multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate

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Systemic vulnerability modelling including physical, socio-economic, health, safety and environmental aspects

DV 5.3.3

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1. Technical References

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2. Technical References

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INDEX FIGURES

1. INTRODUCTION

In the context of **RETURN** project, **Spoke 5 TS1** "*Urban and metropolitan settlements*", **WP 5.3** "*Multi-risk vulnerability and impact assessment and forecasting*", the **Task 5.3.3** "*Urban systemic vulnerability to multiple hazards*", addresses the definition of methodologies and models to assess the overall systemic vulnerability at the urban and metropolitan level, including physical, socio-economic, health, safety and environmental aspects. The results of the activities of the task are reported in the following document **Deliverable 5.3.3** "*Systemic vulnerability modelling including physical, socio-economic, health, safety and environmental aspects*", in line with the work of previous tasks of **WP 3** and **WP 2**.

According to **Deliverable 5.2.1** "*Risk-Oriented Taxonomy and Ontology of Urban Subsystems and Functional Models*", the vulnerability can be generally defined as "the propensity (of exposed elements) of being adversely affected by a (natural) hazard in multiple dimensions: environmental, physical, technical, social, cultural, economic, institutional, or policy-related factors. This condition is strongly tied with and derives from multiple short- and long-term socio-ecological processes defined as underlying risk drivers" and it has been recognized as a critical component of the risk.

Simultaneously, because of the multi-dimensional nature of vulnerability, **Deliverable 5.2.1** provides specific definitions of vulnerabilities (physical, social, economic, environmental, institutional).

According to **DV 5.3.1**, the vulnerability in this document is discussed referring to:

●Single-hazard vulnerability: the propensity of exposed elements to suffer adverse effects when impacted by a specific hazard, avoiding potential vulnerability interactions;

●Multiple-hazard vulnerability: the propensity of exposed elements to suffer adverse effects when impacted by two or more hazards, involving the potential exacerbation of vulnerability when hazards occur close in time.

The concept of systemic vulnerability, investigated in the following **Deliverable 5.3.3**, stems from the comprehension of the interconnectedness of the multiple dimensions within the city as outlined and discussed in **DV 5.2.1**. and **DV 5.2.2**.

The multiplicity and complexity of interactions among different elements and systems that constitute the urban system, as well as urban functions ensuring its livability, safety, and sustainability, make the modeling of urban settlements a challenge.

Deliverable 5.3.3 is developed and organized in two main sections:

Section 1: Conceptualization of vulnerability in multi-risk scenarios, where a conceptual background to define approaches to vulnerability in multi-risk scenarios is provided. The systemic vulnerability is then discussed outlining a framework based on considering socio-eco-technologycal systems and understanding the vulnerability as multidimensional, multidisciplinary and relational concept. Key aspects and influencing factors are explored to individuate potentialities for assessment, models, tools and indicators.

Section 2: Hazards systemic vulnerability, where, referring to the classification of hazards according to **Deliverable 5.3.1**, literature and recent methodologies in the estimation of the vulnerability to be adopted in the context of risk and multi-risk assessment are explained.

Note 1: This document is to be intended as part of an ongoing iterative process. As such it will be subject to further updates and modifications in the following phases of the project, also according to the feedback and consultations among the project partners and with the stakeholders.

2. FRAMEWORKS

2.1 Conceptualization of vulnerability in multi-risk scenarios

Urban settlements are increasingly exposed to multiple hazards, including natural disasters (earthquakes, floods, hurricanes), climate change-induced events (heatwaves, sea-level rise), and anthropogenic hazards (technological failures, conflicts) (UNISDR, 2011;2012). Urban settlements face increasing risks due to interlaced dynamics such as rapid urbanization and socioeconomic inequalities (Gencer, 2013; Gu, 2015; UNISDR, 2019).

The Second Assessment Report on Climate and Cities, developed by the Urban Climate Change Research Network (UCCRN), defines urban vulnerability to disasters as the susceptibility of urban areas - including populations, infrastructure, economies, and ecosystems - to adverse effects from natural or human-induced hazards (Gencer et al., 2018). This vulnerability arises from the interaction between the exposure of urban systems to hazards, their sensitivity, and the capacity of communities to respond and recover effectively (UNDRR, 2015a). An emerging consensus in the literature is growing about the necessity of a **conceptualization of vulnerability** in **multi-risk scenarios based on a holistic understanding** of how different hazards interact and how urban populations, infrastructure, and governance systems respond to these risks (Pescaroli, 2018; Ferreira & Santos, 2023).

Vulnerability has been acknowledged as a key aspect of risk for decades, interpreted differently across various fields of study (Adger, 2006; Fussel, 2007; Birkmann 2013; Blaikie et al. 2014). Studies on urban vulnerability have highlighted its **multidimensional nature** as urban vulnerability can be understood as the propensity of an exposed elements to be adversely affected by a hazard in **multiple dimensions**: spatial, physical, technical, social, economic, environmental, cultural, institutional (Gunaratne et al., 2023; Limongi & Galderisi; 2022). This aspect of vulnerability derives from complex socio-ecological and socio-technical processes that characterize the urban systems, and they are known as underlying risk drivers, which involve interactions between social actors, socio-economic dynamics, and environmental components (Sharifi, 2023; Schneiderbauer et al., 2017).

Vulnerability models typically focus on **single hazards**, whereas **multi-risk frameworks** consider cascading and compounding effects that affect urban resilience (Cutter, 2016; Mohammadi et al., 2024). Vulnerability in multi-risk scenarios refers to the degree to which the components of the **urban system** (e.g., housing, infrastructure, economy, and communities) are **susceptible to harm** from multiple, often interconnected, hazards. Gencer et al. (2018) discuss urban vulnerability as the extent to which cities, populations, infrastructure, or economic systems are at risk from hazards such as heatwaves, storms, or political instability, and their inability to effectively manage or recover from these impacts (Revi et al., 2014; Romero-Lankao et al., 2014). According to this study, urban vulnerability is **a dynamic and relational concep**t that encompasses not only the likelihood of negative outcomes resulting from a hazard but also the underlying sensitivity and capacity of the affected systems to cope (Romero-Lankao & Qin, 2011). It cannot be fully explained by the mere presence of hazards or the inherent attributes of systems; instead, it arises from the interaction of these elements. It is further highlighted that approaches to studying urban vulnerability typically fall into three broad interpretations: vulnerability as impact, inherent or contextual vulnerability, and vulnerability in relation to resilience (O'Brien et al., 2007; Romero-Lankao et al., 2012). Physical, demographic, economic, and environmental factors are all critical in shaping the susceptibility of urban communities to hazards, revealing as vulnerability studies can help in better planning and response to urban risks (Gencer et al., 2018; Gu, 2019).

Given the multi-dimensional nature of vulnerability, the following types are commonly defined (Cfr. **DV 5.2.1**) (Birkmann et al., 2013; IPCC, 2022; Zebisch et al., 2023): physical, social, economic, environmental and institutional (Table 1).

Table 1 Different types of vulnerability reflecting the multi-dimensionality

Vulnerability	Definition
Physical/Structural	The susceptibility and fragility of built environments to physically be damaged during hazards, influenced by factors such as structural integrity and design (Birkmann, 2006; Douglas, 2007; Birkmann et al., 2013). It is generally interpreted as the susceptibility to be damaged of built environment or its individual elements (buildings, infrastructure, etc.). It is described as physical vulnerability, such as building vulnerability, structural vulnerability, vulnerability of physical assets (Limongi & Galderisi 2021).
Social	The extent to which populations are exposed to harm due to individual and collective social attributes, such as age, gender, ethnicity, poverty, social exclusion, and limited access to services. These factors influence well-being and susceptibility in specific contexts (Cutter et al., 2003; Birkmann et al., 2013; Singh et al.2014). Social vulnerability is generally used to describe the capacity to cope with hazardous events, and with their adverse consequences, of the numerous societal components, ranging from individuals to social groups, communities, organisation (Parker, 2009).
Economic	The propensity of economic systems to suffer financial losses and disruptions, including business interruptions, increased poverty, and job loss, as a result of multi-hazard impacts (Cardona et al., 2012; Hallegatte et al., 2017). It is related to the response that economic sectors are able (or unable) to provide in the aftermath of an extreme event and describes both the susceptibility to loss of economic assets and productivity and the capacity of recovery of the economic subsystem (Limongi & Galderis,i 2021).
Environmental/ Ecological	Environmental vulnerability, which is generally referred to the ability of natural resources or natural systems to recover from the impact of hazardous events and which largely depends on their health and integrity level. It refers to the ecosystems, which are largely influenced by long-term effects of human activities. It is mostly studied in respect to climate-related events (Limongi & Galderisi, 2021).
Institutional/Governance	It is related to the organizational shortcomings in the face of adverse conditions (Limongi and Galderisi 2021). The predisposition of governance systems, institutions, and policies to affect disaster response and recovery. Weaknesses in disaster preparedness, decision-making processes, and policy implementation can exacerbate risks (Pelling, 2003; Papathoma-Köhle et al., 2021).

According to literature (Limongi & Galderisi, 2021) the most investigated facet is the social one, followed by physical, structural and economic and environmental vulnerabilities. The less investigated are the institutional and ecological one (Figure 1).

The **multidimensionality perspective** integrates the root causes and processes that produce vulnerability with observable components. Considering in vulnerability conceptualization these context-dependent factors as underlying risk drivers opens for a shift in the understanding of vulnerability from a focused concept (for example limited to physical resistance of engineering structures) to a **more holistic and systemic approach** (Schneiderbauer et al. 2017, Sarmiento 2018).

The discussion on vulnerability in multi-risk scenarios here presented unfolds through an exploration of various frameworks and perspectives. It begins with an analysis of the synergy between Climate Change Adaptation (CCA) and Disaster Risk Reduction (DRR), highlighting how these approaches complement each other in addressing vulnerability by integrating strategies to enhance resilience across different dimensions. Building on this, the conceptualization provided by the Intergovernmental Panel on Climate Change (IPCC) is examined, emphasizing the dynamic and multi-dimensional nature of vulnerability and its ties to socio-ecological and socio-technical processes within the context of climate change. The discussion further considers vulnerability in relation to single hazards, exploring the specific factors that shape susceptibility and adaptive capacity in the face of distinct hazard events. This analysis highlights the contextual and hazard-specific nature of vulnerability, which informs targeted risk management approaches. Lastly, these perspectives converge in a push towards a holistic definition of vulnerability, one that captures the interconnected and compounding nature of risks inherent in multi-hazard scenarios. This cohesive approach aims to bridge existing gaps and foster a more integrative understanding of vulnerability.

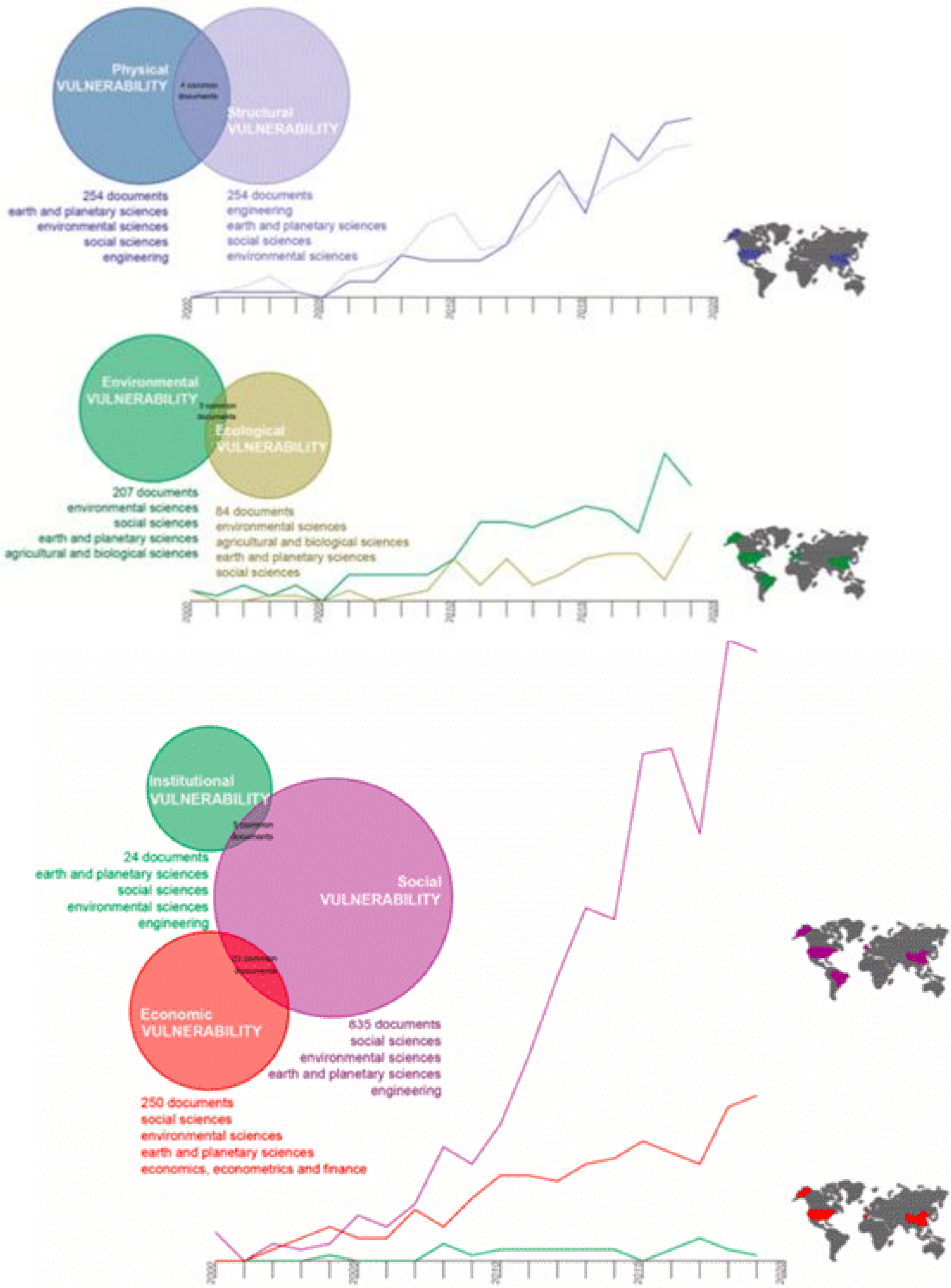


Figure 1. *Results of Scopus search: the most investigated facets of vulnerability in scientific literature. Source: Limongi et al. 2021*

2.1.1 Climate Change Adaptation and Disaster Risk Reduction synergy

The need of an integration of a multi-risk approach within planning and urban policies calls for a convergence of the community of practices related to Disaster Risk Reduction (DRR) and Climate Change Adaptation (CCA) frameworks (Dias et al., 2020; Hemmers et al., 2020; Pabelando, 2024; Visconti et al., 2020; Shaw et al., 2010; Forino et al., 2015). The discourse in literature review highlights as the CCA and DDR belong to different epistemological domains: the first linked to the ecological field and systems and to the concept of resilience, the second to social science, governance, actors and to the concept of vulnerability and as well to natural sciences referring to hazards assessment (Miller et al., 2010; Shaw et al., 2010; Rivera, 2014).

For example, the ranges of stakeholders background, as shown in the stakeholder analysis made by the Horizon project "Espresso" dedicated to investigate the potential synergies between DDR and CCA, are natural science 46%, social science 27%, engineering 27%, DDR (48%), CCA (9%), DDR/CCA (43%) (Zuccaro et al., 2018; Abad et al., 2020).

In the field of urban disciplines, several attempts have been made to find coherence between the Sendai Framework (SFDRR) and the other post-2015 agendas and agreements, in particular the 2030 Agenda for Sustainable Development, the Paris Agreement for the climate, the New Urban Agenda. The SFDRR does not explain how to establish and maintain in practice cross-sectoral coherence and coordination between CCA and DRR (Kelman, 2015) but it is commonly accepted that development and sustainable goals in cities may be facilitated by integrating CCA into DRR (Rivera, 2014; UNISDR, 2015c).

Despite the necessity to converge towards urban practices for vulnerability reduction (economic, social and political) and strengthening of resilience (socio-ecological and socio-technical), holistically and comprehensively, there is still a lack of integration between urban planning development, risks, disasters and climate change (Zuccaro et al., 2018; Islam et al., 2019). This lack of integration is primarily due to insufficient policy frameworks, inadequate funding mechanisms, and poor coordination among stakeholders, which hinder effective implementation at national and subnational levels (Grafakos et al., 2020).

Vulnerability plays a central role in both Climate Change Adaptation (CCA) and Disaster Risk Reduction (DRR), though the two frameworks conceptualize and address it differently due to their distinct priorities and objectives (Birkmann et al., 2015; Pabelando, 2024; Hemmers et al., 2021). In CCA, vulnerability is associated with long-term climate change impacts. It emphasizes that structural and **systemic factors - such as poverty, social inequality, and environmental degradation** - increase susceptibility to gradual climate shifts and extreme events (IPCC, 2014). In contrast, DRR frames vulnerability as the susceptibility to damage from sudden hazards, focusing on preparedness, exposure, and coping mechanisms during and after disasters (UNDRR, 2015a).

The Sendai Framework has contributed to a shift from a culture of response to a culture of prevention, marking a change in the conceptual framework of DRR from managing disasters to managing risk (UNISDR, 2015b; UNISDR, 2015c; Abad et al. 2020). Risk mitigation interventions primarily focus on the resilience of "hard" infrastructure, such as dikes, dams, and hazard-resistant buildings, while "soft" infrastructure - such as nature-based solutions, education, emergency networks, and safety nets - remains less emphasized (Zuccaro et al. 2018; Ullberg et al., 2016; IPCC, 2012). This shift suggests that long-term strategies for disaster prevention are often neglected in favor of more immediate, emergency-focused actions.

In the SFDRR, long-term planning is linked to preparedness for "building back better" during recovery, rehabilitation, and reconstruction. This approach incorporates socio-economic implications, institutional coordination, and governance issues (UNISDR, 2015c). Urban CCA, however, emphasizes the importance of long-term planning by recognizing the socio-environmental dimensions of climate-related risks. These risks are seen as the result of the **interplay between urbanization patterns, land use, morphology, and natural hazards,** making spatial decision-making critical for reducing impacts (Satterthwaite et al., 2007). Urban planning tools like regulatory frameworks and building codes can promote risk reduction by using land-use planning and zoning to prevent construction in risky areas or by strategically locating critical infrastructure (Johnson, 2011). Governance is increasingly seen as a key framework for integrating CCA and DRR, though it remains a complex and evolving topic in the literature (Gero et al., 2011; Forino, 2015). For the integration of DRR and CCA in urban planning and design, the spatial decision-making dimension and urban policies are critical areas for implementation (UNISDR, 2015c; UN-Habitat, 2016).

Vulnerability assessments help identify **the most at-risk populations, systems, or regions**, ensuring that resources and interventions, whether adaptive measures in CCA or preparedness plans in DRR, are directed where they are needed most (Birkmann, 2006a; Birkmann et al., 2015). Accurate vulnerability assessments are necessary for creating strategies that address the root causes of vulnerability (Birkmann 2006b). For instance, in CCA, policies may focus on strengthening adaptive capacity through sustainable land use or resilient infrastructure. In DRR, policies may prioritize emergency preparedness, hazard mapping, and risk reduction programs (IPCC, 2012). Vulnerability assessments can bridge the division between CCA and DRR by identifying shared risks and promoting integrated approaches. For example, analyzing vulnerability to floods can inform both long-term CCA strategies (e.g., restoring wetlands) and short-term DRR measures (e.g., flood warning systems) (Schipper & Pelling, 2006). Understanding vulnerability is essential for building resilience. Reducing vulnerabilities allows communities, ecosystems, and economies to better withstand shocks and recover more quickly from both gradual climate change and sudden disasters (Adger, 2000; Birkmann 2006a).

A key gap in the integration of DRR and CCA is the lack of a common regulatory framework. Both frameworks tend to be planned, implemented, and funded by different government agencies and organizations, and the use of different technical languages often results in a "silo" mentality (Gero et al., 2010; Forino et al., 2015). While the Sendai Framework has made progress by providing guidance for DRR policies and programs (UNISDR, 2015b), **the absence of common methodologies, standards for data collection, and risk assessment processes continues to hinder integration**. Improved transboundary cooperation can help address this gap and promote the implementation of common frameworks (Zuccaro et al., 2018; Rivera, 2014).

In the context of DRR and CCA **integration, multi-disciplinary collaboration i**s critical to enhancing dialogue across various sectors, including social sciences, natural sciences, planning, and architecture (Visconti et al., 2020). This collaboration strengthens decision-making and fosters community engagement by promoting a shared understanding of key concepts and terms (Abad et al., 2020). Moreover, the integration of current studies and measures in DRR and CCA presents opportunities **to transcend sectorial and scalar boundaries by emphasizing a multi-scale, multi-sectoral, and multi-actor approach**. This approach not only coordinates **inter-sectoral knowledge**, **competencies, and responsibilitie**s but also extends the diversity of involved stakeholders and their participation, ensuring more inclusive decision-making (Booth et al., 2020). It promotes dialogue between scientists and policymakers at national and regional levels while also fostering knowledge transfer between academics, professionals, and technical offices at the municipal level.

A comprehensive evaluation of risk must account for both tangible and intangible factors, including urbanization, globalization, social justice, human rights, well-being, and environmental issues such as pollution and ecosystem pressures. These considerations should be integrated into risk management strategies that align with the goals and commitments of the New Urban Agenda (UN, 2016). In addition, sectorial expertise in areas such as human health, cultural heritage, and critical infrastructure plays a central role in addressing these challenges **through a systemic, solutions-oriented approach**. This collaborative framework not only enhances understanding but also fosters innovation through transdisciplinary research, which is essential for developing effective policies and practices to manage multi-risk scenarios affected by geo-physical, hydrological, and climate-related hazards (Hemmers et al. 2020). By facilitating mutual learning and knowledge exchange, this approach can help bridge the gap between scientific research, policy implementation, and community engagement (Abad et al. 2020, Albris et al. 2020).

Table 2. Conceptualization of vulnerability in the Climate Change Adaptation and Disaster Risk Reduction approaches.

