards in Europe (EEA 2024), we added specific hazards to the search string.

The search strings (Appendix C) exclude 'BIM' and 'GIS' because it returned a very low number of records ($n = 22$). Possibly, it is because some researchers refer to specific software related to BIM and GIS. Therefore, the use of BIM and GIS was examined in the assessment of the included studies. Other classes of tools, e.g., BEM (Building Energy Modelling) tools, could also be relevant; however, they did not appear in the selected papers. The same applies to the missing interior and exterior aspects, as no terms used to differentiate them were identified.

Rayyan, a web and mobile app for systematic reviews developed by QCRI (Qatar Computing Research Institute), was used in this study to enhance collaborative screening and provide blind conflict resolution (Ouzzani et al., 2016). Screening and data extraction were then performed manually by the authors. The screening results are displayed in the PRISMA flow chart in Fig. 1.

After removing 89 duplicates, 156 abstracts were screened for eligibility using a blinded two-reviewer approach. After discussion and decision on conflicting screening results, 54 full texts were retrieved and screened. Divergences arose, for example, over the assessment's focus at the building level; in edge cases, we included the studies. Thus, 26 studies were included in this review. Following this screening process, all vulnerability indicators discussed or used in these studies were extracted, aggregated, and analysed.

3.2. *Explorative search approach*

The results indicate a limited number of studies using BIM, as only one study (Agliata et al., 2022) was identified through the systematic approach, which is presented in Section 4.2.1. To explore the current status of the integration of BIM in physical vulnerability assessments, we used a snowball search approach. We started with the BIM study identified in the systematic search and extracted further relevant studies from the reference list. We also used Scopus and WoS to identify articles citing the identified publications. We supplemented these findings with an explorative search based on Boolean query using 'resilience' and 'risk' in combination with 'BIM'. The results ($n = 6$ articles) are presented in Section 4.2.2.

Landslides, floods, and dynamic flooding are the most frequently examined hazards, while heatwaves and cold waves are absent throughout the systematically included studies. This gap is especially critical given the well-documented high mortality rates associated with heatwaves in Europe. As climate change amplifies heatwave occurrence and impact, we wanted to explore this topic further in this research. The aim was to derive indicators comparable to the currently used vulnerability indicators for other geophysical or hydrological hazards. Hence, we conducted an explorative search at the intersection of building design and climate change, using search terms such as 'heatwave impact buildings', 'overheating risk', 'thermal comfort during heatwaves', and 'resilient building design strategies' on Scopus and WoS. As the 6 identified studies did not provide indicators in plain form for a comprehensive vulnerability assessment like the other 26 studies, we extracted and derived indicators from these studies. The findings are presented in Section 4.4.

4. Results

From a total of 26 studies that met the eligibility criteria, we extracted 121 different indicators used for physical vulnerability assessments of buildings. The selection of indicators is often dependent on the research context and overall aim. Some studies addressed potential financial losses, guidance on disaster risk management strategies, guidance on crisis management and emergency services, and building retrofitting (Kappes et al., 2012). Target groups that can use vulnerability indicators were mainly individuals, businesses, and public authorities (Papathoma-Köhle et al., 2019a).

Appendix A provides an overview of these indicators, indicating the hazard context and the corresponding bibliographic references. Their possible values are not referred, as these differ widely across studies and in theory, endless manifestations exist (e.g., height of buildings or building materials). In this chapter we present and interpret the findings structured according to the research questions.

4.1. *Interior and exterior vulnerability indicators (RQ1)*

Regarding RQ1, this review analysis revealed only three studies that assess interior characteristics or interior facility services and define indicators (Çal and Ciravoğlu, 2025; Papathoma-Köhle, 2016; Papathoma-Köhle et al., 2017). The remaining 23 studies consider only external indicators in their vulnerability assessments. These exterior indicators can be collected and evaluated in much simpler ways, either through administrative records (building censuses, cadastral or municipal datasets), remote sensing, or field visits.

The limited attention to interior indicators likely stems from the difficulties involved in their assessment. Assessing interior indicators is much more challenging as it requires either access to detailed building information or the use of time-consuming or challenging research methods, such as interviews with occupants or building owners and interior surveys, which must respect the privacy rights of flat or building residents.

From the three studies that considered interior indicators, we extracted the indicators and listed the associated hazards (flooding and landslide) in Table 1. The absence of values for flood-related indicators limits the comparability across the studies, whereases landslide-related indicators are associated with values related to the location of heating system, electricity supply, and evacuation routes values. This suggests that a degree of operational applicability can be observed for the mentioned indicators in the latter case.

Çal and Ciravoğlu (2025) identified vulnerability indicators for buildings in urban coastal areas that are exposed to sea-level rise and flood hazards. This was done first through a literature review and later by utilising the Delphi method, which was conducted in two rounds. The literature review initially highlighted several vulnerability indicators, including safety stairs, floor height, wall height, furnishing height, and furnishing material. However, after consulting with experts, the indicators for safety stairs and floor height were removed from the assessment framework. Instead, the experts recommended including interior wall material, interior wall cladding, the height of fixed furnishing bodies, and the material of fixed furnishing bodies in the framework. The selection assumed that the building's foundation, envelope, and perimeter are most susceptible to initial damage from sea-level rise and flooding, with interior damage deemed less critical and thus partially excluded.

Papathoma-Köhle (2016) and Papathoma-Köhle et al. (2017) discussed different approaches from the literature for assessing physical vulnerability to debris flows, which can pose a threat to life and cause significant damage to interior components, such as floors and walls, as well as to building features like equipment and furniture. Papathoma-Köhle et al. (2017) recommended considering factors such as the type of floor material, the location of the electricity central appliance and heating central appliance, and the maintenance and condition of the electricity network and heating system when evaluating the physical vulnerability of buildings to debris flows. Additionally, Papathoma-Köhle (2016) emphasised the importance of evacuation possibilities and reiterated the importance of the location of the appliances. This study considered the monetary damage caused by the event. It noted that debris flow entering through windows and doors can lead to structural damage, necessitating interior rehabilitation, repair or retrofitting of exterior and interior walls, replacement of doors and windows, inspection, and reinstallation of electrical, heating, and sewage systems.

In summary, only a small number of interior indicators is currently integrated into a few physical vulnerability assessments, leaving relevant vulnerability aspects and dynamics far from analysis.

4.2. GIS-BIM integration into current vulnerability assessment studies (RQ2)

In what concerns RQ2, this section summarises the current integration of GIS and BIM into vulnerability assessments, while further

Table 1
Interior indicators identified through the Scopus and WoS-based literature review (2000-2025).

Type of hazard	Interior indicator(s)	Value	Reference
Flood	Installation system (Gas, HVAC -heating, ventilation, and air conditioning, Water and Electricity, Metre, Fuse, Socket)	–	Çal and Ciravoğlu (2025)
	Installation control points	–	
	Interior wall material	–	
	Interior wall cladding	–	
	Fixed furnishing body height	–	
	Fixed furnishing body material	–	
	Flooring type	–	
	Floor insulation	–	
	Floor covering	–	
Landslide	Location of heating system	Basement First floor Second floor or upper floors	Papathoma-Köhle (2016)
	Location of electricity central	Basement First floor Second floor or upper floors	
	Evacuation possibilities	Only one floor More floors	
	Floor material	–	Papathoma-Köhle et al. (2017)
	Location of the electricity central appliance	–	
	Maintenance and condition of electricity network	–	
	Location of the heating central appliance	–	
	Maintenance and condition of heating system	–	
	Maintenance and condition of sewage system	–	
	Condition/location of water supply network	–	

considerations are provided in Section 5.3. In addition to the findings from the systematic review presented in Section 4.2.1, additional literature derived from the explorative search is included in Section 4.2.2.

4.2.1. GIS-BIM integration in vulnerability assessments identified via systematic search

Of the 26 studies identified in the systematic search, only Agliata et al. (2022) used BIM, specifically Heritage Building Information Modelling (HBIM), which is based on a reverse-engineering process using data collected through various field surveys to model existing conditions. Agliata et al. (2022) developed an indicator-based method within a GIS environment to generate susceptibility maps for a flood- and landslide-prone site in Italy. Using HBIM, they modelled 405 buildings at BIM LOD (Level of Detail) 200 using Edificius by Acca® and the usBIM platform. The HBIM model of the study area was mainly used to "visualise, navigate and generate perspective and axonometric views of the rendered assets in their context" (Agliata et al., 2022, p. 3). However, the vulnerability indicators were not automatically extracted; therefore, the full potential of this tool was not leveraged.

4.2.2. Results of the explorative search of GIS-BIM Integration

Following a snowball and explorative search, we identified several case studies that illustrate how BIM-GIS integration has been applied to assess physical vulnerability. Pelliccio et al. (2017) created a 3D model of a historical town in the Lazio region (Italy) to evaluate seismic and environmental vulnerabilities (i.e., wind and sunshine exposure), based on photogrammetric surveys from drone imagery and thermal scans. Their research was undertaken using Autodesk Revit, Pro_SAP, and the Autodesk Flow Design plugin. Similarly, using a historical monument in Italy as a case study, Vacca et al. (2018) developed a parametric model in Revit, which was integrated into ArcGIS and ArcScene environments via a dedicated workflow. Matrone et al. (2019) tested two workflows for embedding HBIM models of a church into GIS platforms with GIS LOD (Level of Development) 3 and 4, converting IFC (Industry Foundation Classes) geometries into interoperable formats, including shapefiles and PostGIS layers, and using software such as Revit, ESRI ArcScene, and the Feature Manipulation Engine.

An integration for flood vulnerability assessments was done using CityGML and BIM data in Germany by Gebbeken et al. (2016). Using a transformation of a BIM/IFC file to the GML (Geography Markup Language) format, an automated exposure, vulnerability, and potential damage estimation based on material information was performed in Australia (Amirebrahimi et al., 2016). The aim was to estimate damage costs. ArcGIS and its data interoperability extension were used for this transformation. Results are both a report of damage costs and a visualisation of damaged building components. To estimate the risk of building components, a mixed approach was used. For some external building components, like walls and windows, relevant lateral loads from floodwater were calculated. For others, especially interior components, only water contact was used to indicate possible damage. In a recent study, flood risk in Italy was assessed considering interior components using a combination of GIS and BIM data (Ugliotti et al., 2025). This approach leveraged a PostgreSQL database to unify GIS, BIM, and IoT (Internet of Things) data. The visualisation of exposure and vulnerability in the BIM model was performed using Autodesk Revit 2022 and the Dynamo Plugin.

The mentioned studies demonstrate that BIM-GIS integration offers significant opportunities for detailed physical vulnerability

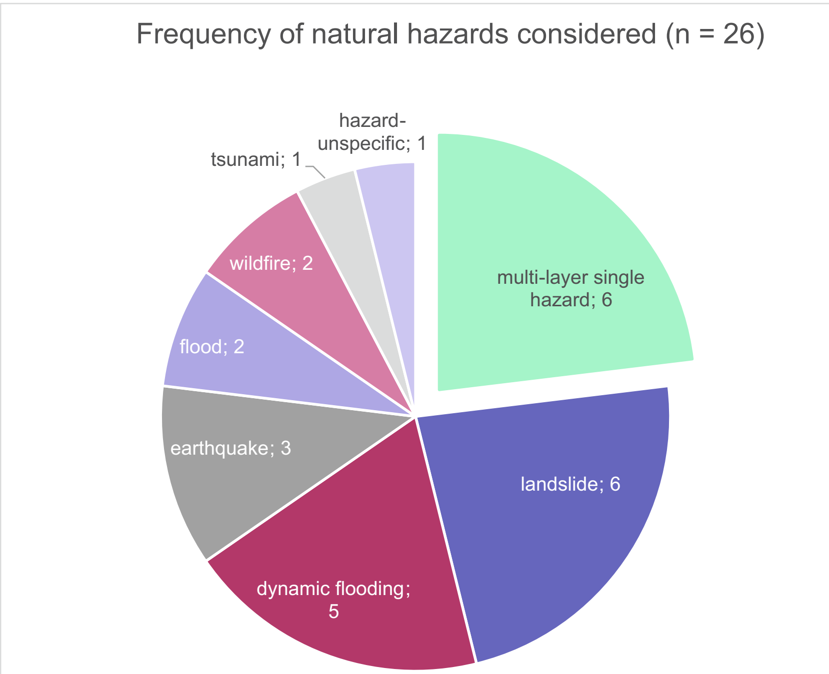

Fig. 2. Frequency of natural hazards in the Scopus- and WoS-based literature review ($n = 26$ studies).

assessments. Overall, its full potential (particularly for automated extraction and scoring of vulnerability indicators) remains largely unexplored.

4.3. Linking indicators to multiple hazards across studies (RQ3)

Multiple (or multi-layer single) hazards (as defined in Section 2, f) were considered within only 6 studies. The remaining 20 studies assessed single hazards. Nevertheless, we identified a share of indicators used for different hazards. Most often, landslide hazards were assessed, followed by dynamic flooding and earthquakes. Fig. 2 displays the frequency of different hazards considered in the 26 studies.