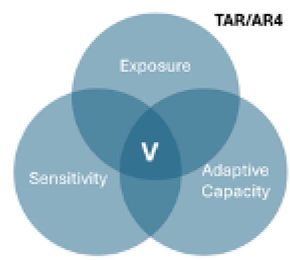
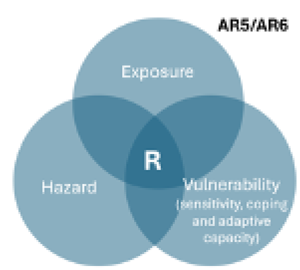
Conceptualization of Vulnerability in CCA	**Conceptualization of Vulnerability in DRR**
Vulnerability in CCA is typically linked to climate variability and long-term environmental changes, such as sea-level rise, desertification, and shifts in weather patterns. It emphasizes the **interaction between exposure, sensitivity, and adaptive capacity** within social, economic, and ecological systems (IPCC 2014, 2022)	Vulnerability in DRR is closely linked to sudden hazards such as earthquakes, floods, storms, and landslides. It prioritizes **reducing exposure and increasing preparedness** to minimize the immediate and short-term impacts of disasters (UNISDR 2015a).
Multi-Scale Nature of Vulnerability related to climate change: Vulnerability in CCA is often assessed at local, regional, and global scales to understand how climate change impacts systems differently. At urban scale, this multi-scalarity is reflected by conceiving the interconnectedness of territorial, city, district and block scales (Renaud et al., 2010; Mikulewicz, 2018).	**Emphasis on Social Vulnerabilities or on physical vulnerability:**Vulnerability in DRR often highlights **social inequalities** (e.g., marginalized groups, gender disparities) that exacerbate the impacts of disasters. It recognizes that disasters are not purely natural events but are shaped by human decisions and vulnerabilities (Cutter et al., 2003).
Long-Term Perspective:CCA emphasizes understanding vulnerability over time, focusing on future projections and scenarios to plan for incremental changes or thresholds that could trigger systemic crises (O'Brien et al., 2007).	**Short-Term Perspective:**While DRR acknowledges long-term risks, it primarily focuses on **reducing immediate risks** through preparedness and response measures, such as early warning systems, evacuation plans, and disaster-resilient infrastructure (Lavell & Maskrey, 2014)

2.1.2 Vulnerability according to the Intergovernmental Panel on Climate Change (IPCC)

The IPCC framework underscores the importance of holistic risk assessment, advocating for strategies that bridge the gap between CCA and DRR. Indeed, these assessments are a crucial step as they help to identify the most appropriate adaptation options and measures, contributing to the formulation of effective strategies to address climate change challenges and reduce risks to vulnerable populations and ecosystems (Estoque at al., 2023).

According to the Intergovernmental Panel on Climate Change (IPCC), this concept has evolved significantly over the course of the various assessment reports as showed in Table 3.

Table 3. Vulnerability definition in the IPCC's Assessment Report from 2001 to 2021.

IPCC Assessment Report	Vulnerability definition	
Third Assessment Report (TAR) (IPCC, 2001) **Fourth Assessment Report (AR4) (IPCC, 2007)**	The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.	
Fifth Assessment Report (AR5) (IPCC, 2014) **Sixth Assessment Report (AR6) (IPCC, 2021)**	The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.	

The definition across the reports developed in the last twenty years shows a growing complexity and integration in the concept of vulnerability of broader socio-economic and adaptive focus. The TAR and the AR4 had a more physical focus, conceptualizing vulnerability as a function of exposure, sensitivity, and adaptive capacity. AR5 refined this definition by expressly referring to interaction among exposure, sensitivity, and adaptive capacity and, therefore, emphasized the concept of "propensity" to be harmed. This definition underlines the idea of physical exposure, sensitivity of taking harm, and capacity for adjustment to impact.

The Fifth Assessment Report marked a shift towards a more dynamic and integrated view of vulnerability integrating socio-economic factors more significantly and addressing how factors such as development, poverty, and governance influence vulnerability. Since the AR5, there is growing evidence that anthropogenic factors, including human destruction of ecosystems and the current unsustainable development patterns (including generally unsustainable consumption and production, increasing population pressure, unsustainable use and management of land, ocean and water resources, etc.), are increasing the vulnerability and exposure of current ecosystems to climate risks (Wang et al., 2022). This was further elaborated in the Sixth Assessment Report reflecting the complexity of vulnerability in the context of contemporary climate challenges and emphasizing the interconnectedness of socio-economic factors, governance, and risk management in shaping vulnerability. Moreover, the report emphasizes that vulnerability is a dynamic and context-dependent phenomenon, contingent on issues related to inequality in adaptive capacity and institutional governance. It highlighted the fact that usually, vulnerable populations are exposed to combined risks from social inequalities and resource scarcity. It further underlines the role of risk management and adaptation strategies that ought to be conducted through comprehensive, equity-based approaches to reduction in vulnerability and building resilience in view of continued and future climate change.

Table 4. Key concept and differences in the vulnerability concept as developed by the IPCC.

Aspect	TAR (2001) and AR4 (2007)	AR5 (2014) and AR6 (2021)
Core Definition of Vulnerability	The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.	The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.
Key Components	Exposure, Sensitivity, Adaptive Capacity	Exposure, Sensitivity, Adaptive Capacity, Socio-economic Context, Governance
Socio-economic Factors	Limited focus on socio-economic aspects, more physical in nature.	Very strong emphasis on socio-economic and political factors, governance, inequality, and equity in adaptation and vulnerability.
Governance and Institutions	Not strongly emphasized.	Governance structures, policies, and institutional capacity are central to shaping vulnerability, particularly in terms of equity and justice.
Temporal Considerations	Acknowledges longer-term climate change impacts, but still with a focus on current exposure.	Emphasizes both current vulnerabilities and future risks, stressing the urgency of adaptation strategies in the context of increasing climate extremes.
Focus on Risk Management	More focused on the scientific understanding of vulnerability and impacts. The AR4 introduces risk management concepts but still focuses more on vulnerability as a static concept.	Strong focus on risk management strategies, adaptation measures, and climate resilience planning as part of the broader vulnerability context.
Integration among Disciplines	Primarily based on physical sciences, with some consideration of socio-economic aspects.	Explicit integration of climate science with development, health, economics, and governance, emphasizing justice and equity.

Through all these reports, it is evident how the definitions of vulnerability have evolved in response to the growing recognition that vulnerability encompasses not only mere exposure to climate impacts but also socio-economic conditions and governance structures affecting both human and ecological systems.

It is also a reflection of the IPCC's shift from a vulnerability-based to a risk-based framework. By placing the focus on risk, the IPCC acknowledges that many interconnected impacts are rooted in hazardous events and thus these should be duly framed through the risk lens and encourages further research in risk management to be better understand the potential consequences of such events. The AR5/AR6 risk framework also underlines the role of exposure and vulnerability in connecting the two research areas of climate change adaptation and disaster risk reduction and management (Estoque et al., 2023).

2.1.3 Towards a holistic definition of vulnerability for multi-risk

In the field of multi-risk studies, understanding the risks faced by urban settlements is closely tied to the conceptualization of vulnerability and the underlying orientation informing its interpretation (Bankoff, 2022). The differences in defining vulnerability stem from the heterogeneity of the disciplines in which this concept is applied (Fuchs et al., 2012; Van de Sand, 2012; Füssel, 2007; IPCC, 2014). Numerous reviews aimed at clarifying the different meanings of the term across various fields of knowledge have been produced (Brown et al., 2017; Thekdi, 2020; Orru et al., 2021; Limongi & Galderisi, 2021)underscoring the fundamental need to establish a reference framework, particularly in climate change research, where multidisciplinary approaches often lead to misunderstandings among researchers from diverse intellectual traditions, such as climate science, risk assessment, economics, and political science (Zebisch et al., 2023). Moreover, it has also been emphasized that addressing ambiguities in the application of the concept requires reference to a specific form of vulnerability. This should be context-driven and situation-specific, interacting with a hazard event to generate risk (IPCC, 2014; Lavell, 2003; Cannon, 2006; Cutter et al., 2008) and characterized to the system under study and the domain of reference (Brooks, 2003; Füssel, 2007).

In reviews focused on the conceptualization, terminology, and classifications of vulnerability, which synthesize prevalent orientations and research traditions (Kasperson, 2005; Füssel, 2007; Gallopín, 2006; Van de Sand, 2012; Hufschmidt, 2011; Bankoff, 2004; Bankoff, 2022), three distinct approaches emerge: **the risk-hazard tradition, the social science (political economy and political ecology), and the resilient thinking.** The theoretical evolution of risk research thus originates from **heterogeneous epistemologies**, starting with questions about who or what is vulnerable and why, as well as examining the causal relationships determining the vulnerability of a subject or system. Different approaches and their epistemologies, although originating from diverse orientations and disciplines, highlight how the development of the risk debate has led to a multidisciplinary and more integrative framework that incorporates concepts from various fields of knowledge. This reinforces the **holistic and cross-cutting nature of understanding** and managing risk (Wisner et al., 2013b).

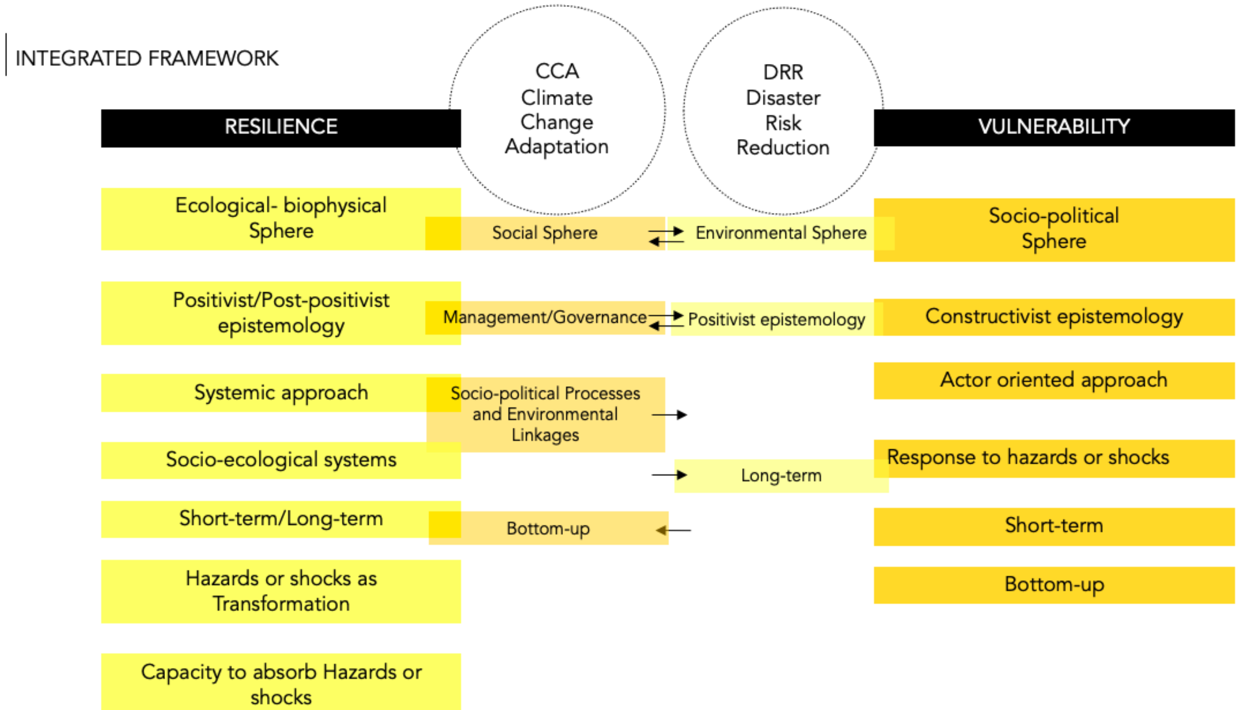


***Figure 2**. Differences and Synergies between resilience and vulnerability studies, adapted from Visconti 2017*

The risk-hazard tradition (disaster risk community) adopts a deterministic model, viewing hazards as natural events causing risk, with vulnerability defined descriptively as potential losses (Füssel, 2007). This technocratic approach (Hilhorst, 2003) emphasizes technological solutions to reduce vulnerability but increasingly incorporates vulnerability interaction with hazards, i.e. risk is seen as the sum of hazard and vulnerability (Wisner et al., 2013a). Frameworks like the PAR model (pressure-and-release) integrate natural hazard and human ecology approaches (Blaikie et al., 1994; Wisner et al., 2013a; Wisner et al., 2004). Risk is seen as a function of exposure, sensitivity, coping, and adaptive capacity (IPCC, 2014).

Social science approaches, including human ecology, political economy, and political ecology, emphasize structural causes of vulnerability, such as poverty, inequality, and marginalization (Hilhorst, 2003; Morrow, 2008). Vulnerability is viewed as a multidimensional construct shaped by political, economic, and institutional factors (Bohle et al., 1994; Miller, 2010). It is framed as a social construct, focusing on differential coping and adaptive capacities (Miller et al., 2010).

In resilience thinking, originating in ecology, resilience refers to a system's ability to recover or persist under stress (Holling, 1996; Walker &Salt, 2012). Vulnerability is the antonym of resilience (Folke et al., 2002), with systems becoming vulnerable when resilience declines. Resilience thinking integrates socio-ecological systems, recognizing complex interactions between society and nature (Hilhorst, 2022). However, the concept's application to social systems requires critical adaptation to avoid oversimplification (Adger, 2000; Davoudi, 2012).

The trend is, therefore, to overcome the separation of approaches, even in urban resilience research (Leichenko, 2011; Olazabal et al., 2012), understood as a holistic and systemic concept. Urban climate vulnerability is considered to encompass the socio-cultural and economic vulnerability of residents, inadequate political capacity of local governments, susceptibility of the built environment, and vulnerability of ecosystem services. These aspects can be categorized into social, institutional, physical, and environmental vulnerabilities (Rosenzweig et al., 2018; Schneiderbauer et al., 2017).

2.2 Systemic Vulnerability of Urban Settlements

The conceptual background of systemic vulnerability in urban settlements emerges from a broader academic discourse on vulnerability within multi-risk frameworks. As discussed in previous sections, understanding the risks urban settlements face is closely tied to the concept of vulnerability and its interpretation, which varies across disciplines (Van de Sand, 2012; Füssel, 2007; IPCC, 2014). Numerous reviews have explored the term's multiple meanings across fields (Füssel, 2007), highlighting the need for a reference framework, especially in climate change research, where multidisciplinary approaches often cause misalignments (O'Brien et al., 2004; Gallopín, 2006). To address conceptual ambiguity, vulnerability must be context-specific, defined relative to the system, hazard, and domain (Brooks, 2003; Füssel, 2007). As noted, "vulnerability can be seen as situation-specific, interacting with a hazard event to generate risk" (Lavell, 2003; Cannon, 2006; Cutter et al., 2008; IPCC, 2014, p.70).

According to Limongi and Galderisi (2021), who review European and international research on vulnerability over the past twenty years, is possible to recognize that the systemic dimension of vulnerability has been the less investigated facet. Physical and social vulnerability result to be the most addressed, often siloing the approaches towards the study of the damage of a single element (buildings, infrastructure, forests) or the capacity of individual and communities (Figure 1).

Systemic vulnerability, though less explored, is a key characteristic of complex urban systems. It reflects the tendency of territorial elements to experience functional disruptions due to their interconnections with other components that are also immaterial. Unlike other forms of vulnerability, systemic vulnerability is primarily influenced by the nature of these linkages rather than the type of hazard itself. Although historically underexamined, systemic vulnerability has been studied in relation to various natural hazards, including earthquakes, floods, and volcanic eruptions, and is now recognized as a crucial factor in understanding urban resilience (Limongi & Galderisi, 2021).

Systemic vulnerability moves beyond isolated risk assessments by acknowledging that urban areas are not only exposed to singular events but also to the interactions of hazards (Gill & Malamud, 2014) and to the interaction of the single hazard with economic, social, cultural, institutional and physical weaknesses. It emphasizes how the disruption of critical infrastructure, governance systems, and social networks can amplify risks and hinder recovery processes (Aubrecht et al., 2012). This perspective aligns with resilience theory, which advocates for adaptive capacities and robust urban planning to mitigate systemic vulnerabilities (Meerow et al., 2016). Thus, systemic vulnerability is rooted in the understanding that cities are complex and dynamic systems, where various components are interdependent.

The concept of systemic vulnerability in urban settlements emerges from this holistic understanding of vulnerability. It reflects the complex and dynamic nature of cities in the face of climate change as a pressing stress summed to the already present threats such as the geomorphological or environmental (e.g. biological, pollution). Urban areas concentrate populations, infrastructure, and economic activities, so becoming focal points of dynamic processes that influence the characterization of urban risk. In fact, the interconnected systems that sustain urban settlements—ranging from social and economic structures to infrastructure and ecological networks—are highly interdependent. This **interconnectedness** introduces vulnerabilities that can be amplified under the pressures of a variety of stresses. Scholars and practitioners emphasize the need for a holistic understanding of these vulnerabilities through both **multi-risk and systems-based approach** to enhance urban resilience and adaptive capacity (Arosio et al., 2020; Laurien et al., 2022).

The resilience framework and systemic thinking constitute the main conceptual references for studying cities' systemic vulnerability (Helfgott 2018, Wolfram et al. 2016, Rus et al. 2018, Seeliger and Turok 2013).

The definition of urban resilience has progressively shifted towards a comprehensive ability of an urban system and all its **constituent social–ecological and social–technical networks,** across temporal and spatial scales, to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity (Meerow et al., 2016; McPherson et al., 2022). Since cities can be understood as complex systems in which various elements and subsystems are highly interconnected, it is essential to examine each component as an integral part of the overall system while also considering the interdependencies between them (Limongi &Galderisi, 2021). Thus, applying systemic thinking to the vulnerability of urban settlement involves understanding that physical, social, economic and environmental vulnerabilities represent different facets **that should be investigated in a relational perspective, comprehending as the different dimensions are influencing each other.** An example of this approach can be foundin studies onurban resilience and vulnerability, where the physical vulnerability of the built environment is related to socio-economic conditions of households, governance, infrastructures or ecosystem services (Mansur et al., 2016; Wilkerson et al., 2018; Malakar et al., 2017; Krellenberg et al., 2017; Apreda et al., 2019; Mazumdar et al., 2016)

As a multifaceted concept, vulnerability calls for a plurality of approaches in its understanding and assessments. However, a foundational reflection on the **complexity of the urban system** can help positioning the discussion of systemic vulnerability in multi-risk urban contexts.

Although widely applied in geography and environmental sciences, complexity theory has been relatively underutilized in vulnerability assessments (Naylor et al., 2020). This is despite its relevance, as insights from resilience and adaptation research highlight its usefulness in understanding **systemic change,** feedback mechanisms, and decision-making processes (Timmermans et al., 2012).

Complexity theory focuses on non-linear relationships within dynamic and unstable systems (Norberg, 2008). It explores how complex behaviors emerge from simple interactions among system components over time (Manson, 2001). Unlike traditional systems theory, which assumes equilibrium, complexity theory emphasizes relational structures that evolve continuously (Preiser et al., 2018). This perspective prevents static interpretations of interconnected processes by considering feedback loops, threshold effects, and the diversity of actors and mechanisms involved (Norberg, 2008; Preiser et al., 2018). Understanding a system within this framework requires analyzing the shifting relationships between its components over time, as well as the movement of stocks and flows within the system (Manson, 2001). During the last decade within the framework of urban complexity in facing hazards emerged the concept of **SETS, Social–Ecological–Technical infrastructure System** (Sharifi, 2023) which emphasizes the importance of **urban built and technological infrastructure in exploring the human- environment interactions in cities** (Grimm et al., 2017; Groffman et al., 2018). This systems approach seeks to expand interdisciplinary approaches to understanding urban complexity in ways that may have increased efficacy for achieving complex goals such as improved urban resilience and sustainability (McPhearson et al., 2016).

Adopting an integrative approach to **human-nature and technological relationships** as interconnected socio-ecological-technical systems (SETS) can enhance the understanding of urban complexity and so as well of vulnerability aspects. This perspective incorporates various disciplinary entry points, such as ecosystem processes, human behavior, political ecology, landscape structure, and social justice, to offer a more comprehensive analysis of SETS dynamics. According to Sharifi (2023), urban resilience and conversely vulnerability is shaped by the intricate and evolving interactions among interdependent subsystems, including the economy, human and social networks, ecological and biophysical systems, governance structures, cultural norms, institutions, and physical infrastructure. These interactions take place across different spatial and temporal scales that need to be better reconsidered (Bixler et al., 2019; Kotzee & Reyers, 2016; McPhearson et al., 2022).

According to this understanding, key aspects influencing the systemic vulnerability of the urban systems can be summarized as follows:

- **Physicality of the Built Environment:** the **physicality of the built environment** plays a crucial role in shaping the **systemic vulnerability of cities**, as urban infrastructure, spatial configurations, and architectural resilience determine how well cities can withstand and recover from shocks as well as buildings, roads, bridges, and utilities form the backbone of urban systems, and their design and material quality significantly affect vulnerability. Poorly planned and maintained built environments can exacerbate risks, leading to cascading failures across urban systems (Amin, 2014). Weak construction standards, unregulated urban expansion, and aging infrastructure heighten exposure to earthquakes, floods, and extreme weather events (Godschalk, 2003). In contrast, cities with robust engineering standards and adaptive architecture—such as elevated structures in flood-prone areas or earthquake-resistant buildings—demonstrate greater resilience (Meerow et al., 2016).

- **Urban Form and Spatial Distribution:** urban form - the spatial patterns of built, infrastructural, and biotic components - is a key determinant of urban complexity and vulnerability (McPhearson et al., 2016). The spatial arrangement of infrastructure and land use influences risk distribution across urban populations. For instance, high-density informal settlements with inadequate access to basic services are disproportionately vulnerable to both environmental hazards and infrastructure failures (Pelling, 2003). Heterogeneity and patchy spatial patterns in urban landscapes complicate efforts to define urban structure and assess its interactions with ecological processes (Pickett & Cadenasso, 2009; Zhang et al., 2013).

- **Infrastructures:** the built environment consists of interdependent infrastructures, meaning failures in one system can trigger cascading disruptions in others. The resilience of urban infrastructure is a major determinant of systemic vulnerability. Infrastructure - ranging from transportation and energy grids to water supply and sanitation - forms the backbone of urban functionality. However, outdated or poorly designed infrastructure can exacerbate the impacts of climate events such as flooding, heatwaves, and storms, as well as geophysical hazards like earthquakes (Rosenzweig et al., 2018), leading to cascading disruptions across urban systems, as demonstrated by events such as the 2011 Great East Japan Earthquake and Hurricane Sandy in 2013 (Pescaroli & Alexander, 2016). Cities reliant on centralized, rigid infrastructure systems are more vulnerable to such cascading failures, whereas those with decentralized, flexible, and redundant systems can adapt more effectively (Ahern, 2011). A taxonomy of grey and green infrastructure is necessary to investigate urban vulnerability from a physical perspective. Grey infrastructure, such as roads, bridges, and drainage systems, require continuous assessment and retrofitting to withstand emerging climate stresses. Meanwhile, green infrastructure, including parks, wetlands, and permeable surfaces, plays a crucial role in mitigating risks by enhancing water absorption, reducing heat islands, and supporting ecological resilience (Rosenzweig et al., 2018). Integrating green infrastructure into urban design can reduce systemic vulnerabilities by improving adaptive capacity and fostering ecosystem-based solutions to urban challenges.

- **Social Inequalities**: social factors such as income inequality, access to resources, and governance structures play significant roles in determining systemic vulnerability. Systemic vulnerability of cities is significantly influenced by social inequalities, as disparities in wealth, access to resources, and political power shape how different communities experience and recover from urban risks (Adger, 2006). Marginalized populations—often concentrated in informal settlements or poorly maintained housing—are more exposed to environmental hazards, economic instability, and infrastructural failures (Wisner et al., 2012). These inequalities create uneven capacities to adapt, reinforcing cycles of vulnerability across generations (Pelling, 2003). For example, in disaster scenarios, lower-income communities may lack access to early warning systems, resilient infrastructure, or adequate post-disaster support, exacerbating their risks (Cutter et al., 2003). Furthermore, systemic vulnerabilities arise from the exclusion of marginalized groups from urban planning and governance processes, leading to policies that fail to address their specific needs (Fainstein, 2010). Social inequalities also influence the resilience of urban infrastructure by affecting investment priorities. Wealthier districts often receive better services, such as flood defenses and reliable public transport, while poorer neighborhoods suffer from neglected infrastructure, making them more susceptible to systemic failures (UN-Habitat, 2020). Addressing these vulnerabilities requires inclusive urban policies that promote equitable access to resources, participatory governance, and social-justice-oriented resilience strategies (Anguelovski et al., 2016; Wisner et al., 2013c).

- **Planetary Boundaries and Ecosystems**: urban settlements are deeply interconnected with planetary boundaries and ecosystems, making them vulnerable to environmental changes and cascading risks. Cities depend on surrounding ecological systems for essential services such as clean water, air purification, and food production, yet these ecosystems are increasingly degraded due to urban expansion, pollution, and climate change (Rockström et al., 2009). The depletion of these natural resources not only threatens biodiversity but also increases the vulnerability of urban populations by reducing their capacity to adapt to shocks (Steffen et al., 2015). Systemic vulnerability emerges from the dependency of human societies on ecosystem services, such as coastal wetlands that provide natural protection against storms (Millennium Ecosystem Assessment, 2005). The loss of these protective ecosystems exposes cities to more severe flooding, erosion, and storm surges, particularly in coastal megacities facing rising sea levels.

- **Governance and Institutional Capacity**: systemic vulnerability of cities is strongly influenced by governance and institutional capacity, as these factors determine how well urban systems can anticipate, respond to, and recover from crises. Weak governance, characterized by corruption, lack of transparency, and poor coordination among agencies, often exacerbates vulnerabilities by delaying critical interventions and misallocating resources (Pelling 2011). Institutions with low adaptive capacity struggle to enforce regulations on land use, infrastructure maintenance, and environmental management, leading to unsafe urban development and increased exposure to risks (Bulkeley & Betsill 2013). In contrast, strong governance frameworks that integrate participatory decision-making and proactive risk management can enhance urban resilience (Rodríguez-Pose & Storper 2020) and influence vulnerability reduction (Wisner et al. 2013c). Moreover, cities with fragmented governance structures often face inefficiencies in responding to disasters and crises, as overlapping jurisdictions and bureaucratic inertia slow down response efforts (Amin 2014). Decentralization and the devolution of power to local governments, when accompanied by adequate funding and expertise, can improve institutional capacity and resilience-building efforts (UN-Habitat 2020).

In conclusion, vulnerability assessments are crucial for understanding the complex interactions between hazards and different forms of vulnerability. These assessments span across physical, economic, sociocultural, and political dimensions, with physical vulnerabilities often being hazard-specific and others, like economic or institutional weaknesses, being more broadly applicable (Brooks, 2003; Birkmann 2006b; Schneiderbauer & Ehrlich, 2006; Cardona et al., 2012). Non-physical vulnerabilities, which are harder to quantify, require mixed methods for evaluation, blending quantitative data with qualitative insights (Meyer, 2011). This is particularly important in local contexts where data may be limited, and participatory approaches, along with expert opinions, can fill knowledge gaps. Factors such as cultural beliefs, governance quality, and the adoption of risk-reduction measures play a significant role in shaping preparedness (Mercer et al., 2012). However, the true extent of vulnerability often becomes evident only post-disaster, with loss and damage data providing valuable validation (Hossain et al. 2019). The uncertainties inherent in vulnerability assessments arise from the limitations in knowledge, data accuracy, and modeling, which can be categorized into 'aleatory' and 'epistemic' uncertainties (Schneiderbauer et al., 2017; Feizizadeh et al., 2017). Despite the wealth of vulnerability frameworks in research, there remains a gap in translating these frameworks into actionable tools, particularly in Europe, where standardized methods could enhance monitoring and comparability (Cardona et al., 2012; Orru et al., 2021). Moving forward, integrating systemic approaches and considering socio-ecological and socio-technological interactions is essential, especially in the context of climate change, where urban vulnerabilities must be continuously assessed within dynamic and shifting socioeconomic and environmental conditions. Vulnerability assessments should, therefore, adopt a coupled human-environmental system perspective, encompassing four critical subsystems: the physical system, the functional system, the socio-anthropic subsystem and the ecological one to effectively address the complexities of systemic vulnerability in urban areas. These subsystems can be understood as (Fistola et. al., 2020; McPhearson et al., 2016; Hillier; 2012):

1. **Physical subsystem**: includes buildings, streets, houses, squares, and all material but non-living components.
2. **Functional subsystem**: encompasses activities, relationships, and all intangible components.
3. **Socio-Anthropic subsystem**: comprises citizens, users, perceptions, and all elements that shape the life of the city.
4. **Ecological subsystem:** ranges from urban green spaces to urban ecosystems, all natural elements and all-living components

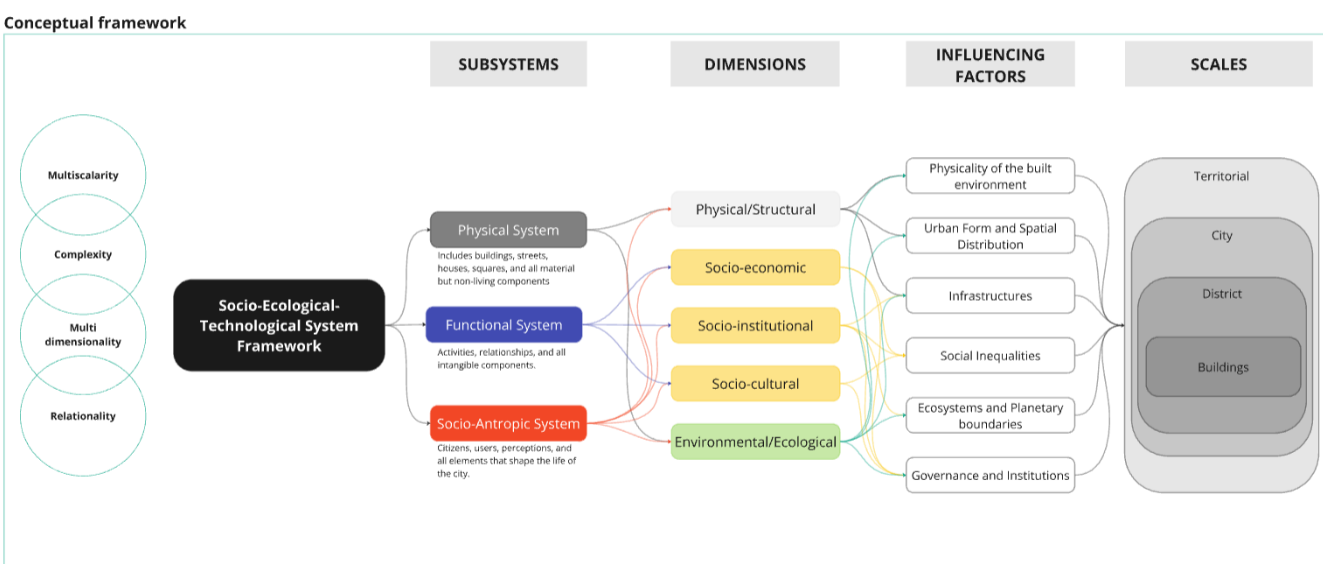


Figure 3. *Conceptual framework for systemic vulnerability of urban settlements*

2.2.1 Review on systemic vulnerability: dimensions, assessments models and tools

A preliminary analysis of the state of the art on systemic vulnerability of urban settlements, carried out to address the automated review procedures, showed that existing assessment frameworks varies in scale, dimensions, methodologies and tools, from qualitative indices to modelling and simulation-based approaches.

Hence, this paragraph aims to return to the state of the art of the scientific literature on systemic vulnerability, with a focus on the different existing models and tools for its assessment. The study has been conducted on three databases: Scopus, Web of Science and Science Direct. The method used is PRISMA for Scoping Reviews (Tricco et al., 2018), an exploratory and meta-analytical research methodology that works on a statistical basis and allows the mapping of the scientific production in a given subject area (Arksey et al., 2005). The main goal of the Scoping Review is to identify the main methods and tools used for the assessment of systemic vulnerability, highlighting the different dimensions considered and the scale of application, with a focus on urban and metropolitan settlements. Furthermore, the review aimed to answer the following research questions: what are the main methodological approaches used to assess systemic vulnerability? How is systemic vulnerability modelled and simulated in the various disciplinary approaches? Specifically, how are the diverse types of vulnerability (physical, social, etc.) integrated into multi-risk assessments and what models and simulation techniques are used for assessment?

Based on these preliminary remarks, this research examined publications over a time span from 2010 to 2025. The methodology employed for the collection of data in the three databases listed above refers to the text string search system: the concept of systemic vulnerability was associated with those related to risk type, assessment and modelling and simulation, using semantic fields able to guarantee the maximum quantitative restitution of the results, given the different forms (both in full and by acronym) with which they are commonly referred to. Nine searches (corresponding to the nine elaborated strings) were carried out, all having in common the concept of systemic vulnerability.

The methodology outlined involved analysing separately the relationships between systemic vulnerability and the issues of assessment and modelling and simulation in relation to the diverse types of risk considered. Only English-language peer reviewed papers falling into the categories of scientific paper, volume, contribution in volume, conference proceedings, review were included in the search. Furthermore, the search was limited to only within the title, abstract and keywords of the content loaded into the databases.

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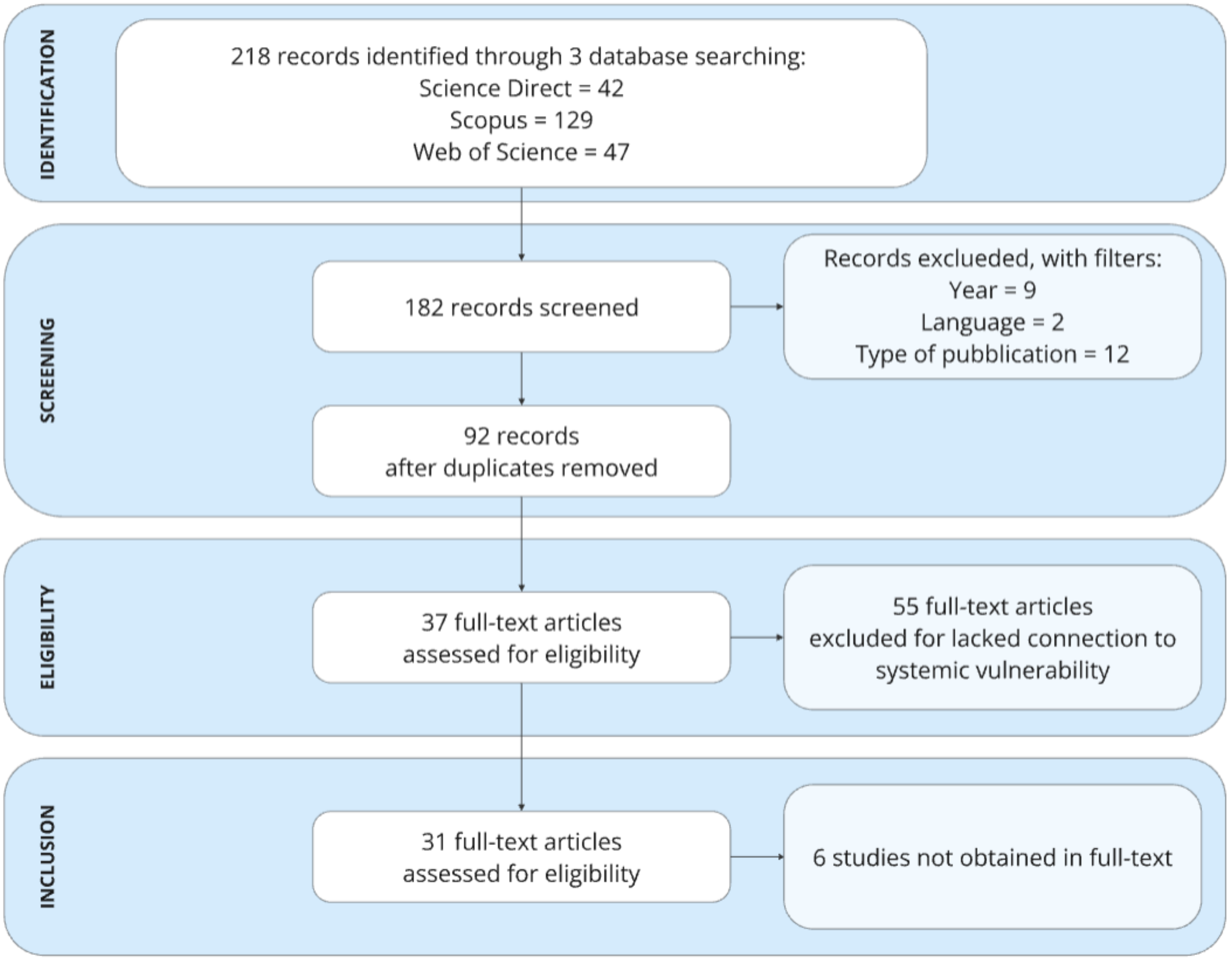


Figure 4. *PRISMA flow diagram of literature review process.*

The search in the three databases returned a total of 218 contributions. By applying the filters of year, publication type and language, the number of contributions was reduced to 182.

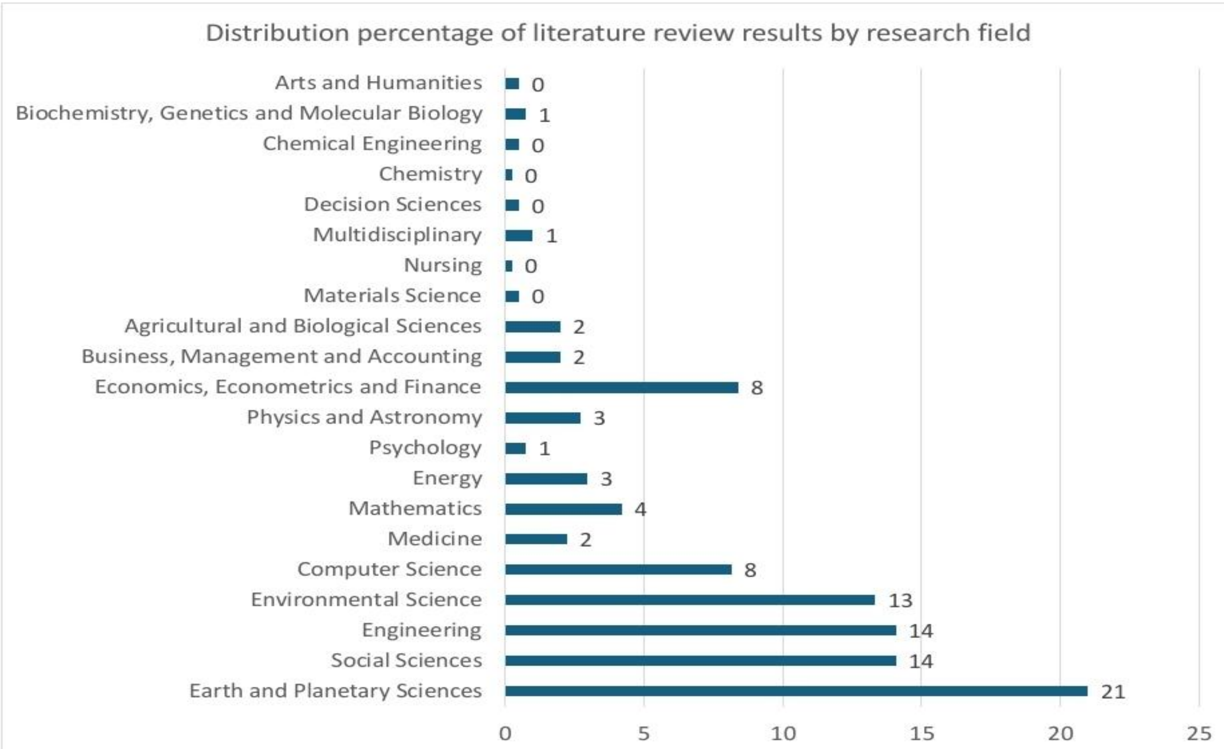
Table 5. Number of contributions after the search in the selected databases.

Database	Number of contributions without applying filters	Number of contributions applying filters
Scopus	129	112
Web of Science	47	31
Science Direct	42	39

The filtered results of the three databases were organized to eliminate any duplicates. Thus organised, the contributions were further filtered through a screening of the abstracts and keywords to understand the research field they belonged to and their coherence with issues related to systemic vulnerability assessment concerning risks and urban settlements. As Table 6 shows, analysing the research fields of the contribution resulting from the literature review, it emerges that the major percentage of them is linked with the Earth and Planetary Sciences (21%), followed by the Social Sciences and Engineering (both equal to 14%) and Environmental Science (13%).

The research fields considered were the Scopus and Science Direct ones, while the Web of Science were adapted to them as they are not the same as label but strictly linked for their mean.

Table 6. Literature review results by research fields



Thus filtered, 31 contributions were selected for analysis concerning the research questions underlying the review process. For each contribution, the research field, evaluation method, model used (if applicable), dimensions of vulnerability involved (physical-structural, social-institutional-economic, ecological), and scale of application (territorial, city, district, building) were identified.

Table 7. Synthesis matrix of the eligible contributions for the review.