Within the six multi-layer single hazard studies, landslide hazards were considered in five studies, as well as flood hazards. Other hazards, such as earthquakes and meteorological hazards, were only marginally considered within multi-layer single-hazard approaches. These six studies consider multi-layer single hazards in their analysis or even just consider multiple hazards in different areas. A coherent multi-hazard analysis that considers the interaction between natural hazards and the dynamics of physical vulnerability was not identified in this review. In contrast, Kappes et al. (2012) propose a potential application of a multi-hazard physical vulnerability assessment.

A total of 13 distinct hazards was considered in the 26 selected studies. Landslides ($n = 11$), floods ($n = 7$), and dynamic flooding ($n = 5$) have been identified as the most prevalent hazards, each occurring 5 times. The term 'landslide' was used in a generic sense to encompass debris flow, rockfall, and related phenomena, in accordance with the classification system outlined by Varnes (1958). Although the search string focused on natural hazards, one study also considered industrial accidents. A cluster of 5 articles focuses on alpine hazards (such as landslides and dynamic flooding).

The 121 indicators are used across different hazard contexts, as presented in Fig. 3 and detailed in Appendix A. This figure visualises how many indicators are used for which hazard. As some indicators are used in multiple hazard contexts, the total number exceeds 121.

Regarding the distribution of studies and indicators across different hazard types, the most frequently considered were dynamic flooding and landslide hazards. Compared with natural disasters in the EU between 1980 and 2017, the highest proportion of fatalities due to natural hazards (85 %) was caused by heatwaves. Geophysical events (earthquakes, tsunamis, volcanic eruptions), meteorological events (storms), and hydrological events (floods, mass movements) each caused only 4 % of the fatalities. In contrast, climatological events (cold waves, droughts, and forest fires) accounted for 3% (ECHO 2021). A comparison of past disaster impacts and the findings of this review reveal a misbalance, as heatwaves are underrepresented in the identified studies, with only one study including them, and in a limited manner (Galderisi and Limongi, 2021). Nevertheless, this subject is addressed in architecture (Wei et al., 2025), due to its increasing importance (Ballester et al., 2023; IPCC, 2023; JRC, 2020). The results of an exploratory review on this topic are presented in Section 4.4.

In contrast to the distribution of fatalities, financial and economic losses in the EU are caused mainly by meteorological (32%) and hydrological events (31%) (ECHO 2021). Given that 20 of the identified studies considered both event types, it can thus be assumed

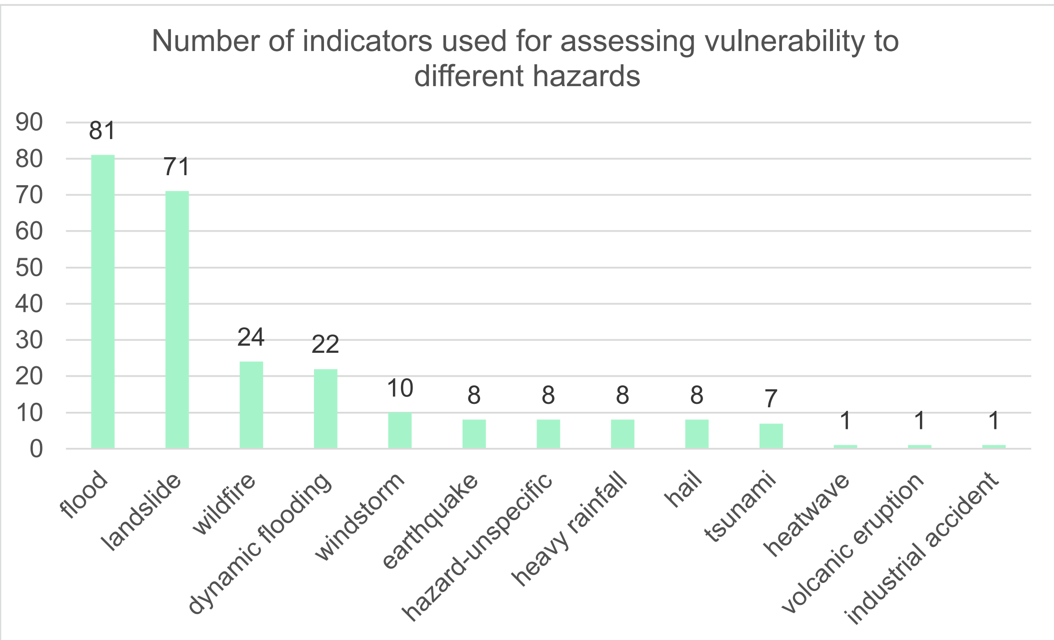

Fig. 3. The number of indicators used for assessing vulnerability to different hazards.

that the use case of guiding risk management to reduce financial losses is the focus of these studies. Regarding future climate trends, the risks of heat waves and other meteorological and hydrological events are increasing in the EU (EEA 2024; EEA 2021; JRC, 2020), underscoring the need to consider all natural hazards.

An in-depth analysis of the indicator usage reveals that 53% (64) of the 121 examined indicators were used in multiple hazard contexts across different studies (see Fig. 3). Although Papathoma-Köhle et al. (2019b) argued that transferring indicator sets to other hazards is difficult due to the characteristics of the hazard events. The observed transferability of indicators improves the cost-benefit ratio of physical vulnerability assessments. After evaluating several indicators, a large share of hazards can be considered, exemplified in Fig. 4. Nevertheless, the transfer of vulnerability indicators and their assessment across different hazards remains challenging, as indicators can have different risk directions (de Ruiter et al., 2017). Depending on the type of hazard, indicators can either increase or reduce vulnerability. For example, trees surrounding a building can reduce heat stress and the impact of landslides but increase the vulnerability to wildfires. This needs to be considered while assessing physical vulnerability to different hazards. In addition, the significance of the indicators varies, while an indicator can have a huge impact on physical vulnerability in one hazard context, it can be less relevant in other contexts. For example, is the location the lowest opening less relevant in context of earthquake hazards, but highly relevant in flood context.

In summary, most studies used 5–8 indicators, with 31% of the selected studies using five indicators to assess physical vulnerability. The most extensive collection of indicators ($n = 55$) was done by Çal and Ciravoğlu (2025). Only two indicators were considered by Uzielli et al. (2008).

4.4. Heatwave-related studies on physical vulnerability identified within explorative search (RQ3)

Heatwaves and cold waves are absent throughout the systematically included studies. As already noted, only Galderisi and Limongi (2021) considered heatwaves using one indicator. Given the emerging heatwave risk in Europe (ECHO 2021; IPCC, 2023), an additional explorative search was conducted to identify physical vulnerability indicators specifically related to heatwaves. The aim was to derive indicators comparable to the currently used vulnerability indicators for other geophysical or hydrological hazards. Hence, we conducted an explorative search in the domain of architectural design, using search terms such as ‘heatwave impact buildings’, ‘overheating risk’, ‘thermal comfort during heatwaves’, and ‘resilient building design strategies’ (6 studies included; Fig. 1). As the 6

Fig. 4. Indicators used for more than 3 of the most represented hazards.

Table 2
Overview of building indicators and their overheating risk levels during heatwaves.

Indicator	Value	Level of overheating risk	Probable rationale	Reference(s)
Building type	Detached house Semi-detached house	*High* *Low*	Detached houses have higher exposure to solar radiation	Hamdy et al. (2017)
Building orientation	Define orientation based on the location of the building and the sun's position	*Low*	Minimised direct sun exposure	Ozarisoy (2022)
Building elevation	Upper floors Ground floor	*High* *Low*	Upper floors have higher exposure to solar radiation, heat accumulation and lack of vertical shading	Hamdy et al. (2017); Hayles et al. (2022)
Structural weight	Light weight Heavy weight	*High* *Low*	Lower thermal mass causes a faster response to exterior temperatures	Velashjerdi Farahani et al. (2024)
Ventilation	Natural ventilation (openable window)	*Medium to high* Ventilation strategies have a significant reduction in overheating risk only when exterior air is cooler than interiors	Increasing air flow when the exterior temperature is lower than the interior temperature has a direct effect in reducing overheating. AC is directly reducing air temperature	Ozarisoy (2022); Velashjerdi Farahani et al. (2021, 2024)
	Mechanical ventilation (includes the Air conditioning- AC system)	*Low* AC works in all conditions if electricity is available		Tao et al. (2025); Velashjerdi Farahani et al. (2021, 2024)
Windows	Traditional windows (poorly insulated) New standard windows (high-quality insulation) Solar protection windows (new insulation and reduced solar transmittance) Traditional fixed windows (picture windows) retrofitted with solar control window film (reduction of solar transmittance without significantly affecting insulation)	*High* *Medium* *Medium* *Low*	The impact of windows on overheating risk is highly dependent on solar transmittance (g-value) rather than heat transfer (U-value)	Velashjerdi Farahani et al. (2021, 2024)
Shading devices	East/West orientation	*Low*	It decreases solar transmittance	Hamdy et al. (2017); Ozarisoy (2022)

identified studies did not provide indicators in plain form for a comprehensive vulnerability assessment like the other 26 studies, we extracted and derived indicators from these studies. The findings are presented below. The heatwave definition varies across European countries based on key indicators. Typically, heatwaves are defined when the daily maximum exterior temperature exceeds a country's specific threshold for more than a certain number of consecutive days. The impact of heatwaves on residents is evaluated using internal overheating risk. This risk, which depends on heatwave severity and building characteristics, contributes to several problems ranging from thermal discomfort of building inhabitants and productivity reduction to illness and death (Hamdy et al., 2017).

For each building indicator, Table 2 shows the associated level of overheating risk, highlights its relative importance, and provides the rationale proposed by the authors. Each indicator's risk level is justified by its possibility for solar gain reduction, night-time cooling, or thermal buffering.

Although mechanical ventilation and air conditioning were considered key solutions to mitigate overheating risk, frequent power disruptions during heatwaves limit their reliability for maintaining interior thermal comfort (Tao et al., 2025). It can also lead to a vulnerability paradox, as residents become accustomed to them (NOTA – Rathenau-Instituut, 1994). In case of a blackout, residents may be at higher risk.

It is important to note that assessing the impact of individual building indicators on overheating risk can be challenging due to the complex interactions among building geometry, occupant behaviour, and local climatic conditions. However, indicator-level understanding can support targeted passive design. The derived indicators show a first possible approach to cover heatwave-related physical vulnerabilities within the indicator-based assessment approaches, while the results of our systematic search reveal a lack of usage of indicators in this topic.

4.5. *Weights of indicators (RQ3)*

4.5.1. *Weighting approaches*

Weighting approaches are designed to reflect the relative importance of a single indicator on overall vulnerability (Becker et al., 2017). The approach is based on the selection of vulnerability indicators that are related to the characteristics of a building and its surroundings, their weighting, their aggregation in a Physical Vulnerability Index (PVI), and finally their verification (Papathoma-Köhle et al., 2023). When aggregating individual indicators, either a specific weighting factor can be assigned, or the factors are automatically calculated as $1/n$, giving equal weight to all indicators. A weighting factor is therefore applied and will shift the results if no proper consideration is given.

The choice of weighting method can influence the PVI, therefore, affecting its interpretability and its utility for decision-makers (Papathoma-Köhle et al., 2019a). PVIs are commonly aggregated into a composite index to summarise the complexity of physical vulnerability and therefore enhance the comparison of building performance across different spatial contexts (Becker et al., 2017;

Nardo et al., 2005). To construct a mathematically sound PVI, the selected indicators need to be weighted before aggregation (Papathoma-Köhle et al., 2019b). This can be a time-consuming process, since it involves expert judgment, multiple-stakeholder input, and/or statistical methods to determine which indicators most significantly affect risk outcomes. But this process can also help to foster discussions on risk reduction based on a spatial overview of vulnerability differences (Nardo et al., 2005).

4.5.2. Insight from the literature review

The publications analysed in this study can be grouped into two broad categories: those with (14) and without (12) weighting of indicators. Among the publications with weighting, a further distinction can be made between the methods used to determine the weights: expert appraisal in 2 of the analysed publications (Kappes et al., 2012; Papathoma-Köhle et al., 2019b), statistical analysis (Gerçek and Güven, 2023; Papathoma-Köhle et al., 2022b, 2022a, 2019a), values from the literature (Agliata et al., 2022; Leal et al., 2021; Taramelli et al., 2022; Xofi et al., 2022) or a Multi-criteria decision making method (MCDM), namely MACBETH and the AHP (Analytic Hierarchy Process) method (Papathoma-Köhle et al., 2023; Saaty, 1987) also directly combined scoring and weighting (Gerçek and Güven, 2023; Tascón-González et al., 2024). A possible PVI progression path for buildings can be recognised when looking at the publications addressing weighting. Many contributions of the last decade were made by Kappes et al. (2012), Papathoma-Köhle et al. (2019b), Papathoma-Köhle et al. (2023). The methodology was originally developed for tsunamis (Papathoma et al., 2003) and subsequently gradually transferred to other hazards. This included a PVI for hydrological events in the mountains (Papathoma-Köhle et al., 2019b), wildfires (Papathoma-Köhle et al., 2022b), and three meteorological hazards: windstorms, heavy rainfall, and hail (Papathoma-Köhle et al., 2023).

The weighting itself is essential for quantitative or semi-quantitative evaluation, the methods used currently have limitations. The limited data basis on which the evaluations are conducted has the greatest impact. Statistical evaluations are often based solely on the analysis of a single hazard.

5. Discussion

This section discusses limitations of our methodological approach and how they were addressed in this research. It then outlines potential future research directions for the research gaps presented in Section 4. These outlooks are based on both findings from the systematic literature search and additional literature references. This supplements the review findings by going beyond a mere collection of the state of the art for exploring future research opportunities.

5.1. Limitations

While this review applied a systematic search, we explored the current integration and consideration of different topics in physical vulnerability assessments. Due to the low number of studies integrating the raised topics, the generalisation of our findings and proposals is limited. However, they provide helpful impulses for further research. Our extensive list of indicators enables fellow researchers to construct, test and validate various physical vulnerability frameworks.

One limitation lies in the integration of various research fields and the related terminological issues. Researchers in building vulnerability, risk and resilience science (such as disaster risk management, structural engineering, and architecture) approach the field utilising diverse terminology, methods, and perspectives. This inconsistency poses significant challenges when attempting to develop a systematic overview. To address this issue, a broad search string was employed in this research to establish a well-grounded basis for vulnerability assessment studies. However, it is important to acknowledge that, despite this inclusive approach, this study is not able to provide an exhaustive overview due to these limitations and does not encompass all research on building vulnerability.

Despite some convergences in indicator selection, significant heterogeneity persists in terminology, definitions, and assessment methods across the selected studies. Differing taxonomies of indicators are evident; for example, up to seven synonyms for a single indicator are used, such as construction year and age of the building. This hampers an accurate and reliable comparison, as a thorough check is needed to determine whether the same indicator is described or whether the underlying definitions differ. A unified framework on terminology by recognised institutions could significantly reduce the terminology issues. Our extensive list of various synonyms can provide a basis for such harmonisation efforts.

Some indicators are not mere vulnerability indicators but represent or alter hazard or exposure. The distance to the hazard zone, for example, influences the impact of the hazard on the building, but not the building's vulnerability. The distinction between vulnerability and exposure is not always clear-cut. This is evidenced by the different definitions of vulnerability, some of which include exposure alongside susceptibility, in line with Thywissen's (2006) findings. In this review, indicators capturing exposure aspects, such as “Building row towards hazard zone (slope, river, torrent) (first row, second row, etc.)”, were integrated into the assessment. The selection process applied a conservative strategy, favouring the inclusion rather than the exclusion of such indicators.

Additionally, the systematic review addressed in this research lacks perspectives from architecture, urban planning, and structural engineering. These fields could be further incorporated through additional exploratory search approaches. Nevertheless, our findings highlight the need for interdisciplinary approaches in disaster risk management science, as already stated by Šakić Trogrlić et al. (2022).

Another limitation of our approach is its focus on European study contexts, selected since European urban environments have unique historical, architectural, and legal characteristics. Nevertheless, important contributions to the field are also developed outside the European context and are considered in the discussion.

5.2. Addressing the imbalance of exterior and interior vulnerability indicators (RQ1)

Interior vulnerability indicators are notably scarcer than exterior ones, as discussed in Section 4. As noted by Çal and Ciravoğlu (2025), the first areas to be damaged during a natural hazard would be the perimeter, foundation, and building envelope, thus interior indicators are less relevant. However, when indicators are selected considering the monetary loss after the event or another hazard type, different sets of indicators may emerge, as discussed by Papathoma-Köhle (2016). Moreover, methods such as automated in situ analysis or scoring from remotely sensed data (Lazzati et al., 2023) tend to favour exterior indicators, since interior spaces are often inaccessible to researchers.

The dependence of buildings on critical infrastructure is sparsely considered in the analysed studies; only seven indicators describe the critical infrastructure status, such as 'location of the electricity central appliance', despite the huge reliance of today's society on critical infrastructures (NOTA – Rathenau-Instituut, 1994; Rinaldi et al., 2001). Many building functions, such as heating, rely on critical infrastructures (Wei et al., 2025).

The relevance of interior indicators differs across hazards. An indicator critical for one hazard may be negligible for another. For instance, open-plan ground floors have been identified as a seismic vulnerability (Xofi et al., 2022), while interior characteristics such as width of fire escape stairway, combustible materials, and the absence of active fire protection systems (e.g., sprinklers, smoke detectors, and fire extinguishers) are crucial in structural fires (Kodur et al., 2019; Zhang, 2023). In flood-prone areas, elevating HVAC units has been proposed as a mitigation strategy (Kousky and You, 2024; Paleo-Torres et al., 2021). Furthermore, essential systems such as backup power (generators, battery storage) play a vital role during and after disasters. These systems include indoor components, and damage to them can significantly compromise post-disaster resilience.

A pathway to identify suitable interior indicators, next to existing expert consensus approaches (Çal and Ciravoğlu, 2025), could be the consideration of building regulations, codes, and standards. Although originally developed for cost estimation and quantity measurement, the CEEC Code offers a detailed framework for categorising interior components, including internal superstructures, finishes, service installations, specialised equipment, and furnishings. It also provides a detailed list of service installations, including energy systems, telecommunication, IT infrastructure, and fire and security systems. Using a structured taxonomy can help prevent the omission of interior elements critical to structural integrity and mechanical functionality, particularly in multi-hazard contexts. This approach can also support the development of context-specific vulnerability indicator sets for various building types, including critical infrastructures, such as community hubs for emergency shelters, hospitals, offices, shopping centres, and museums.

A pressing issue is the availability of data for interior indicator collection, which hugely relies on the participation of building owners or occupants and introduces both organisational and ethical challenges. At the same time, this also enables a more participatory approach to vulnerability assessment than traditional approaches, which typically rely on open geospatial data and are based on a passive role of building stakeholders. Engaging stakeholders in identifying interior indicators can also help raise awareness of risks and encourage proactive mitigation measures.

5.3. Use of building vulnerability indicators in four phases of disaster risk management (RQ1)

Vulnerability assessments are relevant across all phases of disaster risk management (DRM), as detailed below.

1) *Prevention and Mitigation:* Exterior indicators such as the height of the lowest opening, overall building height, or roof type are widely applied to identify structural weaknesses and support floodplain management (de Ruiter et al., 2017). Vegetation surrounding buildings is another recurring indicator, yet it illustrates the dual role of exterior characteristics: while it reduces heat stress during heatwaves, it simultaneously increases wildfire risk (de Ruiter et al., 2017; Papathoma-Köhle et al., 2019b).
2) *Preparedness:* Exterior indicators also guide emergency planning. GIS-based mapping frequently employs construction material, overhanging structures, or number of storeys to identify vulnerable structures and areas with limited evacuation options (Kappes et al., 2012; Galderisi and Limongi, 2021). Single-storey homes in flood zones or buildings made of fragile materials are examples of vulnerability hotspots. However, many studies use only a few easily accessible indicators ($\leq$6), which risks oversimplifying vulnerability dimensions (Çal and Ciravoğlu, 2025).
3) *Response:* During emergency operations, exterior characteristics influence both hazard impacts and intervention feasibility. Indicators such as building accessibility, condition, or the absence of vertical escape routes have been shown to affect real-time rescue priorities (Papathoma-Köhle, 2016; Çal and Ciravoğlu, 2025). Nevertheless, links to critical infrastructure remain underexplored, leaving a gap in how exterior indicators could be integrated into operational response planning.
4) *Recovery:* Post-event assessments often rely on exterior indicators to plan reconstruction. Building typology, roofing system, and maintenance level are frequently used to estimate recovery needs or cost implications (Kappes et al., 2012; Papathoma-Köhle et al., 2017). While these indicators provide valuable insights, relying solely on exterior characteristics overlooks equally relevant interior characteristics and systems, such as the condition of heating or electrical installations (Kodur et al., 2019; Papathoma-Köhle et al., 2022a).

Across Europe, building-level vulnerability assessments rely primarily on exterior indicators due to their practical accessibility and scalability via GIS, cadastral records, and remote sensing (de Ruiter et al., 2017). So far, exterior indicators are well integrated into prevention and preparedness, but their application in response and recovery is less developed (Papathoma-Köhle et al., 2019b). Moreover, the lack of standardised terminology and weighting approaches reduces comparability across studies (Kappes et al., 2012). A unified terminology is crucial for further development and should be developed by recognised institutions. The extensive collection of indicators is a basis for this task. To enhance DRM practices, exterior indicators should be systematically linked with interior characteristics, supported by BIM-GIS integration (Galderisi and Limongi, 2021). This combination can provide a more comprehensive picture of building vulnerability, addressing existing gaps, and fostering the interdisciplinary collaboration needed to strengthen resilience against multiple hazards (Papathoma-Köhle et al., 2022a).

5.4. Research opportunities and gaps in GIS-BIM integration for vulnerability assessment (RQ2)

The integration of GIS and BIM could provide a powerful framework for multi-scalar vulnerability assessments of buildings exposed to natural hazards (Fekete et al., 2025; Mayouf et al., 2022; Rathnasiri et al., 2023; Sertyesilisik, 2017). While GIS excels in spatial analysis and contextual data, e.g., terrain, vegetation, proximity to hazard sources, BIM offers detailed representations of internal building characteristics such as layout, wall materials, floor plans, HVAC systems, and locations of electrical components, all indicators that are particularly relevant for flood, earthquake or heatwave vulnerability (Cao et al., 2023; Dimyadi et al., 2016; Volk et al., 2014). A clear focus of BIM usage in risk management is on flood vulnerability assessments, fire safety, and evacuation aspects (Marmo et al., 2023; Rathnasiri et al., 2023).

However, several challenges limit the seamless integration of these systems. A key barrier lies in semantic and geometric incompatibility, stemming from fundamental differences in data structures, LoDs, and targeted use cases (Bruno et al., 2020; Matrone et al., 2019). In addition, inconsistencies in coordinate systems, geometric representations, and semantic definitions can lead to misalignment or data loss when transferring information between BIM and GIS platforms (Vacca et al., 2018). The integration of BIM and GIS remains technically and semantically challenging. BIM models are often developed in proprietary formats (e.g., IFC), while GIS operates within open geospatial standards (e.g., GML, CityGML, PostGIS). These differences lead to interoperability issues related to coordinate systems, geometric representations, and semantic mismatches (Donkers et al., 2016; Kang and Hong, 2015; Matrone et al., 2019).

Various strategies for integrating GIS and BIM have been explored in recent research. These include preparing BIM objects using both CityGML and IFC standards, extending CityGML to incorporate semantic IFC content, and using the IFC schema as a bridging format to enable GIS-to-BIM conversions (Matrone et al., 2019). Another approach is the conversion of IFC models into GIS-compatible formats or by developing hybrid models using CityGML ADEs (Application Domain Extensions) and PostGIS workflows (Deng et al., 2025; El-Mekawy et al., 2012; Liu et al., 2017). Others apply ontology-based approaches, often using intermediate reference ontologies adding further complexity (Ji et al., 2024). While the conversion from IFC to CityGML is possible using several methods, the conversion to IFC is still not fully feasible (Ji et al., 2024).

Yet, the adoption of these methods remains limited in vulnerability assessment practice. An in-depth root-cause analysis of the challenges is needed to identify the challenges preventing the effective implementation of BIM into physical vulnerability assessments. Recent studies and development suggest promising pathways. The recent CityGML 3.0 standard enhances the conversion of IFC into CityGML, by reducing the necessary changes of semantics (Kutzner et al., 2020). While IFC 4 improves georeferencing, the described semantic mismatches are not yet resolved.

Web-GIS platforms have emerged as effective tools for spatially distributed hazard monitoring and decision support (Daud et al., 2024). When combined with BIM-derived building data, these platforms can enhance vulnerability assessments by incorporating real-time data inputs and participatory feedback. Moreover, digital twin paradigms increasingly merge BIM, GIS, and IoT data to enable dynamic monitoring of building exposure and performance (Liu et al., 2025). This is already employed in prototypes for vulnerability assessments (Ugliotti et al., 2025), paving the way to a shift from static indicator-based assessments to real-time, situational vulnerability modelling.

Despite these opportunities, our review finds that few vulnerability studies exploit the full potential of GIS-BIM integration. Most rely either on GIS-based proxies or post-processed BIM data, without establishing interoperable workflows or assessing data quality and uncertainty propagation. Future works should focus on:

- *Modular interoperability* using open standards (IFC, CityGML, OGC APIs)
- *Digital twins* that integrate sensor data, remote sensing, and BIM for real-time risk monitoring
- *Participatory GIS-BIM platforms* that crowdsource interior vulnerability characteristics (e.g., elevation of circuit breaker panels, insulation types)

Such developments could make vulnerability assessment more accurate, scalable, and transferable across regions and hazards, thereby enhancing its utility in disaster risk reduction and climate adaptation planning.

5.5. Challenges and research gaps in multi-hazard and dynamic vulnerability assessments (RQ3)

Despite many calls for consideration of hazard interrelationships (Kappes et al., 2012; Lee et al., 2024; Wang et al., 2020; Zscheischler et al., 2020), we could not identify a multi-risk approach. The necessity of integrated multi-hazard assessments is emphasised by the fact that approximately 20% of the EU population and 20% of the territory are exposed to multiple hazards (Antofie et al., 2025).