Reference	Subject area	Evaluation Method	Models	Hazard	Dimension (physical-structural, social-institutional-economic, ecological)	Scale (Territorial, City, District, Building)
Albano, R., Pascale, S., Sdao, F., & Sole, A. (2013)	Engineering	Parameter-based scoring system	GIS-based Model	Geophysical	Physical - structural	City
Scaini, C., Felpeto, A., Martí, J., & Carniel, R. (2014)	Engineering	Damage Matrix	GIS-based Model	Geophysical	Physical - structural	Territorial
Walker, B. B., Taylor-Noonan, C., Tabbernor, A., McKinnon, T. B., Bal, H., Bradley, D., & Clague, J. J. (2014)	Geography	AHP method	GIS-based Model	Geophysical	Physical - structural Socio - institutional - economic	Territorial
Porter, H., Wilson, T. M., Weir, A., Stewart, C., Craig, H. M., Wild, A. J., & Buzzella, M. (2025).	Earth Science	Fault Tree Analysis	GIS-based Model	Geophysical	Physical - structural	Territorial
de Vries, J., Atun, F., & Koeva, M. N. (2023)	Urban Studies	Indicator-based approach	Tridimensional Model	Geophysical	Physical - structural	City
Lara-Valencia, F., Garcia, M., Norman, L. M., Anides Morales, A., & Castellanos-Rubio, E. E. (2022)	Urban Studies	Land Suitability Analysis Hydrological modelling	GIS-based model	Climatic	Physical - structural	Territorial

Albulescu, A. C. (2023)	Urban Studies	Network Analysis Weighted Overlay Analysis	GIS-based model	Geophysical	Physical - structural	Territorial
Weir, A. M., Wilson, T. M., Bebbington, M. S., Campbell-Smart, C., Williams, J. H., & Fairclough, R. (2024)	Earth Science	Hazard-Agnostic Analysis Hazard-Dependent Analysis	-	Geophysical	Physical - structural	Territorial
Pitilakis, K., Argyroudis, S., Kakderi, K., & Selva, J. (2016)	Earth Science	Performance Indicators	-	Natural	Physical - structural	Territorial
Wang, F., Zheng, X. Z., Li, N., & Shen, X. (2019)	Engineering	Network Entropy model	-	Multiple	Physical - structural	City
Galderisi, A., & Limongi, G. (2021)	Urban Risk Planning	Multi-Hazard Assessment	Risk-Informed Planning Model	Multi-risk	Social-Institutional-Economic	Territorial
Moradi, M., Delavar, M.R. & Moshiri, B. (2017)	Seismic Risk Assessment	GIS & Multi-Criteria Analysis	Choquet Integral Model	Earthquake	Physical-Structural	City
Pascale, S., Sdao, F., and Sole, A. (2010)	Geology	Landslide Risk Model	Systemic Vulnerability Model	Landslide	Physical-Structural	District
de Vries, J., Atun, F., & Koeva, M. N. (2023)	Disaster Risk Management	3D Risk Communication	Earthquake Disruption Model	Earthquake	Social-Institutional-Economic	Territorial
Beltramino, S., et al. (2022)	Urban Studies	Multi-Disciplinary Assessment	Territorial Vulnerability Framework	Multi-risk	Social-Institutional-Economic	City
Golla, A. P. S., Bhattacharya, S. P., & Gupta, S. (2022)	Engineering	Structural Vulnerability Analysis	Built Environment Response Model	Earthquake	Physical-Structural	Building
Albulescu, A. C., et al. (2022)	Seismic Risk Assessment	Systemic Vulnerability Analysis	Urban Seismic Risk Model	Earthquake	Physical-Structural	City

Pasi, R., et al. (2018)	Urban Resilience	Flood Risk Assessment	Spatial Planning Framework	Flood	Social-Institutional-Economic	Territorial
Hénaff, A., et al. (2018)	Coastal Risk	Historical Hazard Analysis	Coastal Erosion & Submersion Model	Coastal	Ecological	Territorial
Gomez-Zapata, J. C., et al. (2021)	Volcanic Risk	Community Perception & Risk Communication	Volcanic Hazard Model	Volcanic	Social-Institutional-Economic	Territorial
Barclay, J., et al. (2022)	Disaster Studies	Historical Disaster Mapping	Volcanic Response Model	Volcanic	Social-Institutional-Economic	Territorial
Stenfors, E., et al. (2024)	Socio-Hydrological Systems	Climate Vulnerability Assessment	Drought Risk Model	Climate	Ecological	Territorial
Bonadonna, C., et al. (2021)	Applied Volcanology	Volcanic Risk Integration	ADVISE Model	Volcanic	Physical-Structural	Territorial
Dominguez, L., Bonadonna, C., Frischknecht, C., Menoni, S. and Garcia, A. (2021)	Disaster Forensics	Post-Event Impact Assessment	Disaster Forensic Model	Volcanic	Physical-Structural	Territorial
Albulescu, A. C., Larion, D., & Grozavu, A. (2020)	Seismic Vulnerability	Multi-Criteria Assessment	School Seismic Risk Model	Earthquake	Physical-Structural	Building
Hellequin, A.P., Flanquart, H., Meur-Ferec, C., Rulleau, B. (2013)	Social Sciences	Risk Perception Analysis	Coastal Vulnerability Model	Coastal	Social-Institutional-Economic	District
Hürlimann, M. et al. (2024)	Engineering	Multi-Hazard Scenario Analysis	PARATUS Project Model	Multi-risk	Social-Institutional-Economic	Territorial
Sdao, F., Sole, A., Pascale, S., & Giosa, L. (2011)	Geology	Landslide & Flood Combined Risk	Urban Hazard Model	Multi-risk	Physical-Structural	District
Shughrue, C., Seto, K.C. (2018)	Industrial Risk	Network Analysis	Urban-Industrial Risk Propagation Model	Multi-risk	Economic	Global

Greco, M., Martino, G. (2016).	Flood Risk Management	Preliminary Risk Mapping	Coastal Vulnerability Model	Flood	Ecological	Territorial
Atun, F., Menoni, S. (2014)	Urban Studies	Seismic Vulnerability Analysis	ENSURE Methodology	Earthquake	Physical-Structural	City

Based on the research linking systemic vulnerability with modelling and simulation aspects concerning geophysical and climatic risks, it emerges that the studies reported in the table above focus mainly on physical-structural, socio-institutional-economic and, in some cases, ecological dimensions.

Several studies conceptualize systemic vulnerability by examining multi-hazard urban environments and their interdependencies. Galderisi and Limongi (2021) emphasize the importance of integrating exposure and vulnerabilities in urban planning strategies, advocating for a risk-informed approach (Galderisi & Limongi, 2021). Similarly, Beltramino et al. (2022) develop a multidisciplinary framework to assess territorial vulnerability, demonstrating its application in Moncalieri, Italy (Beltramino et al., 2022).

Systemic vulnerability is also analyzed in the context of seismic hazards. Moradi et al. (2017) propose a GIS-based multi-criteria analysis model, integrating game theory and Choquet integral to assess earthquake vulnerability (Moradi et al., 2017). Golla et al. (2022) assess the systemic response of the built environment to earthquakes, emphasizing discrete and interdependent structural vulnerabilities (Golla et al., 2022). Albulescu et al. (2022) investigate the earthquake vulnerability of urban centers in Romania, emphasizing the role of systemic interactions in hazard propagation (Albulescu et al., 2022).

In coastal environments, systemic vulnerability is explored through historical hazard analysis. Hénaff et al. (2018) assess the long-term impacts of coastal erosion and submersion, highlighting the need for historical approaches in vulnerability assessment (Hénaff et al., 2018). Greco and Martino (2016) propose an early-stage flood risk mapping methodology, focusing on coastal areas (Greco & Martino, 2016). Hellequin et al. (2013) analyze community perceptions of coastal submersion risk, contributing to the broader understanding of systemic coastal vulnerabilities (Hellequin et al., 2013).

Systemic vulnerability in volcanic risk is another key research area. Gomez-Zapata et al. (2021) examine community perception and risk communication concerning the Cotopaxi Volcano, demonstrating how systemic factors influence disaster preparedness (Gomez-Zapata et al., 2021). Bonadonna et al. (2021) introduce the ADVISE model, integrating hazard, exposure, vulnerability, and resilience for emergency management in volcanic contexts (Bonadonna et al., 2021). Barclay et al. (2022) provide a historical perspective, mapping responses to volcanic disasters over two centuries and their impact on long-term vulnerabilities (Barclay et al., 2022).

Various methodologies have been developed to quantify and assess systemic vulnerability. Most of the methodologies used in the experiments employ GIS-based spatial analysis, network theory and multi-criteria evaluation methods (MCE) to assess vulnerability in spatial and urban contexts. GIS-based approaches are frequently utilized, particularly in seismic and flood risk assessments. Moradi et al. (2017) and Patel et al. (2021) both emphasize the role of GIS in spatial risk mapping (Moradi et al., 2017; Patel et al., 2021).

Multi-criteria decision analysis (MCDA) is another prominent method. Pasi et al. (2018) incorporate MCDA in urban vulnerability assessments to flooding, linking it to spatial planning frameworks (Pasi et al., 2018). Similarly, Albulescu et al. (2020) apply a multi-criteria assessment to evaluate seismic vulnerability in school buildings in Vaslui, Romania (Albulescu et al., 2020).

Network analysis is used to assess the interconnected nature of systemic vulnerability. Shughrue and Seto (2018) investigate the vulnerabilities of global urban-industrial networks, demonstrating how hazards propagate through economic linkages (Shughrue & Seto, 2018). Similarly, de Vries et al. (2023) utilize 3D modeling to communicate earthquake risk and its systemic implications in Istanbul (de Vries et al., 2023).

Scenario-based simulation techniques are also widely employed. Dominguez et al. (2021) present an integrative post-event impact assessment framework for volcanic eruptions, using forensic investigation methods (Dominguez et al., 2021). Hürlimann et al. (2024) propose a multi-sectoral and multi-hazard risk assessment methodology as part of the PARATUS project, simulating systemic disruptions across different sectors (Hürlimann et al., 2024).

Pascale et al. (2010) develop a systemic vulnerability model for landslide-prone areas, demonstrating its applicability in hazard assessment frameworks (Pascale et al., 2010). Sdao et al. (2011) extend this model to urbanized areas, analyzing the combined risk of landslides and floods (Sdao et al., 2011).

All approaches emphasise systemic interdependencies, such as the interaction between infrastructure networks (i.e. transport, water distribution and electricity) and their cascading failures under hazardous conditions. Other studies integrate scenario-based assessments and employ probabilistic models, fragility functions and weighted overlays to assess potential impacts under different disaster scenarios. Furthermore, a trend towards risk-informed urban planning and emergency response strategies derived from the use of accessibility mapping and decision support tools is emerging. However, there are differences in methodological frameworks and specific considerations related to several types of risk. Some studies, such as Walker et al. (2014) and Scaini et al. (2014), incorporate socio-economic and institutional factors, providing a more holistic view of resilience and decision-making processes, rather than simple assessments of physical damage. Others, such as Porter et al. (2025) and Weir et al. (2024), focus on sector-specific vulnerabilities, such as water supply systems and interdependent critical infrastructure, with a strong emphasis on functional loss rather than direct physical damage. Other studies such as Fei et al. (2019) introduce entropy-based models for urban water networks, distinguishing their approach by avoiding pre-defined failure scenarios.

Overall, the analysed studies share common techniques in assessing systemic vulnerability, but they differ in scope, focus on hazards and the balance between physical-structural and socio-economic dimensions. These variations highlight the need for appropriately tailored methodologies depending on the type of risk, spatial scale, and interconnections between system components.

The reviewed literature highlights the complexity of systemic vulnerability and the necessity of multi-disciplinary assessment approaches. The interpretation of systemic vulnerability varies across different domains, including urban resilience, seismic risk, coastal hazards, and volcanic disasters. Methodologies such as GIS-based analysis, MCDA, network analysis, and scenario-based simulations offer diverse tools for evaluating systemic vulnerabilities.

Future research should focus on integrating these methodologies to develop more robust and adaptive frameworks for systemic vulnerability assessment. The combination of spatial data analytics, network science, and multi-hazard modeling could enhance the predictive capabilities of vulnerability assessments and inform more effective risk mitigation strategies.

2.2.2 Spatial aspects in characterizing systemic vulnerability

The definition of vulnerability and exposure to hazards of different parts of urban settlements depends on several spatial aspects, i.e. the characteristics of the built environment, urban infrastructure, environmental or natural-landscapes. Such features may differ substantially, defining mutual dependencies among the different scales due to the complexity that characterize cities.

To characterize vulnerability, the development of knowledge models of urban settlements must consider the identity and characterization factors of places, the interpretation of their environmental, cultural, functional, and critical characteristics, and the physical component. Thus, knowledge models are configured as complex processes due to the multiplicity of information and data that, at different scales (from building-open spaces to neighbourhoods-urban district), relate type-morphological, physical, functional and performance aspects. These analyses provide an understanding of the vulnerability of built-up spaces, to be considered not as a characteristic of a particular spatial element but as a feature of a complex system in which the elements are interconnected (Sdao et al., 2011).

To understand the dynamic and complex interactions between the elements of urban settlements and overcome the hierarchical classification by elements (territory, city, district, building component), the development of a knowledge framework that considers the relationships between different systems and a set of typo-morphological, environmental, and spatial features of each system can be crucial.

Such conceptualization takes into account the flow of interactions among urban elements and different dimensions (socioeconomic, socio-spatial, environmental), offering a common language to describe the city ecosystem as a set of physical structures coupled with the living entities that make up urban settlements (Figure 5). Accordingly, this approach may reflect the increased complexity of urban system characterization in relation to systemic vulnerability, integrating physical, ecological, functional and socioeconomic aspects into the knowledge models.

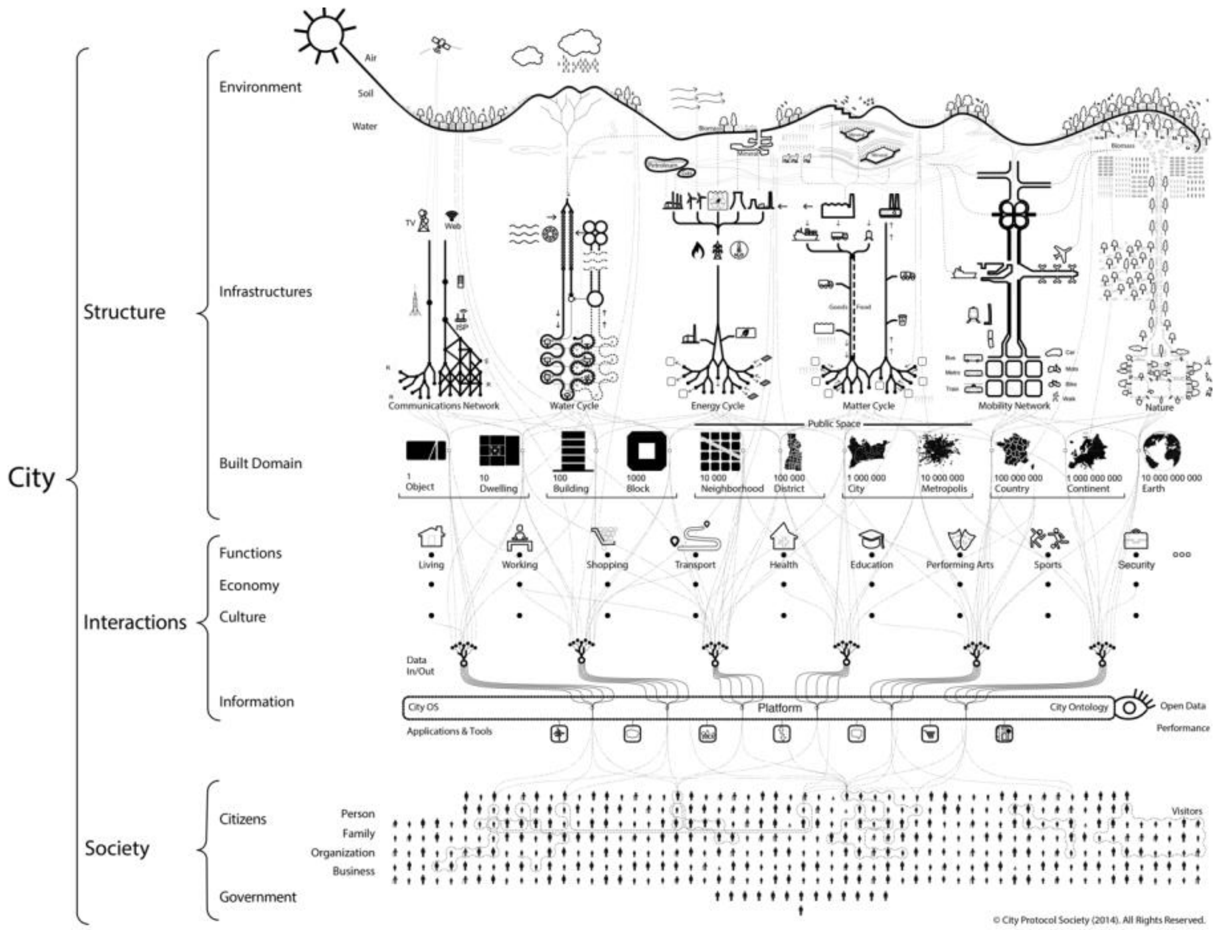


Figure 5. *City Anatomy. City Protocol, 2015. Source: https://cityprotocol.cat/wp-content/uploads/2019/07/CPA-I_001-v2_City_Anatomy.pdf*

2.2.2.1 From territorial to building scales vulnerability

Territorial vulnerability to multihazard can be defined as the predisposition of a geographic area to suffer damage or loss from the impact of multiple hazards (Maletta et al., 2022; Navarro et al., 2023). This concept helps to explain why similar levels of hazard and exposure result in different levels of impact across territories, making hazard impacts unevenly distributed (UN, 2016). In studies about territorial vulnerability, while hazards are physically determined, exposure and vulnerability are socially constructed and linked to socio-economic inequalities (Cutter et al., 2003; Brooks et al., 2005; Myers et al., 2008; Tate et al., 2016; Barreca et al., 2017). Territorial vulnerability to multihazard can be assessed at various scales, ranging from local communities to entire regions or countries (Barros Tavares et al. 2015). The scale of analysis influences the level of detail and the types of data and methods used:

· **local scale**: Focuses on specific district or infrastructure, assessing vulnerabilities in detail;

· **regional/national scale**: Considers broader patterns of vulnerability across larger areas, integrating multiple data sources and modeling techniques.

Various elements contribute to territorial vulnerability to multihazards, including: (1) demographic characteristics, socio-economic status, and access to resources, influencing community vulnerability (Wisner et al., 2003); (2) the built environment, including buildings, transportation networks, energy systems, and communication systems, highly susceptible to hazards (UNISDR, 2015); (3) economic activities, livelihoods, and assets, elements at risk of financial losses and disruptions from hazards (IPCC, 2014); (4) natural ecosystems, biodiversity, and ecosystem services which may suffer degradation, impacting human well-being and resilience (MEA, 2005); (5) cultural heritage (cultural sites, monuments, and traditions) can be damaged or lost due to hazards (Sabbioni et al., 2008).

Territorial vulnerability assessments frequently rely on composite indicators, which have been widely applied in research. Since Cutter et al. (2003) introduced the Social Vulnerability Index (SoVI) to measure vulnerability to environmental hazards, interest in the field has grown significantly (Liu & Li, 2016). Cutter et al. (2003) assessed vulnerability in the U.S. at the county level using principal component analysis (PCA) with 42 independent variables, combining extracted components and by using equal weighting. This methodology enables the reduction of data dimensionality, allowing the identification of patterns and key vulnerability factors (Oppio et al., 2017; Frigerio & Amicis, 2016; Conlon et al., 2020; Yu et al., 2021).

Similarly, the Social Vulnerability Index (SVI) developed by the U.S. Centers for Disease Control and Prevention (Flanagan et al., 2011) and the Strength-Based Social Vulnerability Index (SSVI) by Ogie & Pradhan (2019) provide composite measures of vulnerability. Navarro et al. (2023) analyzed territorial vulnerability at the provincial level in Europe, identifying which regions are most susceptible to natural hazards.

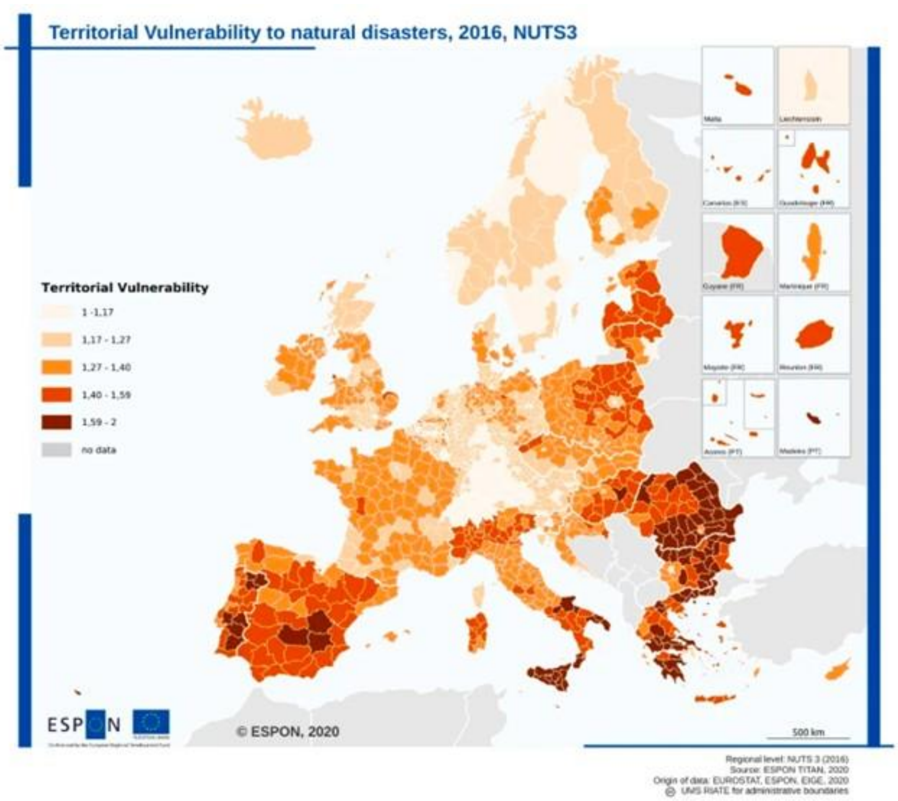


Figure 6. *Territorial vulnerability to natural hazards in Europe: a composite indicator analysis and relation to economic impacts. Source: Navarro et. al 2023.*

Since vulnerability is closely linked to social and economic stratification (Myers et al., 2008), quantifying inequalities through key indicators — such as access to services, legislative frameworks, building age conditions, and demographic factors — enables a better understanding of territorial vulnerability. The level of vulnerability of a given territory contributes to understanding how a natural hazard could escalate into a disaster. By assessing and combining hazards, impacts, and vulnerability, decision-making for disaster risk management can be significantly improved across various territorial scales.

In a multiscale perspective territorial vulnerability it can be useful to understand which are the constraints of a specific territory to which the urban settlements are related. This helps in identifying key drivers of systemic vulnerability in a context-based perspective supporting the study of multiple interrelated scales. Territorial vulnerability at the city scale reflects broad systemic risks, such as infrastructure fragility, climate change impacts, and socio-economic inequalities that can shape urban resilience and the possibility to respond to stresses. At the district scale, vulnerabilities become more localized, influenced by land use patterns, building conditions, and community preparedness. A multiscale perspective integrates these levels, enabling targeted risk reduction strategies that address both macro-urban dynamics and micro-local needs, fostering adaptive and resilient urban settlements.

The district dimension (cfr. Dv 5.5.2), conceptual and spatial, is between the urban scale and the more detailed scale of building blocks. The reference is to areas of 20,000-50,000 inhabitants, contextually defined by multiple aspects that include natural boundaries, geomorphological features, infrastructure system, administrative boundaries, homogeneous urban fabrics, road patterns, homogeneous economic value, construction period, and technical-constructive features. Urban Districts are structured on the basis of different information layers, including elements of urban taxonomies, ontologies, and specific parts of the urban fabric, in a progressive scalarity approach up to building blocks (Losasso, 2021).

The perimeter of the Urban Districts, which can differ from the administrative boundaries, is based on the characteristics of the built environment related to vulnerability and exposure factors such as prevailing building types, density of construction, period of construction, prevailing functions, urban infrastructure, road pattern, physical limits, environmental and natural-landscape aspects (natural limits, etc.).