Six studies covered multi-layer single hazards (Agliata et al., 2022; Galderisi and Limongi, 2021; Godfrey et al., 2015; Kappes et al., 2012; Papathoma-Köhle et al., 2023; Salvati et al., 2021) in this systematic review, ignoring interrelationships between hazards. Not only hazard interrelations but also dynamic aspects of vulnerability are relevant in multi-hazard assessments (De Ruiter et al., 2020).

This leads to a highly dynamic system of interrelationships between hazards and dynamic vulnerability aspects that are difficult to assess (De Ruiter et al., 2020; Gill et al., 2022; Thywissen, 2006; Ward et al., 2022). In addition, it needs to be considered, that one indicator can have different or even diametral implications for vulnerability depending on the hazard in question.

Interactions between different building components can influence physical vulnerability. In particular, complex interactions among building geometry, occupant behaviour, and local conditions are relevant. This can lead to misinterpretations, for example, if a building in a flood zone is designed to be flooded (wet-proofing) (Endendijk et al., 2023; Poussin et al., 2012), windows beneath the expected water level do not increase physical vulnerability. This also affects the consideration of interior indicators. As they may only be affected if exterior barriers fail and these interior characteristics become exposed to the hazard.

6. Conclusions and perspectives

This review addresses critical research gaps by systematically analysing European studies on physical vulnerability assessments at the building level, with a focus on the indicators. Specifically, our objective is to identify the interior and exterior indicators currently used to assess building vulnerability (RQ1). We examined which indicators are collected and evaluated leveraging BIM. Highlighting the benefits and challenges of GIS-BIM integration (RQ2), we additionally explored the use and weighting of indicators across multiple hazards (RQ3). The topics have been selected for their complementary relationship, with one topic directly complementing another. While interior indicators may be relevant across multiple hazards, the integration of GIS and BIM can facilitate their analysis.

This review serves as a call to action to further explore the gaps and opportunities associated with these topics. The proposed considerations should be further examined in terms of their significance and applicability. While we found fruitful applications in neighbouring fields, a 1:1 translation to the field of physical vulnerability assessments cannot be assumed and requires validation through empirical studies and real-world implementations. A unified terminology is crucial for further development and should be developed by recognised institutions.

We identified 26 studies from Scopus and WoS literature review (2000–2025) by using a systematic approach. A set of 121 vulnerability indicators was extracted and analysed. This extensive set provides a basis for further analysis, creation, application, and validation of future vulnerability assessments methods. The selected indicators cover various building characteristics relevant for physical vulnerability assessments and can be measured directly.

Regarding RQ1 (*indicators used in the literature to assess physical building vulnerability*), most existing studies focus on readily accessible exterior indicators derived from administrative records or remote sensing, such as the number of floors and roof type. Interior indicators are rarely addressed in the identified publications due to limited data availability and challenges in systematic assessment (e.g., limited access to interior data, privacy concerns, and the high variability of building layouts over the building's lifespan). Further research is needed considering their relevance during disasters caused by different natural hazards.

Regarding RQ2 (*BIM-GIS integration*), a key gap is the limited integration of advanced spatial data technologies and digital methods that could enhance vulnerability assessments. The development of automated, scalable, and semantically interoperable tools remains essential in the early stages of disaster risk management. Although GIS and BIM are increasingly recognised internationally for their potential, only a few studies make operational use of them, often limited to visualisation. The integration of BIM and GIS, though still emerging in natural hazard vulnerability research, offers a significant opportunity to combine detailed building-level data with environmental context and spatial analytics. If properly integrated, these technologies could support multi-hazard assessments that are adaptable to different geographic scales and building typologies. BIM enables access to interior characteristics and facilities, such as circuit breaker panel locations or heating systems, while GIS provides spatial hazard exposure and contextual factors such as terrain, hydrology, and vegetation. Combined, they enable vulnerability modelling that is both fine-grained/high-resolution and geographically aware. The identified gaps in semantic interoperability, data integration workflows, and real-time monitoring present clear priorities for future research and tool development.

Regarding RQ3 (*indicators for each hazard, weighted methods, and gaps*), we observed that across the 26 analysed studies, geophysical and hydrological hazards are well researched, but applications for heatwaves or cold waves are still lacking. In particular, despite growing impacts and awareness on this topic, physical vulnerability assessments do not cover heatwaves. While in the architectural practice, countermeasures are often implemented, the analysis of the existing building stock and the potential for refurbishment is also important in this regard. Through an explorative search method, we identified seven potential indicators for heatwave vulnerability assessments. The proposed indicators must undergo a rigorous applicability check to ascertain their potential for implementation. Potential frameworks integrating interior indicators need to be further explored. Multi-hazard approaches, which consider the interaction of hazards and dynamic aspects of vulnerability, are missing. In conjunction with the absence of validated indicators, this topic constitutes a significant challenge in the research domain of physical vulnerability indicators.

Although disaster risk management is widely recognised and supported by relevant funding initiatives at the European level, the literature on its integrated and interdisciplinary dimensions remains limited. As demonstrated in this study, first, it is necessary to establish a standardised classification framework to improve comparability and scalability across studies. Second, such framework should encompass complementary domains related to physical vulnerability at different scales (city, district, building). Interprofessional cooperation plays a crucial role in mitigating semantic biases and resolving ambiguities in the interpretation of vulnerability indicators. Vulnerable groups, due to ethnicity, mobility, age, sex, or other socio-economic factors, are generally not considered in the selected works, even though they are particularly affected by disasters (IPCC, 2023; Fekete et al., 2025; Flanagan et al., 2011). Critically analysing vulnerable groups and their interaction with the building stock in future studies is crucial.

These insights are particularly relevant for contemporary architectural practice and urban decision-making. Urban planners and AEC (Architecture, Engineering and Construction)-related stakeholders are expected to contribute to climate-responsive, risk-aware design, especially under new demands from public authorities and investors (Ordóñez Llancce et al., 2025). The indicator frameworks reviewed here, combined with GIS-BIM integration, can support design decisions and guide targeted retrofitting of existing buildings or other preparedness actions to reduce disaster risk. Embedding the analysis of vulnerability indicators into urban and architectural planning-related workflows also implies a closer collaboration among policymakers, civil protection agencies, designers, and urban planners. This data-driven and collaborative approach aligns with current EU policy strategies, as defined in the New European Bauhaus (NEB)[1] and other climate adaptation initiatives, where architecture and urban planning play a strategic role in shaping resilient cities.

The findings of this review call for further research on interior indicators as well as the combination of BIM and GIS approaches in physical vulnerability assessments. In addition, the applicability of indicator-based assessments for climatological hazards such as heatwaves and cold waves needs further research as well as the dynamics of physical vulnerability in the light of multiple hazards. By advancing these areas, future research can support more robust, comparable, and actionable vulnerability assessments for disaster risk reduction, climate adaptation, and sustainable urban and architectural planning.

CRediT authorship contribution statement

Steffen Neuner: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christopher Munschauer:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Alexander Fekete:** Writing – review & editing, Supervision, Conceptualization. **Stefania Stellacci:** Writing – review & editing, Funding acquisition. **Lubos Buzna:** Writing – review & editing. **Daniel Chovanec:** Writing – original draft, Investigation, Formal analysis. **Katarina Holla:** Writing – original draft, Investigation, Formal analysis. **Samuel Kockar:** Writing – original draft, Investigation, Formal analysis. **Ulrich Leopold:** Writing – original draft, Investigation, Formal analysis. **Rongling Li:** Writing – original draft, Investigation, Formal analysis. **Ali Reza Yaghoubi:** Writing – original draft, Investigation, Formal analysis. **Derya Yilmaz:** Writing – original draft, Investigation, Formal analysis. **Catarina Ferreira da Silva:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. List of interior and exterior indicators related to building physical vulnerability from Scopus- and WoS-based literature review (2000–2025)

This table outlines the relationship between indicators at building level and exposure to various hazards. Indicators are sorted by number of hazard contexts in which they are used (descending order), then alphabetically by indicator name, and finally alphabetically by hazard. The indicator names are copied directly from the reference(s). In cases where different references applied synonyms, these are also listed.

Indicator	Number of hazards	Hazard contexts	Reference
Number of floors/Height of the building	8	Earthquake	D'Amico et al. (2016)
		Flood	Tascón-González et al. (2024)
		Dynamic flooding	Taramelli et al. (2022)
		Landslide	Leal et al. (2021)
		Wildfire	Agliata et al. (2021)

(continued on next page)

[1] https://new-european-bauhaus.europa.eu/index_en

(*continued*)

Indicator	Number of hazards	Hazard contexts	Reference
		Windstorm Hail Tsunami	Agliata et al. (2022) Galderisi and Limongi (2021) Harb et al. (2015) Papathoma-Köhle et al. (2022b) Xofi et al. (2022) Godfrey et al. (2015) Pereira et al. (2020) Kappes et al. (2012) Papathoma-Köhle et al. (2023) Puissant et al. (2014) Papathoma-Köhle et al. (2019a) Skoulidou and Kazantzi (2024) Papathoma-Köhle et al. (2025) Papathoma-Köhle et al. (2017) Papathoma-Köhle (2016) Papathoma-Köhle et al. (2019b) Salvati et al. (2021) Çal and Ciravoğlu (2025)
Level of maintenance/Conservation status/Building condition (mix of maintenance and age)/Building state	7	Earthquake Flood Landslide Dynamic flooding Volcanic eruption Industrial accident Tsunami	D'Amico et al. (2016) Godfrey et al. (2015) Uzielli et al. (2008) Skoulidou and Kazantzi (2024) Papathoma-Köhle et al. (2017) Papathoma-Köhle et al. (2019b) Tascón-González et al. (2024) Taramelli et al. (2022) Leal et al. (2021) Agliata et al. (2021) Agliata et al. (2022) Galderisi and Limongi (2021) Kappes et al. (2012) Puissant et al. (2014) Papathoma-Köhle et al. (2019a) Çal and Ciravoğlu (2025)
Material and structure/Construction material type/Building material	6	Dynamic flooding Earthquake Landslide Flood Tsunami Wildfire	Taramelli et al. (2022) Leal et al. (2021) Galderisi and Limongi (2021) Pereira et al. (2020) Kappes et al. (2012) Puissant et al. (2014) Papathoma-Köhle et al. (2019a) Skoulidou and Kazantzi (2024) Papathoma-Köhle et al. (2025) Papathoma-Köhle et al. (2017) Papathoma-Köhle (2016) Papathoma-Köhle et al. (2019b) Salvati et al. (2021) Çal and Ciravoğlu (2025)
Presence of basement/Presence and state of the basement	6	Wildfire Windstorm Hail Landslide Flood Heavy rainfall	Godfrey et al. (2015) Papathoma-Köhle et al. (2023) Papathoma-Köhle et al. (2017) Papathoma-Köhle (2016) Papathoma-Köhle et al. (2019b)
Roof material	6	Wildfire Windstorm Hail Landslide Flood Heavy rainfall	Papathoma-Köhle et al. (2022b) Papathoma-Köhle et al. (2023) Papathoma-Köhle et al. (2025) Papathoma-Köhle et al. (2017) Çal and Ciravoğlu (2025)
Glazing type of window/Door or window material	5	Landslide Heavy rainfall Wildfire Windstorm Hail	Papathoma-Köhle et al. (2023) Papathoma-Köhle et al. (2025) Papathoma-Köhle et al. (2017)
Type of surrounding vegetation/Vegetation density	5	heatwave Wildfire Landslide Dynamic flooding	Galderisi and Limongi (2021) Papathoma-Köhle et al. (2025) Papathoma-Köhle et al. (2017) Papathoma-Köhle et al. (2019b)

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Indicator	Number of hazards	Hazard contexts	Reference
		Flood	
Building orientation/Building alignment	4	Landslide Flood Tsunami Dynamic flooding	Agliata et al. (2021) Agliata et al. (2022) Harb et al. (2015) Papathoma-Köhle et al. (2019a) Papathoma-Köhle et al. (2017) Papathoma-Köhle et al. (2019b) Papathoma-Köhle et al. (2022a) Çal and Ciravoğlu (2025)
Construction year/Building age/Period of construction/ Period of design and construction/Age of building or ratio of service years to design service life/Service year	4	Earthquake Flood Dynamic flooding Landslide	D'Amico et al. (2016) Tascón-González et al. (2024) Taramelli et al. (2022) Leal et al. (2021) Galderisi and Limongi (2021) Harb et al. (2015) Xofi et al. (2022) Pereira et al. (2020) Puissant et al. (2014) Skoulidou and Kazantzi (2024) Papathoma-Köhle et al. (2017) Gerçek and Güven (2023) Çal and Ciravoğlu (2025)
Location relative to adjacent buildings/Building neighbourhood/Neighbouring structures/Building density/Distance to neighbouring buildings	4	Earthquake Wildfire Landslide Flood	D'Amico et al. (2016) Harb et al. (2015) Papathoma-Köhle et al. (2022b) Xofi et al. (2022) Pereira et al. (2020) Papathoma-Köhle et al. (2025) Salvati et al. (2021) Çal and Ciravoğlu (2025) Gerçek and Güven (2023)
Roof overhang (length)	4	Windstorm Wildfire Hail Heavy rainfall	Papathoma-Köhle et al. (2023) Papathoma-Köhle et al. (2025)
Structural typology/Structure type/Structural system/ Construction system	4	Earthquake Landslide Flood Wildfire	D'Amico et al. (2016) Agliata et al. (2021) Agliata et al. (2022) Galderisi and Limongi (2021) Papathoma-Köhle et al. (2022b) Xofi et al. (2022) Godfrey et al. (2015) Uzielli et al. (2008) Çal and Ciravoğlu (2025) Gerçek and Güven (2023)
Basement openings (windows and doors)	3	Landslide Dynamic flooding Flood	Papathoma-Köhle et al. (2017) Papathoma-Köhle (2016) Papathoma-Köhle et al. (2019b) Çal and Ciravoğlu (2025)
Building shape/Footprint/Ground plan layout/Geometry/ Building configuration	3	Earthquake Tsunami Dynamic flooding	Harb et al. (2015) Xofi et al. (2022) Papathoma-Köhle et al. (2019a) Papathoma-Köhle et al. (2019b) Gerçek and Güven (2023)
Building type/Use/Function	3	Dynamic flooding Landslide Flood	Taramelli et al. (2022) Kappes et al. (2012) Puissant et al. (2014) Papathoma-Köhle et al. (2017) Çal and Ciravoğlu (2025)
Distance to the hazard source (river/water, slope or forest)	3	Flood Wildfire Landslide	Çal and Ciravoğlu (2025) Papathoma-Köhle et al. (2025) Godfrey et al. (2015)
Foundation type/Material	3	Tsunami Flood Landslide	Godfrey et al. (2015) Papathoma-Köhle et al. (2019a) Papathoma-Köhle et al. (2017) Çal and Ciravoğlu (2025)
Height of openings/Ground floor windows or doors	3	Landslide Flood Dynamic flooding	Papathoma-Köhle (2016) Papathoma-Köhle et al. (2017) Salvati et al. (2021)

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Indicator	Number of hazards	Hazard contexts	Reference
			Papathoma-Köhle et al. (2022a)
Openings towards hazards (e.g. river or slope side)	3	Dynamic flooding Flood Landslide	Leal et al. (2021) Godfrey et al. (2015) Papathoma-Köhle et al. (2017) Papathoma-Köhle (2016) Papathoma-Köhle et al. (2019b)
Presence and state of the balcony (e.g. fenestration, shutter etc.)	3	Windstorm Heavy rainfall Hail	Papathoma-Köhle et al. (2023)
Presence and state of the gutter/Functioning stormwater-drainage-system	3	Heavy rainfall Flood Landslide	Papathoma-Köhle et al. (2023) Salvati et al. (2021) Çal and Ciravoğlu (2025)
Presence and type of shutter	3	Windstorm Hail Wildfire	Papathoma-Köhle et al. (2023) Papathoma-Köhle et al. (2025)
Presence of in between buildings/Existence of adjacent auxiliary buildings (e.g. garden sheds, garage, etc.)/Annexed structures	3	Flood Landslide Dynamic flooding	Godfrey et al. (2015) Papathoma-Köhle et al. (2017) Papathoma-Köhle et al. (2019b) Salvati et al. (2021) Çal and Ciravoğlu (2025)
Roof slope	3	Windstorm Landslide Heavy rainfall	Papathoma-Köhle et al. (2023) Papathoma-Köhle et al. (2017)
Surrounding wall height	3	Landslide Flood Dynamic flooding	Papathoma-Köhle et al. (2017) Papathoma-Köhle et al. (2019b) Papathoma-Köhle et al. (2022a) Çal and Ciravoğlu (2025)
Surrounding wall material	3	Flood Dynamic flooding Landslide	Papathoma-Köhle et al. (2022a) Papathoma-Köhle et al. (2017) Papathoma-Köhle et al. (2019b) Çal and Ciravoğlu (2025)
Terrain slope/Building located on slope/Steepness of the ground/Terrain topography	3	Wildfire Dynamic flooding Flood	Papathoma-Köhle et al. (2022b) Godfrey et al. (2015) Papathoma-Köhle et al. (2019b) Papathoma-Köhle et al. (2025) Çal and Ciravoğlu (2025)
Accessible from only(?) one way	2	Flood Landslide	Salvati et al. (2021)
Below or semi-below grade of basements	2	Flood Landslide	Salvati et al. (2021)
Boulders near the building	2	Flood Landslide	Salvati et al. (2021)
Building Envelope – Exterior wall material or type	2	Flood Landslide	Çal and Ciravoğlu (2025) Godfrey et al. (2015)
Building occupancy (class)	2	Landslide Flood	Salvati et al. (2021)
Building row towards hazard zone (slope, river, torrent) (first row, second row, etc.)	2	Landslide Dynamic flooding	Kappes et al. (2012) Papathoma-Köhle et al. (2017) Papathoma-Köhle (2016) Papathoma-Köhle et al. (2019b) Papathoma-Köhle et al. (2022a)
Building size/Building compactness	2	Flood Landslide	Godfrey et al. (2015) Papathoma-Köhle et al. (2017)
Cracks in the structure/Warning signs of hazard influence	2	Flood Landslide	Godfrey et al. (2015) Salvati et al. (2021)
Damage of retaining-wall	2	Flood Landslide	Salvati et al. (2021)
Drainage-system-work maintenance-status	2	Flood Landslide	Salvati et al. (2021)
Elevation of pedestrian/driveway access respect ground level	2	Flood Landslide	Salvati et al. (2021) Çal and Ciravoğlu (2025)
Facade/Cladding	2	Wildfire Flood	Papathoma-Köhle et al. (2025) Çal and Ciravoğlu (2025)
First or second or third-driveway-access	2	Flood Landslide	Salvati et al. (2021)
First or second or third-pedestrian-access	2	Flood Landslide	Salvati et al. (2021)
Flood mitigation maintenance-status	2	Flood Landslide	Salvati et al. (2021)

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Indicator	Number of hazards	Hazard contexts	Reference
Flood protection measures (e.g. Flood vents, Flood barrier)	2	Flood Landslide	Salvati et al. (2021) Çal and Ciravoğlu (2025)
Floor height from ground level/Raised 1st floor	2	Dynamic flooding Flood	Godfrey et al. (2015) Papathoma-Köhle et al. (2019b) Salvati et al. (2021) Çal and Ciravoğlu (2025)
Floor material	2	Landslide Flood	Papathoma-Köhle et al. (2017) Çal and Ciravoğlu (2025)
Foundation depth	2	Flood Landslide	Godfrey et al. (2015) Papathoma-Köhle et al. (2017)
Ground floor hydrodynamics (Completely open plan, e.g. no walls, only columns vs. Completely closed plan)/ Ground floor wall openness/Solid ratio	2	Tsunami Flood	Papathoma-Köhle et al. (2019a) Çal and Ciravoğlu (2025)
Ground floor watertight door	2	Flood Landslide	Salvati et al. (2021)
Ground-cracks/Number-of-ground-cracks	2	Flood Landslide	Salvati et al. (2021)
Height/floor area ratio	2	Earthquake Flood	Gerçek and Güven (2023) Çal and Ciravoğlu (2025)
Natural or artificial embankment/protection	2	Dynamic flooding Flood	Papathoma-Köhle et al. (2019b) Çal and Ciravoğlu (2025)
Number of facades with large openings	2	Landslide Flood	Agliata et al. (2021) Agliata et al. (2022)
Number of openings (doors and windows)	2	Flood Landslide	Godfrey et al. (2015) Salvati et al. (2021) Çal and Ciravoğlu (2025)
Permeable surface ratio/Green area ratio	2	Landslide Flood	Galderisi and Limongi (2021) Çal and Ciravoğlu (2025)
Position respect free or buried watercourse	2	Flood Landslide	Salvati et al. (2021)
Protruding parts	2	Landslide Dynamic flooding	Papathoma-Köhle et al. (2017) Papathoma-Köhle et al. (2019b)
Quality of construction/Building structure	2	Flood Landslide	Godfrey et al. (2015)
Roof type/Roof shape/Roof structure	2	Wildfire Flood	Harb et al. (2015) Papathoma-Köhle et al. (2022b) Papathoma-Köhle et al. (2023) Papathoma-Köhle et al. (2025) Çal and Ciravoğlu (2025)
State of non-structural elements	2	Windstorm Hail	Papathoma-Köhle et al. (2023)
Strategic building	2	Flood Landslide	Salvati et al. (2021)
Trees towards hazard zone (slope, river, torrent)	2	Landslide Flood	Kappes et al. (2012)
Type of property	2	Flood Landslide	Salvati et al. (2021)
Use of first floor/Ground floor for residential use	2	Landslide Flood	Papathoma-Köhle et al. (2017) Salvati et al. (2021)
Wall around the building (yes/no)	2	Flood Landslide	Godfrey et al. (2015)
Width-ground-crack	2	Flood	Salvati et al. (2021)
Width-main-cracks	2	Flood	Salvati et al. (2021)
Areaway sizes	1	Flood	Çal and Ciravoğlu (2025)
Basement floor facade (wall) opening	1	Flood	Çal and Ciravoğlu (2025)
Basement floor size	1	Flood	Çal and Ciravoğlu (2025)
Border wall aperture	1	Flood	Çal and Ciravoğlu (2025)
Building coverage ratio	1	Flood	Çal and Ciravoğlu (2025)
Building density	1	Dynamic flooding	Harb et al. (2015) Papathoma-Köhle et al. (2019b)
Building envelope – Exterior wall insulation	1	Flood	Çal and Ciravoğlu (2025)
Building structural – System cladding	1	Flood	Çal and Ciravoğlu (2025)
Building structural – System insulation	1	Flood	Çal and Ciravoğlu (2025)
Building structural – System joints	1	Flood	Çal and Ciravoğlu (2025)
Burnt vegetation	1	Wildfire	Papathoma-Köhle et al. (2022b)
Combustible materials and objects	1	Wildfire	Papathoma-Köhle et al. (2025)
Condition/location of water supply network	1	Landslide	Papathoma-Köhle et al. (2017)
Distance of tree crowns/vegetation	1	Wildfire	Papathoma-Köhle et al. (2025)

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Indicator	Number of hazards	Hazard contexts	Reference
Engineering-based state of the building (Code based or not)	1	Windstorm	Papathoma-Köhle et al. (2023)
Evacuation possibility	1	Landslide	Papathoma-Köhle (2016)
Existence of mitigation measures (in the area)	1	Landslide	Papathoma-Köhle et al. (2017)
Exterior wall joints	1	Flood	Çal and Ciravoğlu (2025)
Fixed furnishing body height	1	Flood	Çal and Ciravoğlu (2025)
Fixed furnishing body material	1	Flood	Çal and Ciravoğlu (2025)
Floor covering	1	Flood	Çal and Ciravoğlu (2025)
Floor insulation	1	Flood	Çal and Ciravoğlu (2025)
Flooring type	1	Flood	Çal and Ciravoğlu (2025)
Forest type	1	Wildfire	Papathoma-Köhle et al. (2025)
Foundation insulation	1	Flood	Çal and Ciravoğlu (2025)
Ground floor and over-hanging tree (No of floors more than ground floor, Ground floor building with tangent trees, Ground floor building with overhanging tree)	1	Wildfire	Papathoma-Köhle et al. (2022b)
Installation control points	1	Flood	Çal and Ciravoğlu (2025)
Installation system (gas, air cond., water and electricity, meter, fuse, socket)	1	Flood	Çal and Ciravoğlu (2025)
Interior wall cladding	1	Flood	Çal and Ciravoğlu (2025)
Interior wall material	1	Flood	Çal and Ciravoğlu (2025)
Location of heating central appliance	1	Landslide	Papathoma-Köhle et al. (2017) Papathoma-Köhle (2016)
Location of the electricity central appliance	1	Landslide	Papathoma-Köhle et al. (2017) Papathoma-Köhle (2016)
Main ground covering/Land cover (the area around the building)	1	Wildfire	Papathoma-Köhle et al. (2022b) Papathoma-Köhle et al. (2025)
Maintenance and condition of electricity network	1	Landslide	Papathoma-Köhle et al. (2017)
Maintenance and condition of heating system	1	Landslide	Papathoma-Köhle et al. (2017)
Maintenance and condition of sewage system	1	Landslide	Papathoma-Köhle et al. (2017)
Number of occupied floors	1	Landslide	Puissant et al. (2014)
Presence and state of the intersections’ waterproofing	1	Heavy rainfall	Papathoma-Köhle et al. (2023)
Property boundary	1	Wildfire	Papathoma-Köhle et al. (2025)
Protective strips/Firebreaks	1	Wildfire	Papathoma-Köhle et al. (2025)
Quality of openings	1	Dynamic flooding	Papathoma-Köhle et al. (2019b)
Rockfall-mitigation-work	1	Landslide	Salvati et al. (2021)
Rockfall-mitigation-work maintenance-status	1	Landslide	Salvati et al. (2021)
Roof condition (maintenance)	1	Landslide	Papathoma-Köhle et al. (2017)
Roof covering	1	Flood	Çal and Ciravoğlu (2025)
Roof insulation	1	Flood	Çal and Ciravoğlu (2025)
Secondary ground covering	1	Wildfire	Papathoma-Köhle et al. (2022b)
Slope-retaining-reinforced	1	Landslide	Salvati et al. (2021)
Slope-retaining-reinforced maintenance-status	1	Landslide	Salvati et al. (2021)
Slope-stabilization-work	1	Landslide	Salvati et al. (2021)
Slope-stabilization-work maintenance-status	1	Landslide	Salvati et al. (2021)
Surroundings (wall or vegetation)	1	Landslide	Papathoma-Köhle (2016)
Wall thickness	1	Dynamic flooding	Papathoma-Köhle et al. (2019b)
Water sources	1	Wildfire	Papathoma-Köhle et al. (2025)
Footprint irregularity	0	none given	Harb et al. (2015)