To identify the system of relationships existing between the various components of urban systems, the analysis and characterization of urban settlements in response to multi-risk conditions is a fundamental step. Addressing the dynamics related to the vulnerability and exposure of urban fabrics, urban systems can be read through a process of classification and modelling that considers the multi-scalar interactions between the subsystems and different interpretative categories (Moudon, 1997). In the next paragraph a refinement of the taxonomy reported in DV 5.2.2 is presented, considering systemic vulnerability aspects.

2.2.2.2 A taxonomy of the physical system of urban settlements (rif. DV 2.2)

The analysis and characterization of urban settlements in response to multi-hazard conditions is a fundamental step as a process aimed to identify the system of relationships that exist among the various components of urban systems. To this end, various analytical approaches can be used, ranging from morphological readings to perceptual interpretations, as well as methodologies able to analyze the interactions of physical phenomena with social, economic and environmental terms (Steiner, 2008). In the framework of the activities of Task 5.2.2 "Integrated physical and socio-ecological exposure to multiple hazards" (Leader: M. Losasso, co-leader: P. Vannucchi), in DV 5.2.2 -"Multi-criteria metrics and methodology for integrated exposure assessment" an urban settlements climate-risk oriented knowledge approach has been developed to categorize and describe the subsystems of the urban area, their relationships and relevant feature that contribute to the increase in impacts arising from different types of risks. For a further understanding of the risk-oriented taxonomy and ontologies of urban settlements, DV 5.2.1 should be also referred to.

The taxonomy incorporates the classification of the urban settlement into sectoral domains (Grey, Green and Soft) as stated in recent national strategic documents (NCCAP and NCCAS, respectively National Climate Change Adaptation Plan and National Climate Change Adaptation Strategies), providing a systemic representation of urban conditions and the interconnections between natural and man-made elements.

The sectoral areas differentiation, the Grey one and the Green one, helps to emphasize the risk-oriented value adopted in the construction of the taxonomy. Although the Grey, unlike the Green, lacks natural features, both can contribute to the reduction of climate risk impacts if addressed by climate-oriented design actions.

Regarding its structure, the Grey sectoral area has been broken down into the system of built-up areas, including building blocks (courtyard blocks, residential units and aggregates) and paved outdoor spaces (squares, urban voids, routes), and technological systems (water, communication, sewage, energy, mobility).

The Green sectoral area consists of systems with natural characteristics within the physical system (Green and Blue), capable of contributing to an adaptation response to climate change. The Green area consists of Vegetated areas (woods, forests, parks, gardens, agricultural areas, urban greening, non-cultivated areas, green-blue infrastructures) and unvegetated areas (non-cultivated areas and bare soil); the Blue system of Water bodies (rivers, riverside, lakes) and Shoreline (beaches and dunes).

It is important to point out that an internal description of the lower level of description – based on aggregation rules and/or technological typification widely used in urban studies and derived through the definition of “root categories” (Berta et al., 2016) as Grey and Green sectoral area – is not an aim of this research: that level of the hierarchy is at the edge of the field of urban design, which is the reference context of the present work.

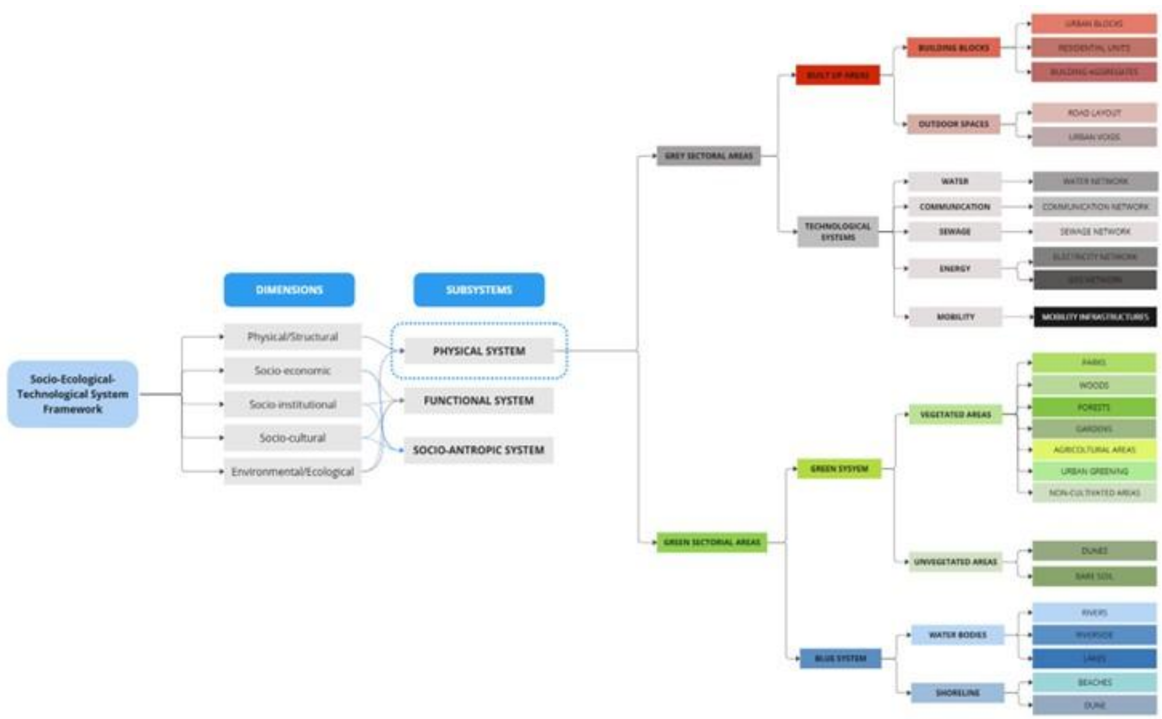


Figure 7. *Refined taxonomy of urban settlements classified by sectoral domains with a focus on the physical system.*

This reading distinguishes the physical component on the one hand and the functional/service component on the other. Moreover, this differentiation allows the elaboration of a knowledge model of the urban system based on the integration of the three identified macro-systems (soft, hard and population) to systematically represent urban conditions and the interconnections between natural elements and those influenced by the anthropic component. Such structure reflects the reference to the three main subsystems of Socio-Ecological-Technological Systems Framework (physical, functional, socio-antropic and ecological systems), as stated in the previous part of the this document (paragraph 2.1) (Figure 7).

2.2.3 Indicators and indexes for systemic vulnerability assessment

The study of vulnerability indices and indicators has gained significant attention in recent years, as they serve as critical tools for assessing societal resilience to various hazards. Vulnerability indicators are categorized across multiple dimensions, including demographic, economic, infrastructural, and environmental factors. Among the most frequently used indicators are: population density (Isidoro et al., 2013; Nath et al., 2015), age distribution (proportion of elderly and children) (Dong et al., 2020; Alam & Haque, 2018), employment rates (Moghadas et al., 2020; Tran et al., 2020), income levels (Spaliviero et al., 2018), fuel poverty (PLANNER), literacy rates (Vicente et al., 2014; Alam and Haque, 2021), and access to healthcare (Dong et al., 2021; Zhu et al., 2019). These indicators provide insights into the susceptibility of populations to adverse events such as natural disasters, economic crises, and climate change impacts.
Several methodologies are commonly employed to evaluate vulnerability indices. Statistical models, such as Principal Component Analysis (PCA) and factor analysis, are widely used for aggregating multiple indicators into composite indices (Cutter & Finch, 2008). These methods help in reducing dimensionality while retaining the most significant contributing factors. Additionally, Geographic Information Systems (GIS) play a fundamental role in spatial vulnerability assessments, enabling the visualization and mapping of risk-prone areas (Moghadas et al., 2019). Composite indices, such as the Social Vulnerability Index (SoVI), integrate multiple indicators to provide a comprehensive assessment of vulnerability at different geographic scales (Ainuddin & Routray, 2012).
Another prevalent approach involves the use of weighted indices, where different indicators are assigned specific weights based on expert judgment or empirical data (Chen & Leandro, 2019). This method allows for tailored assessments that reflect local conditions. Moreover, qualitative methods, such as Delphi surveys and stakeholder consultations, complement quantitative techniques by incorporating expert opinions and community perspectives (Yoga Putra et al., 2019).
Given the complexity and multifaceted nature of vulnerability, hybrid approaches that integrate both quantitative and qualitative methods are increasingly being utilized. These approaches enhance the robustness and applicability of vulnerability assessments, thereby facilitating more effective policy interventions and resource allocations. As the field evolves, advancements in big data analytics and machine learning are expected to further refine the accuracy and predictive capabilities of vulnerability indices, enhancing their role in disaster risk reduction and sustainable development planning.

Table 8.

SUBJECT AREA	HAZARD	DIMENSION	VULNERABILITY INDICATORS	UNIT OF MEASURE	DESCRIPTION	REFERENCE
POPULATION	Heat wave	Statistical Data	Population density	ab/m2	Population per unit land area. Where, Gp = urban population, Hv = district density	World Bank Data Bank
		Demographic Characteristics	Age	%	The proportion of population under 14-year old on the total population.	Dong et al., 2020; Oh et al., 2017
				%	The proportion of population over 65-year old on the total population.	Dong et al., 2020; Oh et al., 2017
				%	Boys under the age of 3	Lundgren & Jonsson, 2012
			Gender	%	The proportion of female population	Dong et al., 2020
			Ethnicity	%	The percentage of population of other ethnicity than white	Reid et al., 2009
			Disadvantage population	ab/m2	Groups of persons that experience a higher risk of poverty, social exclusion, discrimination and violence than the general population, including, but not limited to, ethnic minorities, migrants, people with disabilities, isolated elderly people and children.	PLANNER
			Fuel poverty	ab/m2	People that cannot afford to keep adequately warm at a reasonable cost, given their income.	PLANNER

		Households poverty	€/ab/year	Per capita income	Tran et al., 2020
		Employment	%	Represented by the employment and/or unemployment rate in the city.	Tran et al., 2020
		Household size	n.	Number of household residents	Oh et al., 2017
			%	Share of the elderly population living alone (aged 65 or older)	Oh et al., 2017; Lundgren & Jonsson, 2012
Flooding	Demographic Characteristics	Population density	uD = Gp/Hv	Population per unit land area. Where, Gp = urban population, Hv = district density	Isidoro et al. 2013
		People exposure	registered population at year-end/urban area	Represented by the population density in the city which indicates the number of people might be affected by the flood.	Moghadas et al., 2019
		Age	%	The percentage of people for each age class of population	
		Gender	%	The ratio of men to women, also the % of females (above 15 years old) in the labor force	Sandink & Binns, 2021
		Disadvantage population	ab/m2	Groups of persons that experience a higher risk of poverty, social exclusion, discrimination and violence than the general population, including, but not limited to, ethnic minorities, migrants, people with disabilities, isolated elderly people and children.	PLANNER

		Fuel poverty	ab/m2	People that cannot afford to keep adequately warm at a reasonable cost, given their income.	PLANNER
		Special needs	%	Per cent of the population with a disability	Liao, 2012
		Employment	(average number of employed staff and workers/registered population at yearend) *100%	Represented by the employment and/or unemployment rate in the city.	Moghadas et al., 2020
			%	The percentage of male people who are not in the labor force	Mabrouk and Haoying, 2023
			%	The percentage of unemployed individuals	Mabrouk and Haoying, 2023
Coastal erosion	Demographic Characteristics	Population density	human activities/km	The density of human activities is represented by the density of human activities on different coasts in the same time period or in a specific time period.	Mahapatra et al., 2014; Fu et al., 2022
		Poverty headcount ratio	%	Calculated by population and Housing Census.	Roy et al., 2021
		Dependency ratio	%	Calculated by population and Housing Census.	

			Disability	%	Calculated by population and Housing Census.	
			Employment	Total number	Calculated by population and Housing Census.	
			Literacy rate	%	Calculated by population and Housing Census.	
	Earthquake	Demographic Characteristics	Population above 60 years of age	%	The proportion of population above 60 years of age on the total population. Calculated by population and Housing Census.	Cutter and Finch (2008), Vicente et al. (2014); Ainuddin and Routray (2012)
			Children below 15 years of age	%	The proportion of population below 15 years of age on the total population. Calculated by population and Housing Census.	Alam and Haque (2018), Rahman et al. (2015), Zebardast (2013)
			Female population	%	The proportion of female population on the total population. Calculated by population and Housing Census.	Alam and Haque (2021), Ghajari et al. (2017), Martins (2018), Armaş (2012), Armaş et al. (2017)
			Illiteracy rate	%	Calculated by population and Housing Census.	Vicente et al. (2014), Alam and Haque (2021)
			Family size	Average	Calculated by population and Housing Census.	Armaş (2012), Jena and Pradhan (2020), Martins (2018)
			Population density	pop/hectar	Calculated by population and Housing Census.	Nath et al. (2015), Zebardast (2013), Martins (2018)
HARD	Heat wave	Heat stress	Discomfort	index	Discomfort index (Temperature-humidity index)	Oh et al., 2017
		Built up areas	Access to green spaces	m	Proximity to public natural spaces	Reid et al., 2009

		Technological systems and networks	Air-conditioning	%	The percentage of households with air-conditioning	Tran et al., 2020; Lundgren & Jonsson, 2012
		Green and Blue Infrastructures	Green coverage	green covered area/urban area *100%	Represented by the percentage of green space area in the urban land	Tran et al., 2020
	Flooding	Built up areas	Sturdy housing type	%	The percentage of houses with durable construction materials	Mohtat &. Khirfan, 2021
			Housing age	%	The percentage of houses built before 1986	Kong et al., 2021
			Homeownership	%	The percentage of owner-occupied housing units	Mabrouk and Haoying, 2023
	Coastal erosion	Built up areas	Household density	Per km2	Calculated by population and Housing Census.	Roy et al., 2021
			Proximity of urban center to the shoreline	Km	Spatial location of urban centers.	
			Poor house	%	Calculated by population and Housing Census.	
SOFT	Heat wave	Health	GDP per capita	€/ab	GDP per capita is gross domestic product divided by midyear population. GDP is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources.	Dong et al., 2020

	Convenience to reach medical assistance facilities	km	Distance from own house to medical assistance facilities	Dong et al., 2021
	Acces to safe water	%	The percentage of households with lower access to safe water	Tran et al., 2020
	Health assistance	n.	Health staff per 10,000 people	Dong et al., 2021
		%	Number of public health workers per unit of population	Oh et al., 2017
	Health conditions	%	People with heart- or lung diseases	Öberg, 2009
		%	People with allergies affecting respiration	Öberg, 2009
		%	Proportion of elderly/diabetes (diabetes, age above 65 years)	Reid et al., 2009
	Mortality level	n.	Number of deaths caused by cardiovascular disorders	Oh et al., 2017
		n.	Number of deaths caused by heatstroke/sunstroke	Oh et al., 2017
	Services	n.	GRDP healthcare services and social services	Oh et al., 2017
	Insurance	%	Share of beneficiaries of health insurance	Oh et al., 2017
Education	Educational level	%	The proportion of population with education level below high school	Dong et al., 2020
		%	The percentage of population over the age of 15 who are illiterate	Tran et al., 2020
Law enforcement	National basic livelihood	%	Share of beneficiaries of national basic livelihood guarantees	Oh et al., 2017

		guarantees			
	Emergency	Emergency response	n.	Number of emergency medical centers	Oh et al., 2017
	Economy/Finance	Financial independence	Level (scale)	A state where an individual or household has accumulated sufficient financial resources to cover its living expenses without having to depend on active employment or work to earn money in order to maintain its current lifestyle.	Oh et al., 2017
		Gross Regional Domestic Product (GRDP)	€	Regional GDP is measured according to the definitions of the 1993 System of National Accounts. GDP per capita is calculated by dividing the GDP of a country or region by the population (number of inhabitants) living there.	Oh et al., 2017
Flooding	Health	Social insurance	persons covered of insurances /registered population at year-end	Represented by the various insurances received by the citizens	Ling & Chiang, 2018
		Health access	number of hospitals/ urban area	Represented by the hospital density of the city which indicates the amount of clinic services can be provided during the flood.	Zhu et al., 2019
		Medical capacity	number of hospital beds/registered	Represented by the number of hospital beds per 10000 registered population at year-end, which indicates the medical	Moghadas et al., 2019; Shah et al., 2020

		population at year-end	rescue capacity can be provided during the flood	
	Income	%	The percentage of the low-income population	Spaliviero et al., 2018
	Medical spending	%	The percentage of households spending 30% or more of their income on shelter costs	Spaliviero et al., 2018
	Built-environment conditions	%	The percentage of households living in homes with a need for significant repair	Liao, 2012
	Renter households	%	The percentage of renter households	Spaliviero et al., 2018
Education	Educational attainment equality	%	The percentage of people (25–64 years old) who have no/have certificate, diploma, or degree (including a high school diploma)	Moghadas et al., 2019
Recreational	Public recreational facilities	n.	Parks, sports halls per 10,000 populations	Bahrainy & Bakhtiar, 2016
Ecosystem	Harmony with nature	%	The percentage of land allocated to green spaces and blue spaces. The density of street trees per square meter	Mohtat &. Khirfan, 2021
Mobility	Public transportation service	number of public transport vehicles/registered population at year-end	Represented by the number of public transport vehicles per 10,000 population	Burton et al., 2016; Cutter et al., 2008

Law enforcement	Learning mechanism	number of government policies and regulations	Refers to the ability of learning from previous flood experience; Represented by the government policies and regulations related to flood mitigation. The policies and regulations are reviewed through provincial, municipal or local levels, such as provincial regulations, flood prevention plan, sponge city planning regulations	Yoga Putra et al., 2019
Emergency	Redundancy of emergency services	Yes/No	Presence of fire stations or emergency centers per 10,000 persons	Moghadas et al., 2020
	Civic and social advocacy organizations	Yes/No	Presence of civic and social advocacy organizations per 10,000 persons	Moghadas et al., 2020; de Bruijn et al., 2018
	Duration of evacuation	Hours	The interval of time from the detection of an incident which ultimately requires evacuation to the end of the period required for individuals to physically move out of an area.	Kuhlicke et al. (2011)
	Previous flood experience	Yes/No	Experience with floods in a time before the analysis one	Kuhlicke et al. (2011)
Economy/Finance	Economic tolerance	(total income – expenditure)/total income *100%	Represented by the difference between total household income and expenditure as a percentage of total household income. It reflects the ability to make up for potential economic losses.	Chen & Leandro, 2019; Moghadas et al., 2019

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		Local economic level	per capita gross regional product	Represented by the per capita gross regional product, which indicates the economic capacity for the recovery from the flood.	Chen & Leandro, 2019; Moghadas et al., 2020
Earthquake	Health	Household income	Average	Calculated by population and Housing Census.	Alizadeh et al. (2018), Nath al. (2015), Rahman et al. (2015)
		Economically dependent families	%	Calculated by population and Housing Census.	Alam and Haque (2018, 2021), Ozmen et al. (2014)

3. HAZARDS SYSTEMIC VULNERABILITY

3.1 Vulnerability to Geophysical hazards

3.1.1 The geological characterization of Slope and Ground instabilities

Slope and ground instabilities are significant geological phenomena that occur when the equilibrium of a slope is disrupted, causing the material to move downslope under the influence of gravity. These processes can manifest as landslides, rockfalls and debris flows, posing considerable risks to infrastructure, ecosystems, and human lives.

The slope instabilities arise due to a combination of intrinsic and external factors:

- Intrinsic Factors:

  - **Lithology**: the type of rock or soil significantly influences slope stability. Weak, unconsolidated materials such as clays, silts, or poorly cemented sandstones are more prone to failure compared to well-consolidated rocks.
  - **Structure**: geological structures, such as bedding planes, joints, faults, and folds, can create zones of weakness within a slope. The orientation of these structures relative to the slope face is critical; for instance, bedding planes dipping parallel to the slope can act as slip surfaces.
  - **Weathering**: chemical and physical weathering processes weaken the rock, reducing its strength and cohesion over time, making it more susceptible to failure.

- External Factors:

  - **Hydrology**: water plays a critical role in slope stability. It can reduce the shear strength of materials by increasing pore-water pressure and saturation levels. Heavy rainfall, rapid snowmelt, or changes in groundwater flow can trigger slope movements.
  - **Seismic Activity**: earthquakes generate ground shaking, which can dislodge unstable material and initiate landslides. The intensity and duration of the shaking are crucial determinants.
  - **Human Activity**: anthropogenic actions, such as deforestation, mining, excavation, and construction, can disturb the natural equilibrium of slopes and increase the likelihood of failure.

The movement of materials can occur through different mechanisms:

- **Falls**: rapid, vertical movements of rock or debris, often triggered by mechanical weathering or seismic activity.
- **Slides**: translational or rotational movements along a well-defined surface. Translational slides occur along planar surfaces, while rotational slides involve a curved slip surface.
- **Flows**: rapid movements of saturated materials, such as mudflows or debris flows, which behave like viscous fluids.
- **Creep**: slow, imperceptible deformation of soil or rock, often driven by freeze-thaw cycles or gradual gravitational forces.

The evaluation of slope instabilities relies on a combination of geological mapping, digital modeling, and geophysical methods. These approaches provide complementary insights, enabling a comprehensive understanding of terrain characteristics, subsurface conditions, and potential failure mechanisms.

The integration of geological mapping, digital models like DEMs, and geophysical data is crucial for the understanding of slope instability. Geological mapping provides a surface-level understanding of materials and structures, while DEMs and 3D models analyze terrain and predict failure scenarios.

Geophysics unveils subsurface features, enhancing the overall risk assessment process.

3.1.2 The mechanics of earthquake and wave propagation

The effects of a seismic event in a densely populated region can be devastating, both to the building heritage and social fabric. To understand the impact of an earthquake on an urban area, a thorough understanding of the physical phenomena and the territory from a geological point of view is crucial for risk assessment.

An earthquake is characterized by a sudden release of energy in the Earth's crust that results in ground shaking. This release of energy typically occurs along faults. Faults are fractures which cut the Earth's crust where rocks on either side have moved relative to each other. Earthquakes commonly form along these faults, which can be located at the boundaries of tectonic plates or within the plates themselves. The physical process of an earthquake begins with the accumulation of stress along a fault due to tectonic forces. Over time, as stress exceeds the strength of the rocks, a sudden rupture occurs at a specific point on the fault, known as the hypocenter. This rupture marks the nucleation of the earthquake, where stored elastic energy is rapidly released.