Appendix B. List of scientific publications analysed in this systematic literature review

Author(s)	Publication year	Title
Agliata, R.; Bortone, A.; Mollo, L.	2021	Indicator-based approach for the assessment of intrinsic physical vulnerability of the built environment to hydro-meteorological hazards: Review of indicators and example of parameters selection for a sample area
Agliata, R.; Bortone, A.; Mollo, L.	2022	The impact of the aggregation formula on indicator-based method for the assessment of building susceptibility to hydro-meteorological hazards
Çal, İ.; Ciravoğlu, A.	2025	Determining Vulnerability Indicators of Buildings for Sea-Level Rise and Floods in Urban Coastal Areas
D’Amico, S.; Meroni, F.; Sousa, M.L.; Zonno, G.	2016	Building vulnerability and seismic risk analysis in the urban area of Mt. Etna volcano (Italy)
Galderisi, A.; Limongi, G.	2021	A Comprehensive Assessment of Exposure and Vulnerabilities in Multi-Hazard Urban Environments: A Key Tool for Risk-Informed Planning Strategies

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Author(s)	Publication year	Title
Gerçek, D.; Güven, İ.T.	2023	Urban Earthquake Vulnerability Assessment and Mapping at the Microscale Based on the Catastrophe Progression Method
Godfrey, A.; Ciurean, R.L.; van Westen, C.J.; Kingma, N.C.; Glade, T.	2015	Assessing vulnerability of buildings to hydro-meteorological hazards using an expert based approach - An application in Nehoiu Valley, Romania
Harb, M.M.; De Vecchi, D.; Dell'Acqua, F.	2015	Physical vulnerability proxies from remotes sensing: Reviewing, implementing and disseminating selected techniques
Kappes, M.S.; Papathoma-Köhle, M.; Keiler, M.	2012	Assessing physical vulnerability for multi-hazards using an indicator-based methodology
Leal, M.; Reis, E.; Pereira, S.; Santos, P.P.	2021	Physical vulnerability assessment to flash floods using an indicator-based methodology based on building properties and flow parameters
Papathoma-Köhle, M.	2016	Vulnerability curves vs. Vulnerability indicators: Application of an indicator-based methodology for debris-flow hazards
Papathoma-Köhle, M.; Gems, B.; Sturm, M.; Fuchs, S.	2017	Matrices, curves and indicators: A review of approaches to assess physical vulnerability to debris flows
Papathoma-Köhle, M.; Schlögl, M.; Dosser, L.; Roesch, F.; Borga, M.; Erlicher, M.; Keiler, M.; Fuchs, S.	2022	Physical vulnerability to dynamic flooding: Vulnerability curves and vulnerability indices
Papathoma-Köhle, M.; Schlögl, M.; Fuchs, S.	2019	Vulnerability indicators for natural hazards: an innovative selection and weighting approach
Papathoma-Köhle, M.; Schlögl, M.; Garlichs, C.; Diakakis, M.; Mavroulis, S.; Fuchs, S.	2022	A wildfire vulnerability index for buildings
Papathoma-Köhle, M.; Cristofari, G.; Wenk, M.; Fuchs, S.	2019	The importance of indicator weights for vulnerability indices and implications for decision making in disaster management
Papathoma-Köhle, M.; Ghazanfari, A.; Mariacher, R.; Huber, W.; Lücksmann, T.; Fuchs, S.	2023	Vulnerability of Buildings to Meteorological Hazards: A Web-Based Application Using an Indicator-Based Approach
Papathoma-Köhle, M.; Hausharter, D.; Schlögl, M.; Fuchs, S.	2025	Towards a wildfire vulnerability index using expert judgement
Pereira, S.; Santos, P.P.; Zêzere, J.L.; Tavares, A.O.; Garcia, R.A.C.; Oliveira, S.C.	2020	A landslide risk index for municipal land use planning in Portugal
Puissant, A; Van Den Eeckhaut, M; Malet, JP; Maquaire, O.	2014	Landslide consequence analysis: a region-scale indicator-based methodology
Salvati, P.; Ardizzone, F.; Cardinali, M.; Fiorucci, F.; Fugnoli, F.; Guzzetti, F.; Marchesini, I.; Rinaldi, G.; Rossi, M.; Santangelo, M.; Vujica, I.	2021	Acquiring vulnerability indicators to geo-hydrological hazards: An example of mobile phone-based data collection
Skoulidou, D.; Kazantzi, A.K.	2024	Indicator-based risk assessments for urban hazard resilience: an application for flash floods
Taramelli, A.; Righini, M.; Valentini, E.; Alfieri, L.; Gatti, I.; Gabellani, S.	2022	Building-scale flood loss estimation through vulnerability pattern characterisation: application to an urban flood in Milan, Italy
Tascón-González, L.; Ferrer-Julià, M.; García-Meléndez, E.	2024	Methodological approach for mapping the flood physical vulnerability index with geographical open-source data: an example in a small-middle city (Ponferrada, Spain)
Uzielli, M.; Nadim, F.; Lacasse, S.; Kaynia, A.M.	2008	A conceptual framework for quantitative estimation of physical vulnerability to landslides
Xofi, M.; Domingues, J.C.; Santos, P.P.; Pereira, S.; Oliveira, S.C.; Reis, E.; Zêzere, J.L.; Garcia, R.A.C.; Lourenço, P.B.; Ferreira, T.M.	2022	Exposure and physical vulnerability indicators to assess seismic risk in urban areas: a step towards a multi-hazard risk analysis

Appendix C. Search strings used for Scopus and WoS

C.1. Search string used for Scopus

TITLE-ABS-KEY (("Building vulnerabilities" OR "Building vulnerability" OR "built environment vulnerabilities " OR "built environment vulnerability" OR "physical vulnerability" OR "physical vulnerabilities" OR "Building susceptibility" OR "built environment susceptibility" OR "Building Robustness" OR "built environment Robustness" OR "structural vulnerability") AND indicator* AND ("cold wave" OR drought OR earthquake OR flood OR heatwave OR landslide OR tsunami OR wildfire OR "disaster risk" OR "natural hazard*" OR "hydro-meteorological hazard*" OR hazard*)) AND (LIMIT-TO (DOCTYPE, "re") OR LIMIT-TO (DOCTYPE, "ar"))

C.2. Search string used for WoS

TS= (("Building vulnerabilities" OR "Building vulnerability" OR "built environment vulnerabilities " OR "built environment vulnerability" OR "physical vulnerability" OR "physical vulnerabilities" OR "Building susceptibility" OR "built environment susceptibility" OR "Building Robustness" OR "built environment Robustness" OR "structural vulnerability") AND indicator* AND ("cold wave" OR drought OR earthquake OR flood OR heatwave OR landslide OR tsunami OR wildfire OR "disaster risk" OR "natural hazard*" OR "hydro-meteorological hazard*" OR hazard*))

Data availability

The data that support the findings of this study are openly available in the Zenodo repository at https://doi.org/10.5281/zenodo.21376830.

References

Agliata, R., Bortone, A., Mollo, L., 2021. Indicator-based approach for the assessment of intrinsic physical vulnerability of the built environment to hydro-meteorological hazards: Review of indicators and example of parameters selection for a sample area. Int. J. Disaster Risk Reduct. 58. https://doi.org/10.1016/j.ijdrr.2021.102199.

Agliata, R., Bortone, A., Mollo, L., 2022. The impact of the aggregation formula on indicator-based method for the assessment of building susceptibility to hydro-meteorological hazards. Int. J. Disaster Risk Reduct. 72. https://doi.org/10.1016/j.ijdrr.2022.102850.

Amirebrahimi, S., Rajabifard, A., Mendis, P., Ngo, T., 2016. A framework for a microscale flood damage assessment and visualization for a building using BIM–GIS integration. Int. J. Digit. Earth 9, 363–386. https://doi.org/10.1080/17538947.2015.1034201.

Antofie, T.-E., Luoni, S., Tilloy, A., Sibilia, A., Salari, S., Eklund, G., Rodomonti, D., Bountzouklis, C., Corbane, C., 2025. Spatial identification of regions exposed to multi-hazards at the pan-European level. Nat. Hazards Earth Syst. Sci. 25, 287–304. https://doi.org/10.5194/nhess-25-287-2025.

Ballester, J., Quijal-Zamorano, M., Méndez Turrubiates, R.F., Pegenaute, F., Herrmann, F.R., Robine, J.M., Basagaña, X., Tonne, C., Antó, J.M., Achebak, H., 2023. Heat-related mortality in Europe during the summer of 2022. Nat. Med. 29, 1857–1866. https://doi.org/10.1038/s41591-023-02419-z.

Becker, W., Saisana, M., Paruolo, P., Vandecasteele, I., 2017. Weights and importance in composite indicators: closing the gap. Ecol. Indic. 80, 12–22. https://doi.org/10.1016/j.ecolind.2017.03.056.

Birkmann, J., 2006. Indicators and criteria for measuring vulnerability: theoretical bases and requirements. In: Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies. United Nations Univ. Press, Tokyo, pp. 55–77.

Bruno, N., Rechichi, F., Achille, C., Zerbi, A., Roncella, R., Fassi, F., 2020. Integration of historical GIS data in a HBIM system. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XLIII-B4-2020 427–434. https://doi.org/10.5194/isprs-archives-XLIII-B4-2020-427-2020.

Büyüközkan, G., Ilıcak, Ö., Feyzioğlu, O., 2022. A review of urban resilience literature. Sustain. Cities Soc. 77, 103579. https://doi.org/10.1016/j.scs.2021.103579.

Çal, İ., Ciravoğlu, A., 2025. Determining vulnerability indicators of buildings for sea-level rise and floods in urban coastal areas. Sustainability 17. https://doi.org/10.3390/su17010027.

Cao, Y., Xu, C., Aziz, N.M., Kamaruzzaman, S.N., 2023. BIM–GIS integrated utilization in urban disaster management: the contributions, challenges, and future directions. Remote Sens. 15, 1331. https://doi.org/10.3390/rs15051331.

Cerè, G., Rezgui, Y., Zhao, W., 2017. Critical review of existing built environment resilience frameworks: directions for future research. Int. J. Disaster Risk Reduct. 25, 173–189. https://doi.org/10.1016/j.ijdrr.2017.09.018.

D'Amico, S., Meroni, F., Sousa, M.L., Zonno, G., 2016. Building vulnerability and seismic risk analysis in the urban area of Mt. Etna volcano (Italy). Bull. Earthq. Eng. 14, 2031–2045. https://doi.org/10.1007/s10518-015-9804-4.

Daud, M., Ugliotti, F.M., Osello, A., 2024. Comprehensive analysis of the use of web-GIS for natural hazard management: a systematic review. Sustainability 16, 4238. https://doi.org/10.3390/su16104238.

de Ruiter, M., Ward, P., Daniell, J., Aerts, J., 2017. A comparison of flood and earthquake vulnerability assessment indicators. Nat. Hazards Earth Syst. Sci. 17, 1231–1251. https://doi.org/10.5194/nhess-17-1231-2017.

De Ruiter, M.C., Couasnon, A., Van Den Homberg, M.J.C., Daniell, J.E., Gill, J.C., Ward, P.J., 2020. Why we can no longer ignore consecutive disasters. Earths Fut. 8. https://doi.org/10.1029/2019ef001425.

Deng, Z., Hijazi, I., Kolbe, T.H., 2025. CityGML 3.0 as a hub: integrating BIM, GIS, and point cloud data for 3D streetspace modeling comprising roads, bridges and tunnels. ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. X-4/W6-2025 65–72. https://doi.org/10.5194/isprs-annals-X-4-W6-2025-65-2025.

Desouza, K.C., Flanery, T.H., 2013. Designing, planning, and managing resilient cities: a conceptual framework. Cities 35, 89–99. https://doi.org/10.1016/j.cities.2013.06.003.

Dimyadi, J., Pauwels, P., Amor, R., 2016. Modelling and accessing regulatory knowledge for computer-assisted compliance audit. ITcon 21, 317–336.

Donkers, S., Ledoux, H., Zhao, J., Stoter, J., 2016. Automatic conversion of IFC datasets to geometrically and semantically correct CityGML LOD3 buildings. Trans. GIS 20, 547–569. https://doi.org/10.1111/tgis.12162.