Once an earthquake occurs, the fault experiences displacement. The amount of slip depends on the magnitude of stress release. The surrounding crust undergoes adjustments, often leading to aftershocks, which are smaller earthquakes occurring in the aftermath of a major event.
The rupture propagates along the fault plane, generating seismic waves that travel outward in all directions. These seismic waves are classified into two main types: ***body waves*** and ***surface waves***:

Body Waves – These travel through the Earth's interior and include:

- **P-waves (Primary waves)**: the fastest seismic waves, traveling as compressional waves that push and pull the material in the direction of propagation
- **S-waves (Secondary waves)**: slower than P-waves, they move as shear waves, oscillating perpendicular to the direction of propagation and cannot travel through liquids.

Surface Waves – These travel along the Earth's surface and cause most of the ground shaking. The two main types are:

- **Love waves**: cause horizontal shearing motion, moving the ground side to side.
- **Rayleigh waves**: create a rolling motion, similar to ocean waves, moving both vertically and horizontally.

Seismic waves interact with different layers of the Earth, undergoing reflection, refraction, and attenuation. The speed and behavior of these waves provide valuable information about the Earth's internal structure. As seismic waves propagate, they lose energy due to absorption and scattering. This process, known as attenuation, depends on the material properties and the distance from the earthquake source. Higher frequencies attenuate more rapidly than lower frequencies, affecting the intensity of ground shaking experienced at different locations.

The study of faults is fundamental to understanding seismic hazards and mitigating risks associated with earthquakes. Active faults require detailed investigation to ensure public safety, infrastructure planning, and contribute to scientific knowledge. In fact, although it is not yet possible to predict earthquakes, the detailed and multidisciplinary study of the fault zone allow us to know important parameters for modeling the physical process of an earthquake and better understand the factors which favors the seismic slip.

In order to acquire useful information for the study of earthquakes, active fault zones are studied at different scales:

- **Satellite Data:** by utilizing satellite data, it is possible to detect and monitor ground displacements. In particular, InSAR data allow researchers to assess ground movement variations, the affected area, and approximate the seismic source in the event of an earthquake.

- **Remote Sensing Data:** the use of drones enables the acquisition of high-resolution optical or LiDAR images, even in areas covered by dense vegetation. This helps identify landscape changes associated with fault scarps.

- **Field Analysis**: faults are extensively studied in the field. A structural geological approach is crucial for identifying tectonic features. Understanding the length of an active and capable fault is essential for estimating and modeling seismogenic phenomena associated with that structure. The magnitude of an earthquake is closely linked to the fault's length, making this parameter fundamental in rupture modeling. A key approach in the study of active and capable faults at the field scale is paleoseismology. This multidisciplinary field investigates recent deposits, landscape morphology, and chemical analyses for dating fault-affected layers. The data obtained are crucial for understanding the frequency of major earthquakes recorded along specific faults.

- **Microstructural Analysis:** Microstructural studies on fault surface samples provide critical insights into deformation processes occurring along fault zones. Advanced instrumentation enables researchers to examine weakening mechanisms that facilitate rupture propagation and, consequently, influence earthquake intensity.

Tectonic Setting and faulting in Italy

Italy is one of the most tectonically active regions in Europe, situated at the complex convergent boundary between the African and Eurasian plates. This interaction has shaped the geological structure of the Italian Peninsula, giving rise to significant fault systems, seismic activity, and the formation of major mountain chains such as the Alps and the Apennines. The dynamic tectonic environment of Italy has led to a long history of earthquakes and volcanic activity, making it a crucial area of study for geologists and seismologists.

The tectonic setting of Italy is primarily defined by the ongoing convergence of the African and Eurasian plates. This process has resulted in the formation of multiple thrust faults, and extensional basins. The main geological features that characterize the Italian tectonic framework include:

1. **The Alps** – Located in northern Italy, the Alps were formed due to the collision between the African and Eurasian plates during the Cenozoic era. This region is primarily dominated by compressional tectonics and thrust faulting.
2. **The Apennines** – Running along the length of the Italian Peninsula, the Apennines were also formed due to the complex interaction between the African and Eurasian plates.

Unlike the Alps, the Apennines exhibit a mix of compressional and extensional tectonics, leading to the development of normal faulting and basin formation in the central and southern regions.

Due to its complex tectonic setting, Italy is one of the most seismically active regions in Europe. The highest seismic hazard is found in the central and southern Apennines, where normal faulting dominates. Historical earthquakes, such as the 1908 Messina earthquake and tsunami (Mw 7.1), the 1915 Avezzano earthquake (Mw 6.7), and the 1980 Irpinia earthquake (Mw 6.9), have demonstrated the destructive potential of seismic activity in Italy.

The role of 3D geological model in enhancing seismic risk assessment in urban areas

The rapid expansion of urban areas, combined with growing impacts of climate change, has greatly increased the vulnerability of cities to natural hazards such as earthquakes, landslides, and floods. This evolving risk landscape requires innovative tools and strategies for effective and sustainable territorial management. Among these, 3D geological modeling provides valuable insights that significantly improve urban planning and risk mitigation. These models, developed by integrating surface and subsurface geological, geophysical, and geotechnical data, offer a comprehensive understanding of a geological setting of a given area.

Through the study of interactions between lithological layers and subsurface features, 3D geological models provide essential insights for managing seismic risks. According to numerous works, earthquake impacts are strongly influenced by geological and geotechnical factors, such as the subsurface structure of basin areas, where seismic wave amplification occurs due to resonance effects. These phenomena are especially pronounced in urban areas built on alluvial plains, like many Italian cities, where subsurface stratification of sand, silt, clay, and gravel create a high rheological contrast. Such conditions could significantly increase the ground shaking, amplifying the destructive power of earthquakes and posing severe risks to infrastructure and human life.

Physics-based ground motion simulations, when combined with high-resolution 3D geological models, allow for dynamic, three-dimensional assessments of site amplification processes. These simulations are crucial for understanding how seismic waves propagate through complex geological settings during the time (Antonietti et al., 2020). However, their reliability depends on the quality of the input data, highlighting the key role of detailed 3D geological models in seismic risk management (Infantino et al., 2020).

Moreover, in seismically active regions, capable fault zones bordering both basins and urban area which represent the sources of earthquakes, could cause dramatic ground displacement. For example, earthquakes with a magnitude of 6.5 or higher can produce fault displacements of up to one meter, leading to severe damage to critical infrastructure such as pipelines, bridges, and communication networks (displacement on Paganica fault, Aquila earthquake). Such disruptions can greatly hinder post-earthquake recovery efforts. In this context, 3D geological modeling is key for accurately representing the geometry of active fault zones, providing crucial information to understanding surface ruptures and their potential impacts.

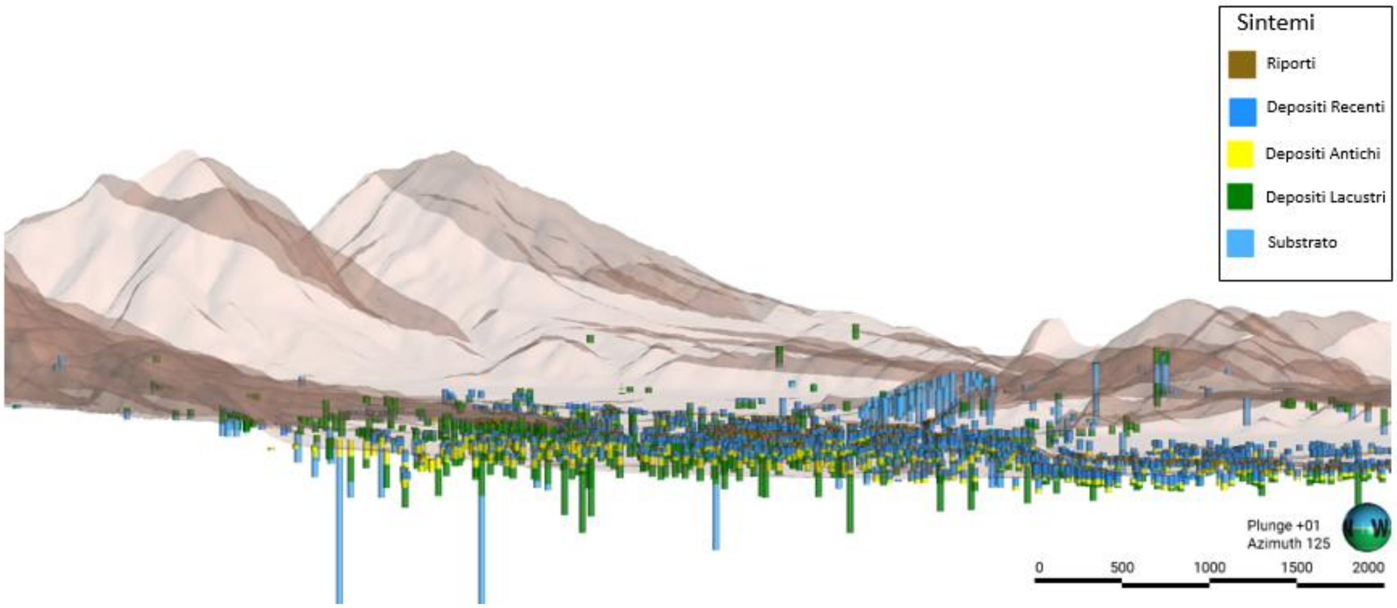


Figure 8. *3D geological model of the urban area of Florence. High precision DEM (in brown) represents the earth surface. The geological model of the subsurface was built using well logs data, geophysical survies and field data.*

3.1.3 Seismic hazard: Analysis of building envelope vulnerabilities to natural hazards

Background

Interest in building technical elements' vulnerability is relatively recent and mainly related to the occurrence of high intensity and low frequency events, neglecting the study of the effects of slow-onset events, characterised by low intensity and high frequency (Castelluccio et al., 2022). Italian guidelines, such as those provided by the Italian Civil Protection Department (Linee guida per la riduzione della vulnerabilità di elementi non strutturali arredi e impianti, 2009), and US guidelines, provided by the National Institute of Standards and Technology (Recommendations for improved seismic performance of non-structural components, 2008) and the Federal Emergency Management Agency (4. FEMA E-74, 2012) emphasise how damage to so-called “non-structural” elements can entail at least three types of consequences: economic losses; disruptions to services; and threats to people’s safety (O’Reilly and Calvi, 2021).

Among the most vulnerable building elements there are the technical elements of the building envelope, such as plasters and decoration, roof cornices and balconies. Low-intensity seismic forces, which do not significantly impact load-bearing structures, can have significant impacts on building facades, as reported with reference to the bradyseism activities of the Neapolitan area (Fraiese at al., 2024). It has been stated that the risk factors influencing façade safety are the design criteria, the construction details, and the maintenance activities it undergoes (Moghtadernejad and Mirza, 2021). During the service life of a facade, various mechanical and environmental forces, involving aggressive environmental deterioration mechanisms influence the performance of the system and cause it to deteriorate gradually. The resulting degradation must be determined by a careful inspection and corrective action must be taken to improve the façade performance. Lack of appropriate action can lead to serious deterioration affecting the façade before the end of its service life and can cause detachment of façade components, leading to death/injuries, as reported by Moghtadernejad and Mirza (2021) and Ruggiero at al. (2021).

An evaluation system has been developed, considering the type of deterioration, its extent and the impact energy of potential detachment (Ruiz et al., 2019). In parallel, to concerns explicitly related to people's safety, there is a growing research interest in describing the impact of climate change on the performance of the building envelope. Extreme weather events can cause performance loss and require a revision of maintenance policies and design guidelines (Souza et al., 2018) or planning for adaptation strategies.

Within this background, the Building Risk can be defined as the risk for people triggered by a damaged building envelope, not only to analyse the effects of hazardous events on the building but primarily to consider the hazardous events that the building itself may pose to the surrounding context (Castelluccio et al., 2024). Therefore, some studies have been developed on how to assess the vulnerability of the building envelope, as the more vulnerable the envelope is the more likely the analysed hazardous event occurs (e.g., potential injuries to people due to the damaged building envelope, road obstruction, especially escape routes, etc.). The contribution is included in the existing Storylines (DV 5.3.1) and aligned with the identified impacts (physical building damage) and related risks (physical loss of buildings' elements; injuries and fatalities; loss of productive systems; socio-economic damages to households).

Envelope's vulnerability analysis

The building envelope is exposed to several natural hazards, but those which trigger most interventions are meteorological hazards, ground collapse and earthquakes, but the age of the elements and the lack of maintenance are to be considered too. Also, according to the Statistic Yearbook of the Italian National Fire Brigades (2018), roofs, chimneys, windows, plasters and cornices are the most frequently damaged building elements. Thus, they are more vulnerable than other building elements, as technical element vulnerability is defined as the element's tendency to sustain damage when exposed to a hazard.

The vulnerability analysis is conducted separately for each hazard (i.e., it is a single-hazard analysis), it is to say, it does not address the combined effects of multiple hazards, whether occurring simultaneously or in sequence. However, some recommendations on how to reduce the vulnerability of building envelopes in a multi-hazard scenario of interest can be derived from the results.

The vulnerability assessment involves two key steps. First, the vulnerability of each technical element is determined by considering its technological characteristics and physical condition. Next, the overall vulnerability of the envelope is calculated as a weighted average, where the vulnerabilities of the individual technical elements are weighted according to the area they occupy on the envelope.

The hazards under analysis were retrieved from the risk matrix (Deliverable n. 5.3.1) of the Return project. The list of technical elements of interest refers to the Return Taxonomy (Deliverable n. 5.2.1), and it is reported in Figure 9. It includes attribute 14 – roof shape, attribute 20 – exterior wall, attribute 21 – openings/windows, attribute 22 – cornice construction technique, and attribute 24 – household drain system material. These attributes provide for the technical elements' technological characterisation and detailing. For example, a roof cornice is characterised by its construction technique, and several sub-attributes concerning the intrados and extrados shape, the face height, and the finishing description. The readers can find the full description of the technical elements of the building envelope in Deliverable n. 5.2.1.

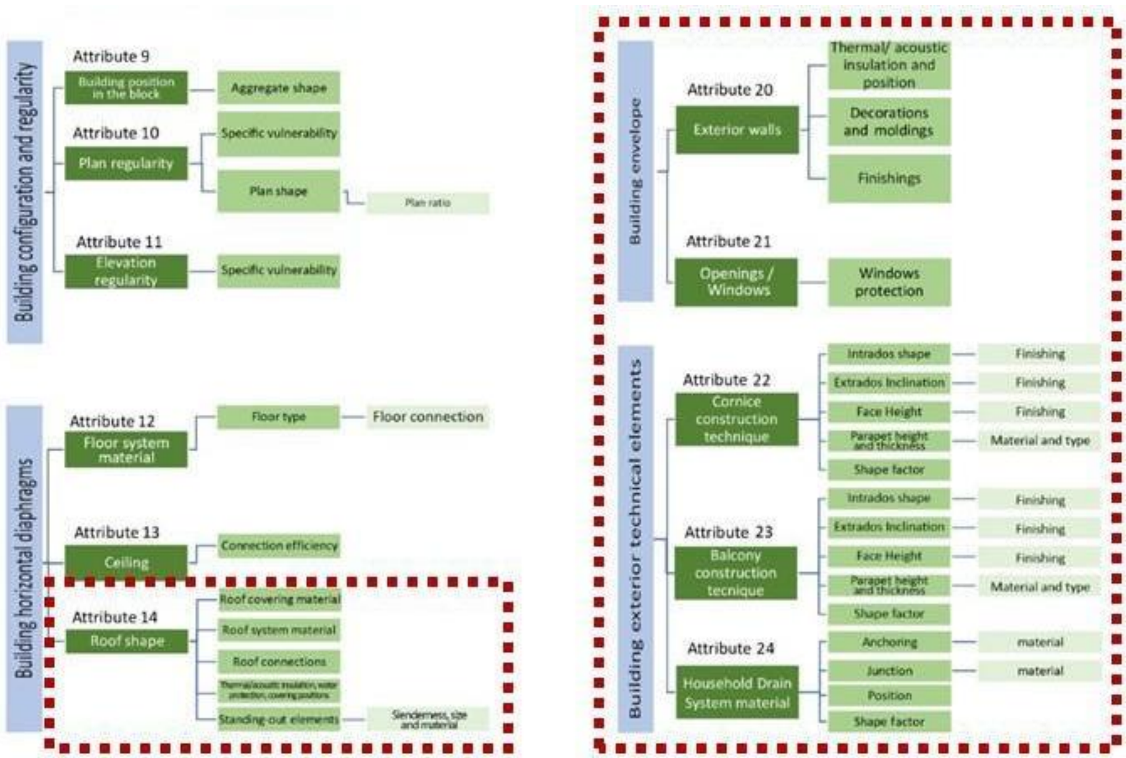


Figure 9*. Analysed attributes (in red boxes)*

Technology-related vulnerability

The technology-related vulnerability analysis at the element scale is discussed in Deliverable 5.3.2, but it is here briefly reviewed, with reference to Attribute 23 – Balcony, to guide the reader through the vulnerability assessment method. Anyway, this contribution extends the results exposed in the Deliverable n. 5.3.2 to the building scale, presenting a methodology for assessing the vulnerability of the entire building envelope, described later in the text.

Qualitative and quantitative approaches can be employed to determine the propensity of a technical element to sustain damage when exposed to external forces. A qualitative approach is particularly suitable when a high-level, comprehensive understanding of the subject is required as a precursor to more detailed investigations. Given the relatively novel nature of research on the vulnerability of building envelope technical elements, a qualitative approach has been adopted. This involved a review of scientific literature, international and national guidelines, technical reports, and expert opinions. Through this process, a preliminary assessment of technical elements' vulnerability to the four identified hazards was conducted, establishing a solid foundation for more detailed studies.

The authors first identified vulnerability factors to evaluate how individual elements respond to specific hazards. For instance, deformability and fragility are key vulnerability factors for assessing susceptibility to earthquakes, the sloped surface and low water absorption coefficient are deemed to be relevant against heavy rainfall, the thermal expansion coefficient for high temperatures and solar exposure, and the mass and the type of connection to the support are to be evaluated in the case of extreme wind pressure. These factors are used to determine how specific characteristics of an element affect its overall vulnerability. For example, a reinforced concrete balcony with a high shape factor is more vulnerable to earthquakes than one with a lower shape factor, as the damage increases with a higher height-to-span ratio. Similarly, a masonry balcony is more vulnerable to earthquakes than a reinforced concrete balcony.
Vulnerability grades are expressed on a four-point scale, ranging from "low" to "very high." Table 9 and Table 10 summarize the vulnerability grades assigned to various balcony configurations (attribute 23). A preliminary assessment may consider only the balcony construction technique (attribute 23), as shown in Table 9.

Table 9. Vulnerability of the balcony construction technique

ID	Attribute	Vulnerability grade per hazard			
	23 Balcony construction technique	Earthquake	Heavy Rain	High Temp.	Wind
--	Unknown*	n.a.	n.a.	n.a.	n.a.
BMG	Masonry, generic	Very high	Very high	Low	Low
BMM	With metal cantilever	High	High	High	Low
BCC	Cast-in-place Reinforced Concrete	Moderate	Moderate	Low	Low
BCP	Precast Reinforced Concrete	High	Moderate	Low	Low
BS	Steel	Low	Low	Very high	Moderate
BW	Wood	High	Very high	Low	Moderate
CC	Composite/other	Very high	Very high	Very high	Very high
	*vulnerability analysis does not consider unknown data				

Sub-attributes can be used for a more refined evaluation when a higher level of detail is required (Table 10). To account for the combined influence of multiple characteristics (e.g., construction material and geometric configuration), further studies and data, such as mechanical analyses or statistical modelling, are required. However, it must be said that not all sub-attributes contribute to the vulnerability assessment of a technical element (Table 10). For example, a balcony is vulnerable to heavy rainfall if the slope of the slab (sub-attribute 23.2: extrados inclination) is negligible and if the water-proofing membrane is absent. However, the intrados shape and finishing do not influence the balcony vulnerability to rainfall.
Whereas applicable, the element's vulnerability has been evaluated by picking the maximum value derived from the sub-attribute vulnerability (within the single-hazard analysis). This

approach simplifies the assessment process while maintaining a conservative stance in the absence of detailed information. This means that a steel balcony with a very high shape factor (H/L < 0.15) has a high vulnerability to earthquakes, as the construction material is assumed not to compensate for the high overhang of the element. In other cases, some sub-attributes are used to amplify the vulnerability of the technical element under analysis. For example, masonry parapets amplify the vulnerability of the balcony to earthquakes, while steel parapets do not.
The vulnerability value associated with each technological characteristic is to be used to compare different solutions. Still, it is not meant to be used to associate a specific value of hazard intensity to a defined damaged state of the element under analysis. However, the qualitative approach serves as a solid reference for further merely quantitative studies, to be conducted either by simulations or by statistical analysis, whereas data are available. In the next sub-section, a semi-quantitative approach is introduced to move from the vulnerability assessment at the element scale to the overall building envelope vulnerability assessment, considering also the role played by the physical condition.

Table 10. Vulnerability of the balcony sub-attributes (finishing, geometric configuration and parapet)

ID	Sub-attribute	Vulnerability grade per hazard			
	23.1.1 Intrados Finishing	Earthquake	Heavy Rain	High Temp.	Wind
--	Unknown*	n.a.	n.a.	n.a.	n.a.
BIP	Plaster finishing	Moderate		Moderate	
BIB	Brut	Low		Very high	
BID	Decorated	Very high		Low	
	23.2 Extrados inclination	Earthquake	Heavy Rain	High Temp.	Wind
--	Unknown*	n.a.	n.a.	n.a.	n.a.
0	Flat extrados		Very high		
1	Inclined extrados		Low		
	23.2.1 Extrados Finishing	Earthquake	Heavy Rain	High Temp.	Wind
--	Unknown*	n.a.	n.a.	n.a.	n.a.
BEB	Brut		Very high		
BEW	Extrados with waterproof membrane only		Moderate		
BEWPD	Extrados with waterproof membrane and paving and drip edge		Low		
BEPD	Extrados with paving and drip edge		High		
BEWP	Extrados with waterproof membrane and paving, no drip edge		Moderate		
BEP	Extrados with paving only		Very high		
	23.5 Shape factor	Earthquake	Heavy Rain	High Temp.	Wind
--	Unknown*	n.a.	n.a.	n.a.	n.a.
BSF1	H/L > 0.4	Low			Low
BSF2	0.4 < H/L < 0.15	Moderate			Moderate
BSF3	H/L < 0.15	Very high			Very high
	23.4.1 Parapet material	Earthquake	Heavy Rain	High Temp.	Wind

--	Unknown*	n.a.	n.a.	n.a.	n.a.
BPMA	Masonry	Very high	Very high	Low	Low
BPRC	Concrete / Reinforced concrete	Moderate	Moderate	Low	Low
BPST	Steel	Low	Low	Very high	Low
BPWO	Wood	Low	Very high	Moderate	Very high
BPCO	Combined/Composite	Very high	Very high	Very high	Very high

*vulnerability analysis does not consider unknown data

Vulnerability conditioned by the physical condition

The semi-quantitative approach consists of translating the qualitative vulnerability grades (low, moderate, high, and very high) into scalars in order to combine the contributions of different technical elements on the overall vulnerability of the building envelope against a specified hazard of interest. An additional vulnerability factor that has been considered, but is not included in the taxonomy, is the physical condition, i.e., the degradation level. Indeed, the poorer the physical condition the more likely the element will report damage when a hazardous event occurs.

In a merely qualitative manner, which is fine to rapidly formulate an idea on the propensity of an element to suffer damage when subject to a specific hazard, one could use the information on the potentially poor physical condition by increasing the vulnerability grade of one unit. For example, a steel balcony which suffers from extensive oxidation is no longer low vulnerable to earthquakes, but it might become moderately or highly vulnerable. However, a more precise and quantitative evaluation of the vulnerability adjusted by the degradation level has been proposed, accounting for the type of detected anomaly and its extent, as suggested by similar works on the topic of facade vulnerability (Ruggiero et al., 2021, Ruiz et al., 2019, Souza et al., 2018) .

The adjusted vulnerability (V_i) at the element scale is the combination of the technological-related vulnerability (V'_i) and the degradation level (β_i), as per Eq. 1).

$$V_i = f(V'_i, \beta_i) \quad 1)$$

where:

- V_i is the vulnerability of one technical element adjusted by the degradation level;
- β_i is the degradation level of one technical element;
- V'_i is the vulnerability of one technical element depending on its technological characteristics only. It varies from “low” to “very high” vulnerability.

The degradation level (β_i) depends on the severity of the detected anomaly (C_k) and the relative incidence on the element’s surface (I_k), as per Eq. 2).

$$\beta_i = f(I_k, C_k)$$

2)

Four types of anomalies have been defined (absent or very mild, mild, advanced, and severe), ranging from aesthetic issues only to mechanical deterioration and partial collapse. Each severity level has been assigned a value ranging from 1 to 4.

The importance of the degradation condition on the overall building envelope vulnerability compared to the technological characteristics has been proposed based on data from the Italian Fire Brigades. Data shows that poor condition is the most frequent cause of emergency interventions performed on building envelopes during 2023. The impact is so relevant that elements that collapsed due to poor conditions are twice those collapsed due to wind (44% vs 21%), four times those collapsed due to rainfall and hailstorm (44% vs 10%), and twenty times those collapsed due to earthquakes (44% vs 2%).

Once the vulnerability at the element scale is set, the façade vulnerability (V_f) is calculated as the average of the elements' vulnerabilities (V_i) weighted by their surface incidence (as per Eq. 3).

$$V_f = f(I_i, V_i, A_i)$$

3)

where:

- V_f is the vulnerability of the entire facade (no relative weights have been introduced for technical elements, which can change according to the analysed hazard);
- i is the number of facades elements;
- A_i is the area of one element - intrados surface of projecting elements is not part of this area;
- I_i is the incidence of one element on the facade.

The same formulation can be adopted at the building level, where the overall vulnerability of the envelope (V_{be}) can be calculated as the weighted average of the vulnerability of the elements constituting the envelope (i.e., facades, the basement - whereas of interest - and the roof), as per Eq. 4).

$$V_{be} = f(I_f, V_{fk}, A_{fk})$$

4)

where:

- V_{be} is the vulnerability of the entire envelope;
- V_{fk} is the vulnerability of one part of the envelope (such as one facade);
- A_{fk} is the area of one part of the envelope;

- I_f is the incidence of one facade on the envelope.

Based on these results, the adjusted vulnerability varies from "low" (green-coloured) to "very high" (red-coloured), details on this grading system are under validation by means of expert opinion, supported by a field survey involving building facades placed in the city of Naples.
The results that one can get from this vulnerability assessment method consist of a structured way of comparing different elements based on their vulnerability grades. Based on this comparison, it can be understood if a building envelope is consistently vulnerable to a hazard, and thus requires major renovation interventions (such as, refurbishment of the entire facade) or if minor localised interventions are needed (for example, replacing the roof cornice water-proofing membrane only). An example of a façade vulnerability map is reported in Figure 10 where the areas of major concern in case of an earthquake can be easily identified.

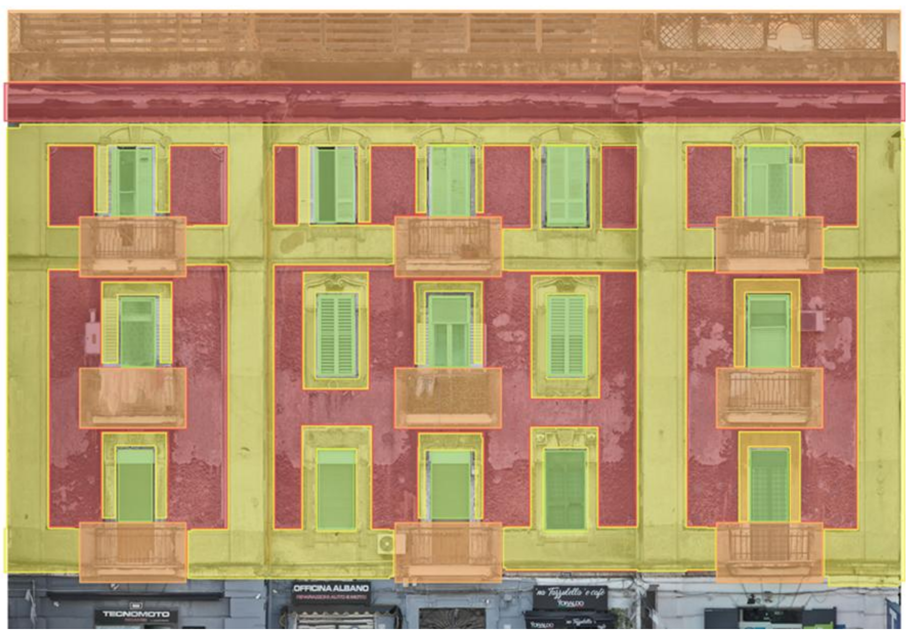


Figure 10. *An earthquake-related façade vulnerability map*

The results also support multi-hazard analysis, where the hazards are supposed to occur independently. Figure 11 reports the vulnerability values for each facade's element to earthquakes and rainfall respectively. The results one can get from the vulnerability analysis are useful to compare different facades or different parts of the facade to understand where to intervene first to reduce the vulnerability to more than one hazard per time, or to reduce the risk to people where the vulnerability cannot be modified.

The vulnerability values consider the technological characteristics of the elements and their degradation level. Thus, this approach can help in understanding whether vulnerability is triggered by technological solutions or poor conditions. Figure 12 shows the elements' vulnerability grades to rainfall and their degradation levels. As the analysed facade is in poor condition, its vulnerability is heavily conditioned by this, which means that vulnerability could be reduced by intervening on the envelope to resolve the detected pathologies.

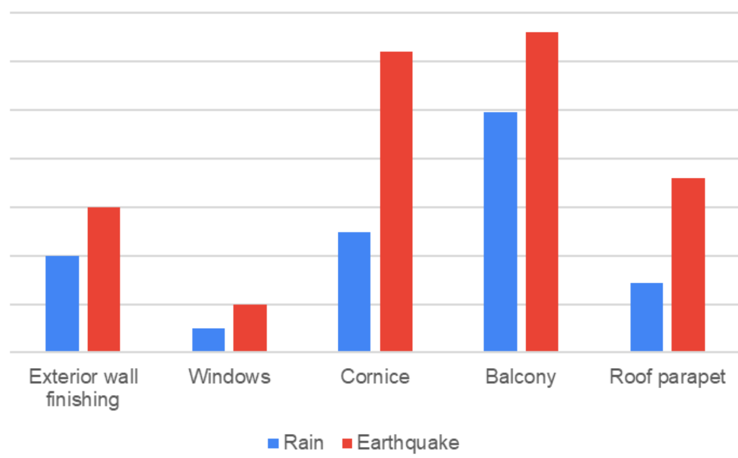


Figure 11. *Facade's technical elements vulnerability to earthquakes and rainfall*

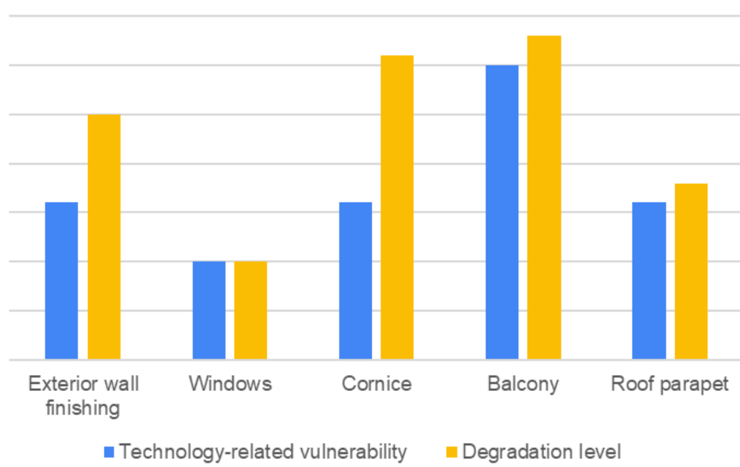


Figure 12. *Comparison of technology-driven vulnerability grades and degradation level (the analysed hazard is the rainfall)*

Case study: the Bagnoli district

An analytical application of the described methodology is proposed here, and a set of 136 buildings located in the Bagnoli district (NA) are used as case study. The district is located along the coast in the western area of Naples, within the area of the Phlegraean Fields, a vast volcanic region highly affected by the phenomenon of bradyseism (Figure 13). In this regard, the district represents a significant urban context for the analysis of the envelope's vulnerability, where an in-depth assessment of the condition of building envelopes and the evaluation of their corresponding vulnerabilities appears essential, considering the peculiar phenomenon they are subjected to and the related Building Risk they might pose in turn to the surrounding context (Fraiese et al., 2024, Castelluccio et al., 2024). In this sense, the methodology is here applied to assess the envelopes vulnerability to seismic hazard related to this area.

***Figure 13**. Identification of the Bagnoli District within the Phlegraean Fields Area*

Within the Bagnoli district, main road axes were selected among the evacuation routes identified in the Municipal Emergency Plan for Volcanic Risk. These axes were prioritised to the optimization of evacuation procedures, helping to ensure their security and the swift movement of residents during possible emergencies. After identifying and selecting the main road axes, 136 buildings were chosen, focusing on those with facades directly facing sidewalks, roadways, and access routes, as shown in Figure 14.

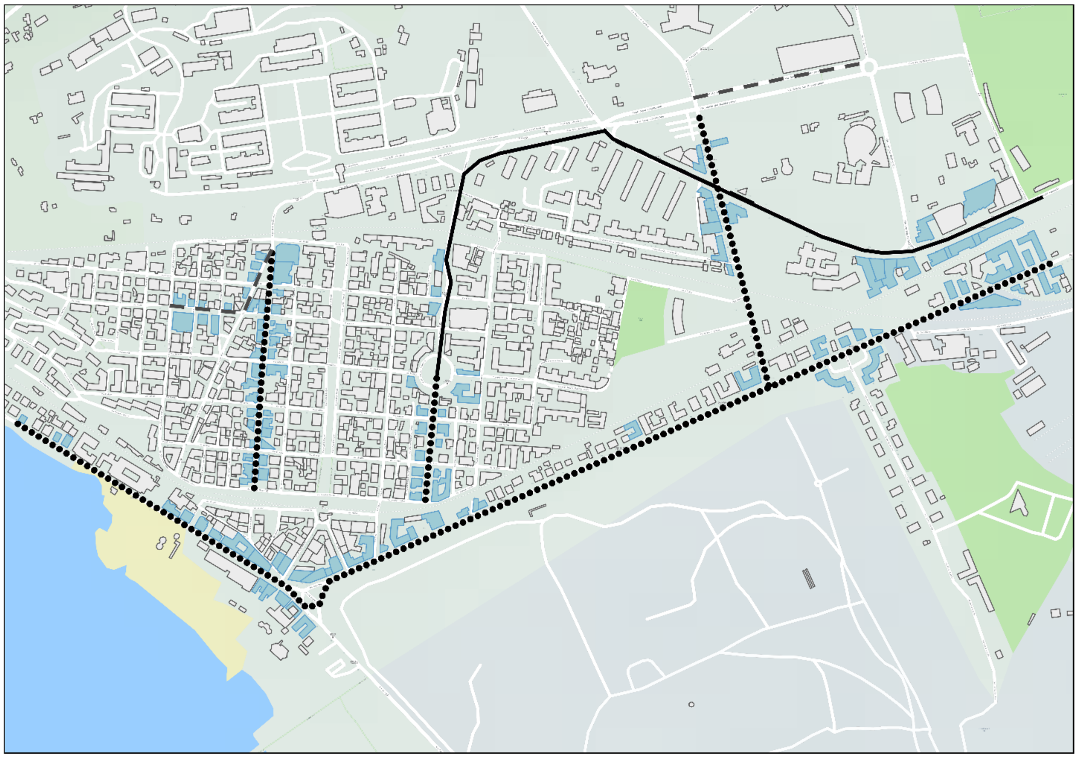


Figure 14. *Identification of the main road axes and the 136 buildings under study*

Subsequently, a direct field survey of all 136 buildings was conducted using a rapid survey form, which focused on collecting data relevant to assessing the vulnerability of building envelopes to seismic hazard, with particular reference to the bradyseism. Since the methodology is applied to a specific hazard — in this case, bradyseismic events — the survey prioritised data that could influence an envelope's performance under low-intensity seismic forces. The collected data included dimensions, materials, construction techniques, and the physical condition of technical elements and their components, as well as general information about the buildings themselves. The survey aimed to document not only the presence of these elements but also their vulnerability-related key factors, which are known to influence their behaviour under seismic stress. For example, in the case of roof cornices, two critical vulnerability factors were assessed: the constructive typology (e.g., reinforced concrete, masonry, or metal) and the form factor (i.e., the ratio between the cornice's height and depth). These elements are particularly relevant because seismic vulnerability is influenced by the mass and overhang of projecting components, and as previously discussed, larger and more protruding elements are more vulnerable to seismic forces, which can both increase the risk of detachment or collapse during an earthquake.

Most of the surveyed buildings have 3 (around 28%) or 4 (21%) floors. Buildings with 8 (15%) and 2 (12%) floors also make up a significant portion, while buildings with 1 (7%), 5 (7%), 6 (4%), 7 (4%) and 9 (2%) floors are less common, but still relevant in the dataset. They consist primarily of reinforced concrete (43%), followed by masonry structures (36%), with a smaller proportion having a mixed construction typology (21%). The ground floor height varies across the surveyed buildings, with common ranges being 2.50 to 3.49 meters, 3.50 to 5.00 meters, and in some cases over 5 meters. Similarly, the average floor height mostly falls between 2.50 and 5.00 meters. The facades' general physical condition surveyed varies significantly, with 40% showing moderate decay, 35% well-maintained, and 25% in severe decay. Concerning the technical elements of the envelopes, Figure 15 shows a summary of the construction techniques of the surveyed roof parapets, roof cornices, balconies, finishing and claddings.

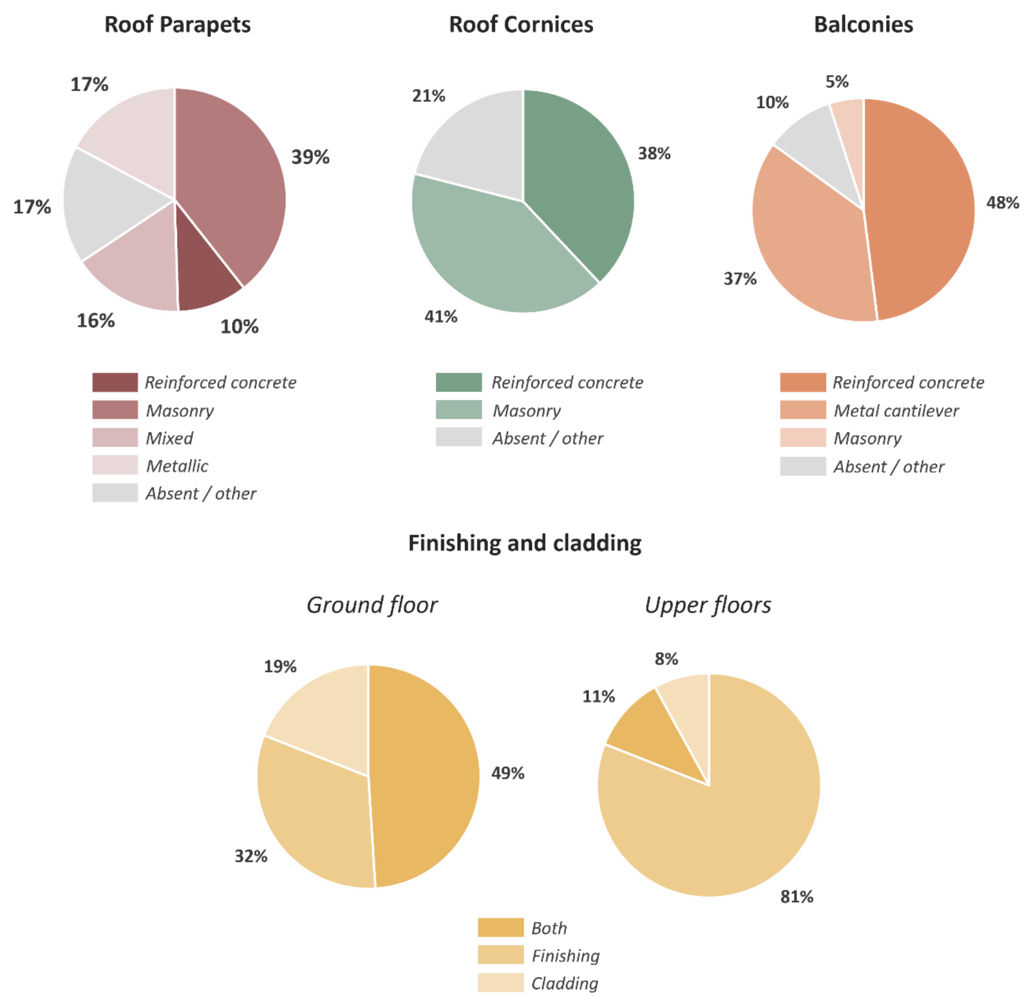


***Figure 15**. Prevalent construction techniques of some technical elements surveyed*

To follow up on the example provided regarding the vulnerability levels of the balcony sub-attributes, a more detailed description of the relevant data collected for this technical element is described.

Concerning the form factor, the majority of balconies in the dataset (57%) fall within the range of 0.15 < H/a < 0.4, indicating that these balconies have a "Moderate" vulnerability to earthquakes (Table 9). This type of balcony is vulnerable to seismic forces, as the greater projection increases the risk of detachment or collapse during an earthquake. A significant proportion of balconies (28%) have a form factor of H/a > 0.4, meaning they have smaller overhangs relative to their height. This range is considered less critical compared to higher form factors, as the projection is more balanced in proportion to the height and were therefore assigned with a "Low" vulnerability level (Table 9).

The intrados finishing refers to the material and treatment applied to the underside of the balcony slab. The majority of balconies (80%) are finished with plaster and paint, a traditional finishing technique that may degrade over time and contribute to increased vulnerability if not properly maintained. The assigned vulnerability grade was "Moderate", except for 7% of them, which featured decorative elements, raising the vulnerability grade to "Very High" (Table 9).

The parapet material describes the material used for the balcony railings. The dataset shows that steel parapets are by far the most prevalent, accounting for 81% of the balconies. This material is commonly used due to its strength and flexibility and can be therefore assigned with a "Low" grade of vulnerability. Combined / composite parapets account for around 2% of the dataset, while masonry-only and reinforced concrete parapets are rare, each representing less than 1%.

Even though the extrados finishing is not considered in the vulnerability assessment for seismic hazard, a description of the surveyed characteristics is still presented to better present the reasoning behind the proposed methodology, describing them with reference to the heavy rain hazard. The extrados finishing refers to the treatment on the upper surface of the balcony slab. The most common finishing is waterproof membrane and pavement with a drip edge, representing 51% of the balconies. This finishing type is essential for preventing water infiltration, with the drip edge directing water away from the building facade and balcony edges, reducing the risk of structural damage caused by moisture accumulation. Without this feature, rainwater can easily flow along the balcony surface and infiltrate cracks, causing deterioration of both the slab and facade over time. The second most common category is waterproof membrane with pavement only, accounting for 29%. Other less frequent finishing types include non-detectable and no longer present, each representing less than 1%. However, this data was collected during fieldwork but was not analysed or used to obtain the results reported below.