El-Mekawy, M., Östman, A., Hijazi, I., 2012. A unified building model for 3D urban GIS. ISPRS Int. J. Geo-Inf. 1, 120–145. https://doi.org/10.3390/ijgi1020120.

Endendijk, T., Botzen, W.J.W., De Moel, H., Aerts, J.C.J.H., Slager, K., Kok, M., 2023. Flood vulnerability models and household flood damage mitigation measures: an econometric analysis of survey data. Water Resour. Res. 59, e2022WR034192. https://doi.org/10.1029/2022WR034192.

European Commission, Directorate-General for European Civil Protection and Humanitarian Aid Operations E.C.H.O., 2021. Overview of natural and man-made disaster risks the European Union may face, 2020. Publications Office of the European Union. https://doi.org/10.2795/1521.

European Environment Agency (EEA), 2021. Europe's changing climate hazards. An index-based interactive EEA report. https://doi.org/10.2800/458052.

European Environment Agency (EEA), 2024. European Climate Risk Assessment. Publications Office of the European Union. https://doi.org/10.2800/8671471.

Fekete, A., Neuner, S., Munschauer, C., Buzna, L., Chovanec, D., Holla, K., Kockar, S., Leopold, U., Stellacci, S., Yilmaz, D., Da Silva, C.F., 2025. An upscaling multi-level and multi-hazard risk assessment for heat and other natural hazards concerning vulnerable groups in Žilina, Slovakia. Nat. Hazards. https://doi.org/10.1007/s11069-025-07722-1.

Flanagan, B.E., Gregory, E.W., Hallisey, E.J., Heitgerd, J.L., Lewis, B., 2011. A social vulnerability index for disaster management. J. Homel. Secur. Emerg. Manag. 8. https://doi.org/10.2202/1547-7355.1792.

Forzieri, G., Feyen, L., Russo, S., Vousdoukas, M., Alfieri, L., Outten, S., Migliavacca, M., Bianchi, A., Rojas, R., Cid, A., 2016. Multi-hazard assessment in Europe under climate change. Clim. Change 137, 105–119. https://doi.org/10.1007/s10584-016-1661-x.

Fuchs, S., Frazier, T., Siebeneck, L., 2018. Physical vulnerability. In: Fuchs, S., Thaler, T. (Eds.), Vulnerability and Resilience to Natural Hazards. Cambridge University Press, Cambridge, pp. 32–52.

Galderisi, A., Limongi, G., 2021. A comprehensive assessment of exposure and vulnerabilities in multi-hazard urban environments: a key tool for risk-informed planning strategies. Sustainability 13. https://doi.org/10.3390/su13169055.

Gebbeken, N., Videkhina, I., Pfeiffer, E., Garsch, M., Rüdiger, L., 2016. Risikobewertung und Schutz von baulichen Infrastrukturen bei Hochwassergefahr. Bautechnik 93, 199–213. https://doi.org/10.1002/bate.201600003.

Gerçek, D., Güven, İ.T., 2023. Urban earthquake vulnerability assessment and mapping at the microscale based on the catastrophe progression method. Int. J. Disaster Risk Sci. 14, 768–781. https://doi.org/10.1007/s13753-023-00512-y.

Gill, J.C., Malamud, B.D., 2014. Reviewing and visualizing the interactions of natural hazards: interactions of natural hazards. Rev. Geophys. 52, 680–722. https://doi.org/10.1002/2013RG000445.

Gill, J.C., Duncan, M., Ciurean, R., Smale, L., Stuparu, D., Schlumberger, J., de Ruiter, M., Tiggeloven, T., Torresan, S., Gottardo, S., Mysiak, J., Harris, R., Petrescu, E.-C., Girard, T., Khazai, B., Claassen, J., Dai, R., Champion, A., Daloz, A.S., Cipollone Blanco, F., Torres Campillo, C., Antolin Palomino, I., Ferrario, D., Tatman, S., Tjssen, A., Vaidya, S., Adesiyun, A., Goger, T., Angiuli, A., Audren, M., Machado, M., Hochrainer-Stigler, S., Šakić Trogrlić, R., Daniell, J., Bulder, B., Krishna Swamy, S., Wiggelinkhuizen, E.-J., Pacheco, J.D., Appulo, L., Orth, R., Sillmann, J., Ward, P., 2022. D1.2 Handbook of Multi-hazard, Multi-Risk Definitions and Concepts. https://doi.org/10.5281/ZENODO.7870260.

Godfrey, A., Ciurean, R.L., van Westen, C.J., Kingma, N.C., Glade, T., 2015. Assessing vulnerability of buildings to hydro-meteorological hazards using an expert based approach - an application in Nehoiu Valley, Romania. Int. J. Disaster Risk Reduct. 13, 229–241. https://doi.org/10.1016/j.ijdrr.2015.06.001.

Godschalk, D.R., 2003. Urban hazard mitigation: creating resilient cities. Nat. Hazards Rev. 4, 136–143. https://doi.org/10.1061/(ASCE)1527-6988(2003)4:3(136).
Granger, K., Jones, T., Leiba, M., Scott, G., 1999. Community Risk in Cairns. A Multi-Hazard Risk Assessment, Cities Project. Australian Geological Survey Organisation.
Hamdy, M., Carlucci, S., Hoes, P.-J., Hensen, J.L.M., 2017. The impact of climate change on the overheating risk in dwellings—a Dutch case study. Build. Environ. 122, 307–323. https://doi.org/10.1016/j.buildenv.2017.06.031.
Harb, M.M., De Vecchi, D., Dell'Acqua, F., 2015. Physical vulnerability proxies from remotes sensing: Reviewing, implementing and disseminating selected techniques. IEEE Geosci. Remote Sens. Mag. 3, 20–33. https://doi.org/10.1109/MGRS.2015.2398672.
Hayles, C.S., Huddleston, M., Chinowsky, P., Helman, J., 2022. Summertime impacts of climate change on dwellings in Wales, UK. Build. Environ. 219, 109185. https://doi.org/10.1016/j.buildenv.2022.109185.
IPCC, 2023. Climate change 2023: synthesis report. In: Core Writing Team, Lee, H., Romero, J. (Eds.), Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Geneva, Switzerland.
Ji, Y., Wang, Y., Wei, Y., Wang, J., Yan, W., 2024. An ontology-based rule mapping approach for integrating IFC and CityGML. Trans. GIS 28, 675–696. https://doi.org/10.1111/tgis.13155.
JRC, 2020. Climate Change Impacts and Adaptation in Europe: JRC PESETA IV Final Report. European Commission. Joint Research Centre. Publications Office, LU.
Kang, T.W., Hong, C.H., 2015. A study on software architecture for effective BIM/GIS-based facility management data integration. Autom. Constr. 54, 25–38. https://doi.org/10.1016/j.autcon.2015.03.019.
Kappes, M.S., Papathoma-Köhle, M., Keiler, M., 2012. Assessing physical vulnerability for multi-hazards using an indicator-based methodology. Appl. Geogr. 32, 577–590. https://doi.org/10.1016/j.apgeog.2011.07.002.
Khanmohammadi, S., Arashpour, M., Bai, Y., 2020. Applications of building information modeling (BIM) in disaster resilience: present status and future trends. In: Presented at the ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction. IAARC Publications, pp. 1380–1387.
Kochskämper, E., Glass, L.-M., Haupt, W., Malekpour, S., Grainger-Brown, J., 2025. Resilience and the sustainable development goals: a scrutiny of urban strategies in the 100 resilient cities initiative. J. Environ. Plan. Manag. 68, 1691–1717. https://doi.org/10.1080/09640568.2023.2297648.
Kodur, V., Kumar, P., Rafi, M.M., 2019. Fire hazard in buildings: review, assessment and strategies for improving fire safety. PSU Res. Rev. 4, 1–23. https://doi.org/10.1108/PRR-12-2018-0033.
Kohler, N., 2018. From the design of green buildings to resilience management of building stocks. Build. Res. Inf. 46, 578–593. https://doi.org/10.1080/09613218.2017.1356122.
Kousky, C., You, X., 2024. The role of insurers in driving post-hurricane risk reduction investments. Npj Nat. Hazards 1, 36. https://doi.org/10.1038/s44304-024-00035-6.
Kutzner, T., Chaturvedi, K., Kolbe, T.H., 2020. CityGML 3.0: new functions open up new applications. PFG – J. Photogramm. Remote Sens. Geoinformation Sci. 88, 43–61. https://doi.org/10.1007/s41064-020-00095-z.
Lak, A., Hasankhan, F., Garakani, S.A., 2020. Principles in practice: toward a conceptual framework for resilient urban design. J. Environ. Plan. Manag. 63, 2194–2226. https://doi.org/10.1080/09640568.2020.1714561.
Lazzati, M., De Angeli, S., Boni, G., Cattari, S., Romão, X., 2023. Definition of multi-hazard vulnerability indicators for cultural heritage buildings. In: Presented at the 9th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering Methods in Structural Dynamics and Earthquake Engineering, Athens, Greece, pp. 2709–2724. https://doi.org/10.7712/120123.10595.20690.
Leal, M., Reis, E., Pereira, S., Santos, P.P., 2021. Physical vulnerability assessment to flash floods using an indicator-based methodology based on building properties and flow parameters. J. Flood Risk Manag. 14. https://doi.org/10.1111/jfr3.12712.
Lee, R., White, C.J., Adnan, M.S.G., Douglas, J., Mahecha, M.D., O'Loughlin, F.E., Patelli, E., Ramos, A.M., Roberts, M.J., Martius, O., Tubaldi, E., Van Den Hurk, B., Ward, P.J., Zscheischler, J., 2024. Reclassifying historical disasters: from single to multi-hazards. Sci. Total Environ. 912, 169120. https://doi.org/10.1016/j.scitotenv.2023.169120.
Liu, X., Wang, X., Wright, G., Cheng, J., Li, X., Liu, R., 2017. A state-of-the-art review on the integration of building information modeling (BIM) and geographic information system (GIS). ISPRS Int. J. Geo-Inf. 6, 53. https://doi.org/10.3390/ijgi6020053.
Liu, X., Antwi-Afari, M.F., Li, J., Zhang, Y., Manu, P., 2025. BIM, IoT, and GIS integration in construction resource monitoring. Autom. Constr. 174, 106149. https://doi.org/10.1016/j.autcon.2025.106149.
Malgwi, M.B., Fuchs, S., Keiler, M., 2020. A generic physical vulnerability model for floods: review and concept for data-scarce regions. Nat. Hazards Earth Syst. Sci. 20, 2067–2090. https://doi.org/10.5194/nhess-20-2067-2020.
Marmo, R., Pascale, F., Sicignano, E., 2023. A review of building information modelling applications for disaster resilience assessment. In: Gaspar, F., Mateus, A. (Eds.), Sustainable and Digital Building. Springer International Publishing, Cham, pp. 269–277. https://doi.org/10.1007/978-3-031-25795-7_21.
Matrone, F., Colucci, E., De Ruvo, V., Lingua, A., Spanò, A., 2019. HBIM in a semantic 3D GIS database. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XLII-2/W11 857–865. https://doi.org/10.5194/isprs-archives-XLII-2-W11-857-2019.
Mayouf, M., Sharif, A., Shelbourn, M., 2022. BIM and building resilience: a hybrid mechanism to integrate measures against flooding. In: Construction in the Century (CITC) - 12, 16th - 19th May 2022, Amman, Jordan.
Meerow, S., Newell, J.P., Stults, M., 2016. Defining urban resilience: a review. Landsc. Urban Plan. 147, 38–49. https://doi.org/10.1016/j.landurbplan.2015.11.011.
Moreira, L., de Brito, M., Kobiyama, M., 2021. Review article: a systematic review and future prospects of flood vulnerability indices. Nat. Hazards Earth Syst. Sci. 21, 1513–1530. https://doi.org/10.5194/nhess-21-1513-2021.
Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., 2005. Tools for Composite Indicators Building. (JRC, 2005). (No. EUR 21682 EN). JRC.
Navarro, D., Cantergiani, C., Abajo, B., Gomez De Salazar, I., Feliu, E., 2023. Territorial vulnerability to natural hazards in Europe: a composite indicator analysis and relation to economic impacts. Nat. Hazards. https://doi.org/10.1007/s11069-023-06165-w.
NOTA – Rathenau-Instituut, 1994. Stroomloos: Kwetsbaarheid van de samenleving, gevolgen van verstoringen van de elektriciteitsvoorziening (Blackout. Vulnerability of Society and Impacts of Electricity Supply Failure).
Organisation for Economic Co-operation and Development (Ed.), 2008. Handbook on Constructing Composite Indicators: Methodology and User Guide.
Ordóñez Llancce, A., Lim, Y., Esteban, T.A.O., Van Leeuwen, J., Ninan, J., 2025. From silos to synergy: conceptualizing an integrated infrastructure design for climate resilience in Rotterdam. Clim. Risk Manag. 47, 100691. https://doi.org/10.1016/j.crm.2025.100691.
Ouzzani, M., Hammady, H., Fedorowicz, Z., Elmagarmid, A., 2016. Rayyan—a web and mobile app for systematic reviews. Syst. Rev. 5, 210. https://doi.org/10.1186/s13643-016-0384-4.
Ozarisoy, B., 2022. Energy effectiveness of passive cooling design strategies to reduce the impact of long-term heatwaves on occupants' thermal comfort in Europe: climate change and mitigation. J. Clean. Prod. 330, 129675. https://doi.org/10.1016/j.jclepro.2021.129675.
Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M., Akl, E.A., Brennan, S.E., Chou, R., Glanville, J., Grimshaw, J.M., Hróbjartsson, A., Lalu, M.M., Li, T., Loder, E.W., Mayo-Wilson, E., McDonald, S., McGuinness, L.A., Stewart, L.A., Thomas, J., Tricco, A.C., Welch, V.A., Whiting, P., Moher, D., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ n71. https://doi.org/10.1136/bmj.n71.
Paleo-Torres, A., Zhao, M., Gurley, K., Pinelli, J.-P., Baradaranshoraka, M., 2021. Modeling the influence of flood mitigation measures on the vulnerability of coastal residential construction. Nat. Hazards Rev. 22, 04021040. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000507.
Papathoma, M., Dominey-Howes, D., Zong, Y., Smith, D., 2003. Assessing tsunami vulnerability, an example from Herakleio. Crete. Nat. Hazards Earth Syst. Sci. 3, 377–389. https://doi.org/10.5194/nhess-3-377-2003.
Papathoma-Köhle, M., 2016. Vulnerability curves vs. vulnerability indicators: application of an indicator-based methodology for debris-flow hazards. Nat. Hazards Earth Syst. Sci. 16, 1771–1790. https://doi.org/10.5194/nhess-16-1771-2016.
Papathoma-Köhle, M., Gems, B., Sturm, M., Fuchs, S., 2017. Matrices, curves and indicators: a review of approaches to assess physical vulnerability to debris flows. Earth Sci. Rev. 171, 272–288. https://doi.org/10.1016/j.earscirev.2017.06.007.

Papathoma-Köhle, M., Cristofari, G., Wenk, M., Fuchs, S., 2019a. The importance of indicator weights for vulnerability indices and implications for decision making in disaster management. Int. J. Disaster Risk Reduct. 36, 101103. https://doi.org/10.1016/j.ijdrr.2019.101103.
Papathoma-Köhle, M., Schlögl, M., Fuchs, S., 2019b. Vulnerability indicators for natural hazards: an innovative selection and weighting approach. Sci. Rep. 9. https://doi.org/10.1038/s41598-019-50257-2.
Papathoma-Köhle, M., Schlögl, M., Garlichs, C., Diakakis, M., Mavroulis, S., Fuchs, S., 2022b. A wildfire vulnerability index for buildings. Sci. Rep. 12. https://doi.org/10.1038/s41598-022-10479-3.
Papathoma-Köhle, M., Hausharter, D., Schlögl, M., Fuchs, S., 2025. Towards a wildfire vulnerability index using expert judgement. Int. J. Wildland Fire 34, WF24114. https://doi.org/10.1071/WF24114.
Papathoma-Köhle, M., Schlögl, M., Dosser, L., Roesch, F., Borga, M., Erlicher, M., Keiler, M., Fuchs, S., 2022a. Physical vulnerability to dynamic flooding: vulnerability curves and vulnerability indices. J. Hydrol. 607. https://doi.org/10.1016/j.jhydrol.2022.127501.
Papathoma-Köhle, M., Ghazanfari, A., Mariacher, R., Huber, W., Lücksmann, T., Fuchs, S., 2023. Vulnerability of buildings to meteorological hazards: a web-based application using an indicator-based approach. Appl. Sci. 13. https://doi.org/10.3390/app13106253.
Pelliccio, A., Saccucci, M., Grande, E., 2017. HT_BIM: parametric modelling for the assessment of risk in historic centers. Disegnarecon 10, 5.1–5.12.
Pereira, S., Santos, P., Zêzere, J., Tavares, A., Garcia, R., Oliveira, S., 2020. A landslide risk index for municipal land use planning in Portugal. Sci. Total Environ. 735. https://doi.org/10.1016/j.scitotenv.2020.139463.
Poussin, J.K., Bubeck, P., Aerts, J.C.J.H., Ward, P.J., 2012. Potential of semi-structural and non-structural adaptation strategies to reduce future flood risk: case study for the Meuse. Nat. Hazards Earth Syst. Sci. 12, 3455–3471. https://doi.org/10.5194/nhess-12-3455-2012.
Puissant, A., Van Den Eeckhaut, M., Malet, J., Maquaire, O., 2014. Landslide consequence analysis: a region-scale indicator-based methodology. Landslides 11, 843–858. https://doi.org/10.1007/s10346-013-0429-x.
Quigley, M., Blair, N., Davison, K., 2018. Articulating a social-ecological resilience agenda for urban design. J. Urban Des. 23, 581–602. https://doi.org/10.1080/13574809.2018.1440176.
Rathnasiri, P., Adeniyi, O., Thurairajah, N., 2023. Data-driven approaches to built environment flood resilience: a scientometric and critical review. Adv. Eng. Inform. 57, 102085. https://doi.org/10.1016/j.aei.2023.102085.
Rinaldi, S.M., Peerenboom, J.P., Kelly, T.K., 2001. Identifying, understanding, and analyzing critical infrastructure interdependencies. IEEE Control Syst. 21, 11–25. https://doi.org/10.1109/37.969131.
Saaty, R.W., 1987. The analytic hierarchy process—what it is and how it is used. Math. Model. 9, 161–176. https://doi.org/10.1016/0270-0255(87)90473-8.
Saja, A.M.A., Goonetilleke, A., Teo, M., Ziyath, A.M., 2019. A critical review of social resilience assessment frameworks in disaster management. Int. J. Disaster Risk Reduct. 35, 101096. https://doi.org/10.1016/j.ijdrr.2019.101096.
Šakić Trogrlić, R., Donovan, A., Malamud, B.D., 2022. Invited perspectives: views of 350 natural hazard community members on key challenges in natural hazards research and the sustainable development goals. Nat. Hazards Earth Syst. Sci. 22, 2771–2790. https://doi.org/10.5194/nhess-22-2771-2022.
Salvati, P., Ardizzone, F., Cardinali, M., Fiorucci, F., Fugnoli, F., Guzzetti, F., Marchesini, I., Rinaldi, G., Rossi, M., Santangelo, M., Vujica, I., 2021. Acquiring vulnerability indicators to geo-hydrological hazards: an example of mobile phone-based data collection. Int. J. Disaster Risk Reduct. 55. https://doi.org/10.1016/j.ijdrr.2021.102087.
Sertyesilisik, B., 2017. Building information modeling as a tool for enhancing disaster resilience of the construction industry. Trans. VŠB – Tech. Univ. Ostrava Saf. Eng. Ser. 12, 9–18. https://doi.org/10.1515/tvsbses-2017-0002.
Skoulidou, D., Kazantzi, A., 2024. Indicator-based risk assessments for urban hazard resilience: an application for flash floods. Environ. Hazards 24 (4), 339–364. https://doi.org/10.1080/17477891.2024.2396913.
Tao, M., Gou, Z., Ma, N., 2025. Assessment of thermal comfort and thermal resilience in dwellings during heat waves: a case study of a near-zero energy house. J. Build. Eng. 109, 113052. https://doi.org/10.1016/j.jobe.2025.113052.
Taramelli, A., Righini, M., Valentini, E., Alfieri, L., Gatti, I., Gabellani, S., 2022. Building-scale flood loss estimation through vulnerability pattern characterization: application to an urban flood in Milan, Italy. Nat. Hazards Earth Syst. Sci. 22, 3543–3569. https://doi.org/10.5194/nhess-22-3543-2022.
Tascón-González, L., Ferrer-Julià, M., García-Meléndez, E., 2024. Methodological approach for mapping the flood physical vulnerability index with geographical open-source data: an example in a small-middle city (Ponferrada, Spain). Nat. Hazards 120, 4053–4081. https://doi.org/10.1007/s11069-023-06370-7.
The Rockefeller Foundation & Arup, 2016. City Resilience Index: Understanding and Measuring City Resilience.
Thywissen, K., 2006. Components of Risk. A Comparative Glossary. United Nations University, Institute for Environment and Human Security (UNU-EHS), Bonn.
Tilloy, A., Malamud, B.D., Winter, H., Joly-Laugel, A., 2019. A review of quantification methodologies for multi-hazard interrelationships. Earth Sci. Rev. 196, 102881. https://doi.org/10.1016/j.earscirev.2019.102881.
Ugliotti, F.M., Daud, M., Iacono, E., 2025. Spatial insights for building resilience: the territorial risk management & analysis across scale framework for bridging scales in multi-hazard assessment. Smart Cities 8, 27. https://doi.org/10.3390/smartcities8010027.
United Nations Office for Disaster Risk Reduction (UNDRR), 2017. The Sendai Framework Terminology on Disaster Risk Reduction. “Vulnerability” [WWW Document]. URL. https://www.undrr.org/terminology/vulnerability (accessed 16.07.25).
Uzielli, M., Nadim, F., Lacasse, S., Kaynia, A.M., 2008. A conceptual framework for quantitative estimation of physical vulnerability to landslides. Eng. Geol. 102, 251–256. https://doi.org/10.1016/j.enggeo.2008.03.011.
Vacca, G., Quaquero, E., Pili, D., Brandolini, M., 2018. GIS-HBIM integration for the management of historical buildings. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XLII–2 1129–1135. https://doi.org/10.5194/isprs-archives-XLII-2-1129-2018.
Varnes, D.J., 1958. Landslide types and processes. In: Landslides and Engineering Practice. Highway Research Board Special Report, Washington, DC, USA, pp. 20–47.
Velashjerdi Farahani, A., Jokisalo, J., Korhonen, N., Jylhä, K., Ruosteenoja, K., Kosonen, R., 2021. Overheating risk and energy demand of Nordic old and new apartment buildings during average and extreme weather conditions under a changing climate. Appl. Sci. 11, 3972. https://doi.org/10.3390/app11093972.
Velashjerdi Farahani, A., Jokisalo, J., Korhonen, N., Jylhä, K., Kosonen, R., 2024. Simulation analysis of Finnish residential buildings' resilience to hot summers under a changing climate. J. Build. Eng. 82, 108348. https://doi.org/10.1016/j.jobe.2023.108348.
Volk, R., Stengel, J., Schultmann, F., 2014. Building information modeling (BIM) for existing buildings — literature review and future needs. Autom. Constr. 38, 109–127. https://doi.org/10.1016/j.autcon.2013.10.023.
Wang, J., He, Z., Weng, W., 2020. A review of the research into the relations between hazards in multi-hazard risk analysis. Nat. Hazards 104, 2003–2026. https://doi.org/10.1007/s11069-020-04259-3.
Ward, P.J., Daniell, J., Duncan, M., Dunne, A., Hananel, C., Hochrainer-Stigler, S., Tijssen, A., Torresan, S., Ciurean, R., Gill, J.C., Sillmann, J., Couasnon, A., Koks, E., Padrón-Fumero, N., Tatman, S., Tronstad Lund, M., Adesiyun, A., Aerts, J.C.J.H., Alabaster, A., Bulder, B., Campillo Torres, C., Critto, A., Hernández-Martín, R., Machado, M., Mysiak, J., Orth, R., Palomino Antolín, I., Petrescu, E.-C., Reichstein, M., Tiggeloven, T., Van Loon, A.F., Vuong Pham, H., De Ruiter, M.C., 2022. Invited perspectives: a research agenda towards disaster risk management pathways in multi-(hazard-)risk assessment. Nat. Hazards Earth Syst. Sci. 22, 1487–1497. https://doi.org/10.5194/nhess-22-1487-2022.
Wei, M., Jiang, Z., Pandey, P., Liu, M., Li, R., O'Neill, Z., Dong, B., Hamdy, M., 2025. Energy resilience in the built environment: a comprehensive review of concepts, metrics, and strategies. Renew. Sustain. Energy Rev. 210, 115258. https://doi.org/10.1016/j.rser.2024.115258.
Xofi, M., Domingues, J.C., Santos, P.P., Pereira, S., Oliveira, S.C., Reis, E., Zêzere, J.L., Garcia, R.A.C., Lourenço, P.B., Ferreira, T.M., 2022. Exposure and physical vulnerability indicators to assess seismic risk in urban areas: a step towards a multi-hazard risk analysis. Geomat. Nat. Hazards Risk 13, 1154–1177. https://doi.org/10.1080/19475705.2022.2068457.

Zhang, C., 2023. Review of structural fire hazards, challenges, and prevention strategies. Fire 6, 137. https://doi.org/10.3390/fire6040137.
Zou, Y., Kiviniemi, A., Jones, S.W., 2017. A review of risk management through BIM and BIM-related technologies. Saf. Sci. 97, 88–98. https://doi.org/10.1016/j.ssci.2015.12.027.
Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R.M., Van Den Hurk, B., AghaKouchak, A., Jézéquel, A., Mahecha, M.D., Maraun, D., Ramos, A.M., Ridder, N.N., Thiery, W., Vignotto, E., 2020. A typology of compound weather and climate events. Nat. Rev. Earth Environ. 1, 333–347. https://doi.org/10.1038/s43017-020-0060-z.