Based on the technological characteristics surveyed for each balcony, the technological-related vulnerability (V'_i) was assessed accordingly as the maximum value of the vulnerability grades associated with different technological features described, (i.e., construction techniques and shape factors). Multiplying the technological-related vulnerability (V'_i) previously assessed with the degradation levels observed (β_i), the relevant adjusted vulnerability (V_i) to earthquake of each balcony was assessed (Eq. 1). Figure 9 shows the distribution of the obtained adjusted vulnerabilities, where the different levels are represented using the following colour scale: red for Very high vulnerability, orange for High vulnerability, yellow for Moderate vulnerability, and green for Low vulnerability. To provide a comparison reference, the distribution of the adjusted vulnerability is presented for the technical element roof cornice as well.

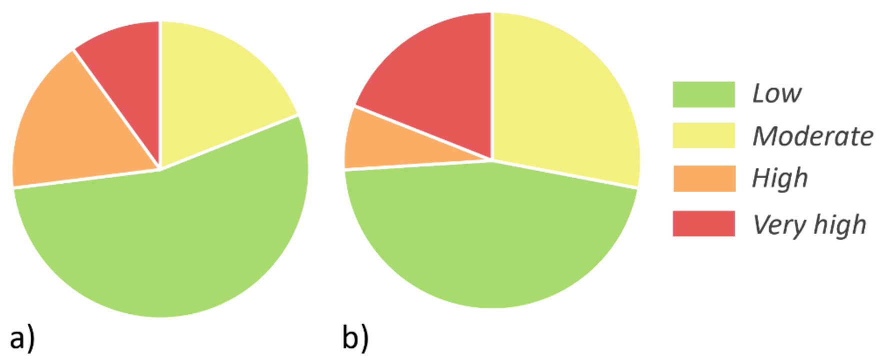


Figure 16. *Distribution of vulnerability levels for the technical elements a) balcony and b) cornice*

The pie chart in Figure 16 a illustrates the adjusted vulnerability levels to earthquakes for the technical element balcony, with the majority classified as having Low vulnerability, indicating a generally stable condition. However, nearly one-third of balconies fall into Moderate to High vulnerability levels, suggesting the need for prioritised interventions or adaptation measures. Although a smaller portion is rated as Very High vulnerability, these balconies pose a constant Building Risk and could become an immediate hazard in the event of an earthquake.

In Figure 16 b, the vulnerability levels for cornices are presented, showing that almost half are rated Low vulnerability. However, a significant portion exhibits Moderate to High vulnerability, indicating the need for urgent monitoring or restoration measures. Additionally, a notable share falls within the Very High vulnerability level, posing critical hazards to the surrounding environment.

In the end, 136 facade vulnerability grades were obtained, showing that the majority of the facades assume Moderate and High vulnerability grades, while around 40% of them have a Low vulnerability to earthquakes. Preventive and risk reduction interventions are to be planned according to these results.

These findings underscore the importance of targeted interventions to reduce Building Risk associated with balconies and cornices under seismic hazards. The focus should be on High and Very High vulnerability elements, which present immediate danger, followed by a phased intervention strategy addressing Moderate and Low vulnerability levels. This approach ensures an efficient allocation of resources while progressively lowering overall seismic risks in a risk-informed manner.

The same procedure was conducted for all technical elements surveyed for each building, enabling eventually the assessment of both the relevant facade vulnerabilities (V_f) (Eq. 3) and the overall vulnerabilities of the envelopes (V_{be}) (Eq. 4).

3.1.4 Seismic hazard: Analysis of building vulnerability at different scales

Introduction

The economic impacts resulting from the damage and disruption caused by the 1994 Northridge earthquake (USA) and the 1995 Kobe earthquake (Japan) led to the development of a conceptual approach aimed at designing structures to mitigate the effects of earthquakes (O'Reilly and Calvi, 2019). This approach, known as Performance-Based Earthquake Engineering (PBEE) (Priestley and Calvi, 1997) has been integrated into seismic guidelines (Eurocode 8 and FEMA 356) and establishes a relationship between required building performance and seismic hazard levels.

A key aspect of PBEE is the incorporation of monetary loss and downtime into structural design, which defines the Loss-Based Earthquake Engineering (LBEE) framework (Cornell and Krawinkler, 2000). Applications of LBEE can be found in (Miranda and Aslani, 2003 and Dolce et al. 2021), with the objective of advancing risk-targeted methods.

Moreover, the risk can be estimated in terms of expected annual loss, as example through the Pacific Earthquake Engineering Research (PEER) Center's framework or by the Italian "Sisma Bonus" guidelines (Ministry Decree n.58, 2017).

This design philosophy is closely linked to society's need for informed decision-making in addressing seismic risk. The costs and benefits of seismic protection are not only complex scientific challenges but also have significant economic implications, emphasizing the necessity of risk mitigation planning at the regional level.

The economic consequences of the 1999 Izmit (Turkey) and Athens (Greece) earthquakes further underscored the urgency of a global initiative to assess seismic risk across European regions. In response, the European Commission launched the RISK-UE project (Mouroux et al., 2004) to develop a comprehensive methodology for risk analysis. Seismic risk is determined by the interplay of three key components: exposure, hazard, and fragility and recent scientific studies have focused on defining resilient mitigation strategies to address this risk (Anelli et al., 2019).

Fragility curves are essential tools for evaluating the structural response of buildings in seismically active regions. They establish a link between the seismic intensity at a given site and its impact on both structural and non-structural elements (Anelli et al., 2021). These curves enable the estimation of the probability that a structure will exceed a specific damage state or performance level during an earthquake. Fragility curves can be developed using analytical, empirical, expert judgment, or hybrid approaches (Deliverable 5.3.2).

Analytical approaches assess the seismic response of structures through numerical or mechanical models (Vona et al., 2018). Empirical approaches rely on observed damage data collected from post-earthquake surveys (Rosti et al., 2020). Expert judgment approaches use expert opinions to estimate expected damage and its consequences (ATC 1985). Hybrid approaches integrate elements of the aforementioned methods (Rossetto et al., 2014). Additional information can be found in (Deliverable 5.3.2).

Given these different methodologies, the need for a standardized procedure to develop consistent fragility curves for specific building typologies is evident. Vulnerability curves, on the other hand, describe the relationship between the damage factor and a selected ground motion parameter. The damage factor is typically expressed as the expected repair cost, represented as a fraction of the building's replacement cost, allowing for the assessment of direct economic losses resulting from damage to structural and non-structural components. A significant step toward defining a methodology for seismic risk reduction was taken by the Italian Civil Protection Department, which developed a National Risk Assessment document (DPC 2018). This initiative involved the creation and collection of vulnerability models to generate damage scenarios and risk maps for Italy. Additionally, it facilitated the comparison and integration of results from various modeling approaches (Dolce et al., 2019).

Fragility curves for seismic risk assessment at building scale

A common method for estimating the fragility curve of single structures is adopting the Incremental Dynamic Analysis (IDA) (Vamvatsikos and Cornell, 2002). IDA involves scaling each ground motion in a suite, estimating the damage level (e.g. the maximum drift) reached in the structure by increasing the ground motion, until it causes structure collapse. This process produces a set of Intensity Measure (IM) values associated with the onset of collapse for each ground motion, as illustrated in Figure 17 a). The probability of collapse at a given IM level, can then be estimated as the fraction of records for which collapse occurs at a level equal or lower than IM level. A plot of these probabilities is shown in Figure 17 b) and it is a cumulative distribution function. Fragility function parameters can be estimated from this data (Figure 17 a) by taking logarithms of each ground motion's IM value associated with the onset of collapse and computing their mean (Eq. 5) and standard deviation (Eq. 6) (Ibarra and Krawinkler 2005).

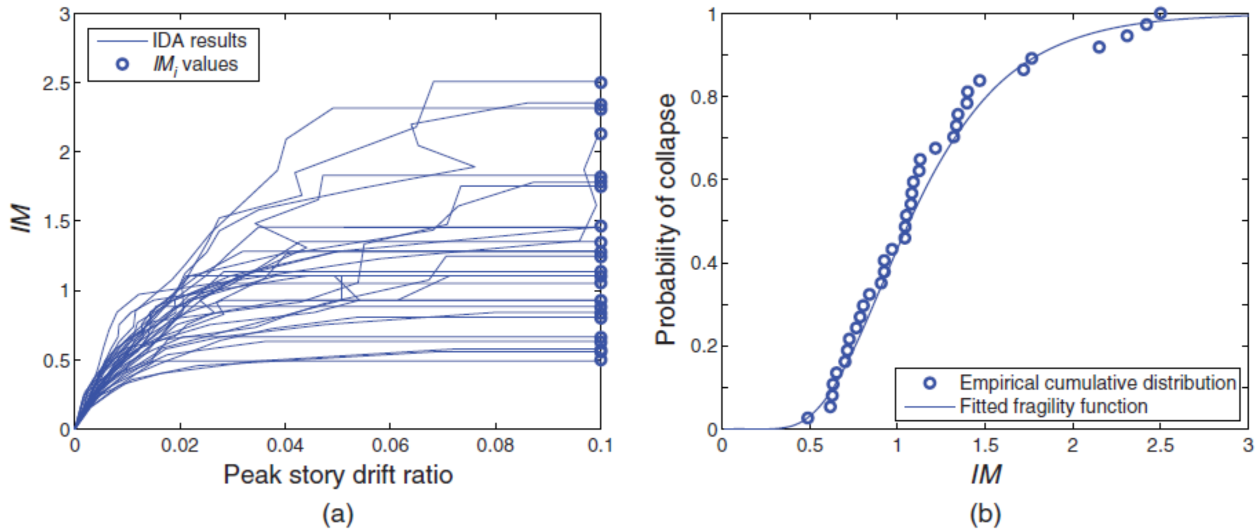


Figure 17.*(a) Example of incremental dynamic analyses; (b) observed fractions of collapse as a function of IM and fragility function estimated using Eq. 5) and Eq. 6) (Baker, 2015).*

$$ln\ (\theta) = \frac{1}{n}\sum_{i=1}^{n} ln\ (IM_i) \qquad 5)$$

$$\beta = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(ln\ (IM_i/\theta))^2} \qquad 6)$$

where:

n is the number of ground motions considered and IM_i is the IM value associated with the onset of collapse for the i_{th} ground motion. This is a method of moments estimator because ln θ and β are the mean and standard deviation, respectively, of the normal distribution representing the ln(IM) values.

Rather than incremental dynamic analysis, structural analyses are sometimes performed at a discrete set of IM levels, at each of which different ground motions are used. This Multiple Stripes Analysis (MSA) approach is common when using the conditional spectrum or other approach to select ground motions representative of a specific site and IM level, because the ground motion target properties change at each IM level and thus the representative ground motions change as well (Iervolino et al., 2010). With this approach, the analysis need not be performed up to IM amplitudes where all ground motions cause collapse. With data of this type, one cannot use the estimation approaches described earlier because the IM_i values associated with the onset of collapse for a given ground motion are not known. The appropriate fitting technique for this type of data is the Maximum Likelihood Estimation approach (MLE). In (Baker, 2015) this statistical method for estimating the parameters of fragility functions using results from nonlinear dynamic structural analyses is shown.

The method can be applied to results obtained by both the Incremental Dynamic Analysis (IDA), in which a suite of ground motions is repeatedly scaled to identify the IM level at which each ground motion induces collapse, and Multiple Stripes Analysis (MSA), which involves conducting analyses at specified IM levels, each associated with a unique set of ground motions.

As widely used, the lognormal cumulative distribution function (Iervolino et al., 2023) is adopted to approximate the fragility curves:

$$P(DM \geq dm_i | IM = im) = \Phi\left(\frac{ln\left(\frac{im}{\theta}\right)}{\beta}\right)$$

7)

where: Φ is the normal cumulative distribution function and Θ and β are the median and standard deviation of *ln(im)*, related to the damage state dm_i.

For a given intensity level $IM=im_j$, there are z_j observed structural responses related to a defined engineering demand parameter out of n_j total observations and the probability of observing z_j is given by the binomial distribution (Baker, 2015):

$$P\left(z_j \; in \; n_j ground \; motions\right) = \left(n_j \; z_j \;\right)\hat{p}_j^{z_j}\left(1 - \hat{p}_j\right)^{n_j - z_j}$$

8)

where: $\hat{p}_j$ is the probability that a ground motion with intensity im_j causes the reaching of z_j and corresponds to the fragility function as defined by Eq. 7).

The maximum likelihood approach identifies the fragility function parameters (Θ and β) that give the highest likelihood of producing the observed structural response. With data from multiple *im* levels, one takes the product of the binomial probabilities at each *im* level to get the likelihood for the entire dataset:

$$Likelihood = \prod_{j=1}^{m}\left(n_j \; z_j \;\right)\hat{p}_j^{z_j}\left(1 - \hat{p}_j\right)^{n_j - z_j}$$

9)

where:

m is the number of *im* levels, and ∏ denotes a product over all tests.

Replacing the fragility function given by Eq. 7) in place of $\hat{p}_j$ and because the parameters which maximize the likelihood function also maximize the logarithm of the likelihood function, *Θ* and β can be numerically identified solving:

$$\{\theta^\wedge, \beta^\wedge\} = argmax_{\theta,\beta} \sum_{j=1}^{m} \left\{ ln\left(n_j\ z_j\right) + z_j ln\Phi\left(\frac{ln\left(\frac{im_j}{\theta}\right)}{\beta}\right) + \left(n_j - z_j\right) ln\left(1 - \Phi\left(\frac{ln\left(\frac{im_j}{\theta}\right)}{\beta}\right)\right)\right\}$$

10)

Through Eq. 10), *Θ* and β are identified. In this way, the discrete fragility curves can be expressed by continuous functions via Eq. 7).

The calculation of the seismic fragility curves for steel structures including soil-structure interaction are evaluated in (Akhoondi and Behnamfar, 2021). The concept of cumulative damage has been investigated in (Mohammadgholipour and Billah, 2024) concluding that it is an important issue, especially when a structure is under multiple earthquakes as in case of mainshock-aftershock ground motions.

The Incremental N2 method (IN2) (Dlšek and Fajfar, 2004) can substitute the IDA curve in the probabilistic framework for seismic design and assessment of structure fragility. In particular, this simplified method can be adopted for assessing the seismic failure probability of buildings by combining Cornell's closed-form solution with the N2 method (Fajfar, 1999) to estimate the annual probability of a structure reaching a near-collapse state. The approach involves: (a) determining the building's seismic capacity through pushover analysis (b) estimating the dispersion of this capacity (c) incorporating seismic hazard data.

Fragility curves for seismic risk assessment at territorial scale

In the context of the systemic vulnerability at urban district level, the estimation of fragility curves at "large scale" are required. Fragility curves in a discrete form can be developed for all building typologies identified in EMS-98 (Grunthal, 1998) (Table 11). The typological classification system was introduced to group structures with similar expected behavior during seismic events. However, it is important to note that certain structural characteristics influencing seismic

response - such as the fundamental period of vibration (T_1), damping coefficient, and soil amplification effects - are not considered in this classification.
The EMS-98 macroseismic scale classifies European buildings into six vulnerability classes (A to F), with decreasing vulnerability from A to F. It also provides a model for assessing seismic intensity based on observed post-earthquake building damage. This model defines twelve degrees of macroseismic intensity (IM), where IM = 1 indicates no observable effects, and IM = 10-12 signifies the destruction of most or all buildings. Additionally, it categorizes damage into five levels (DM):

- DM1 – Slight damage
- DM2 – Moderate damage
- DM3 – Severe damage
- DM4 – Very severe damage
- DM5 – Total collapse

For each vulnerability class and intensity level, EMS-98 uses qualitative linguistic descriptors (e.g., “few,” “many,” “most”) to express the probability of expected damage. These qualitative assessments are used to construct Damage Probability Matrices (DPMs).
Lagomarsino and Giovinazzi (2006), proposed the combined use of fuzzy set theory and probability theory to numerically translate these DPMs into a quantitative format, enabling a more precise evaluation of seismic vulnerability.

Table 11. European building typology classification

Typologies	Building types
Unreinforced Masonry	M1 - Rubble stone
	M2 - Adobe (earth bricks)
	M3 - Simple stone
	M4 - Massive stone
	M5 - Unreinforced Masonry (old bricks)
	M6 - Unreinforced Masonry withR.C. floors
Reinforced/confined masonry	M7 - Reinforced/confined masonry
Reinforced Concrete	RC1 - Concrete Moment Frame
	RC2 - Concrete Shear Walls
	RC3 - Dual System

In (Lagomarsino and Giovinazzi, 2006), the mean damage μ_D ($0 < \mu_D < 5$) of the expected discrete damage distribution, for each typological class, conditional on an intensity *im*, is given by:

$$\mu_D = 2.5\left[1 + tanh\left(\frac{im + 6.25V - 13.1}{Q}\right)\right]$$

11)

where:

V is the vulnerability index (Table 12), *im* is the seismic intensity and Q=2.3 is the ductility index. The vulnerability index V depends on the building type and its structural features. Five levels of vulnerability are provided: V^{--} (less vulnerable and probable); V^{-} (less vulnerable and more probable); V (mean); V^{+} (more vulnerable and probable); V^{++} (more vulnerable and less probable) (Table 12). The hazard is described in terms of the macroseismic intensity (*im*), according to the European macroseismic scale EMS-98.

Table 12. Values of the vulnerability index for masonry and RC building types

Typologies		Building type	V^{--}	V^{-}	V	V^{+}	V^{++}
Masonry	M1	Rubble stone	0,62	0,81	0,873	0,98	1,02
	M2	Adobe (earth bricks)	0,62	0,687	0,84	0,98	1,02
	M3	Simple stone	0,46	0,65	0,74	0,83	1,02
	M4	Massive stone	0,3	0,49	0,616	0,793	0,86
	M5	U Masonry (old bricks)	0,46	0,65	0,74	0,83	1,02
	M6	U Masonry—r.c. floors	0,3	0,49	0,616	0,79	0,86
	M7	Reinforced /confined masonry	0,14	0,33	0,451	0,633	0,7
Reinforced Concrete	RC1L	Frame in r.c. (without E.R.D)	0,3	0,49	0,644	0,8	1,02
	RC1M	Frame in r.c. (moderate E.R.D.)	0,14	0,33	0,484	0,64	0,86
	RC1H	Frame in r.c. (high E.R.D.)	-0,02	0,17	0,324	0,48	0,7
	RC2L	Shear walls (without E.R.D)	0,3	0,367	0,544	0,67	0,86
	RC2M	Shear walls (moderate E.R.D.)	0,14	0,21	0,384	0,51	0,7
	RC2H	Shear walls (high E.R.D.)	-0,02	0,047	0,224	0,35	0,54

(E.R.D.) means earthquake resistant design.

Adopting the binomial distribution to identify the probability of having a damage level d_{mi} (with i=1:5) conditional on *im*:

$$P(DM = d_{mi}|IM = im) = \frac{5!}{i!\,(5-i)!}\left(\frac{\mu_D}{5}\right)^i\left(1 - \frac{\mu_D}{5}\right)^{5-i}$$

12)

where:

! indicates the factorial operator. The discrete form of the fragility curve, which corresponds to the probability of a structure of reaching a damage state or worse as a function of ground motion intensity $P(DM \geq dm_i|IM = im)$, can be obtained:

$$P(DM \geq dm_5|IM = im) = P(DM = dm_5|IM = im)$$
$$P(DM \geq dm_i|IM = im) = P(DM = dm_i|IM = im) + P(DM \geq dm_{i+1}|IM = im) \text{ for } i\text{=4:1}$$

13)

The maximum likelihood estimation is then usually adopted for fitting fragility functions to structural analysis data and provide fragility curve in a continuous form. Starting from the discrete values of the fragility function, evaluated for different intensity levels (*im*), the continuous curves are obtained by adopting Eq. 10). When *Θ* and β are identified, the continuous fragility curve can be approximated by Eq. 7).

For the sake of example, Figure 18 shows the discrete fragility curve derived by the macroseismic method (structural analysis data) and the fitted fragility functions obtained via the *MLE*, with reference to masonry building M2, for the vulnerability index *V* and V^+ (Table 12) and all damage states dm_i with *i=1:5*.

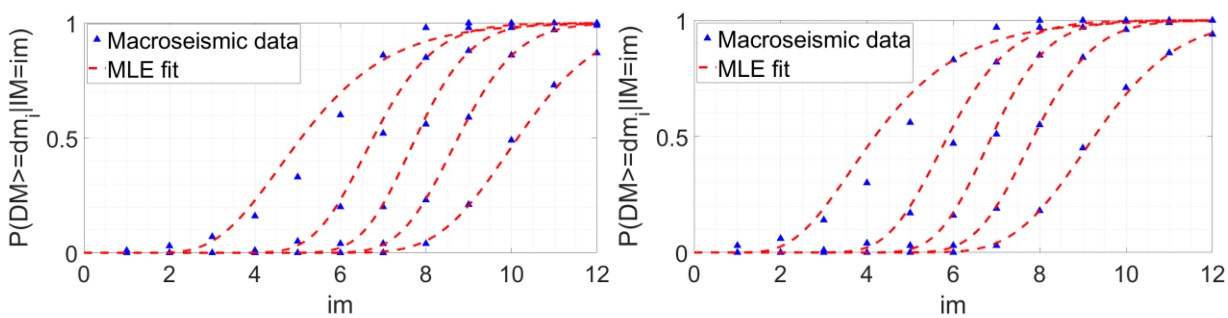


Figure 18*. Discrete fragility curves derived by the Macrosesimc method and fitted fragility functions obtained via maximum likelihood estimation. Masonry building (M2) - vulnerability index V and V+ (Table 12) - damage state dmi with i=1:5.*

Seismic risk assessment

In recent years, it has become widely recognized that seismic design must address multiple performance objectives. Society demands a level of protection that adequately mitigates various types of failures threatening human lives. Beyond life safety, there are additional societal responsibilities, including ensuring the continued operation of critical facilities and preventing excessive damage that could have significant long-term impacts.

Performance-Based Earthquake Engineering (PBEE) acknowledges that some damage is inevitable during seismic events, but it emphasizes the need to demonstrate that this approach represents the most cost-effective solution. Consequently, structural engineers face the challenge of predicting potential damages and their likelihood to support informed decision-making. This necessitates the development of methodologies that incorporate loss estimation strategies, enabling the quantification of performance and ensuring consistent seismic protection for both existing and new structures.

Performance evaluation must encompass the structure itself, its components, nonstructural systems, and building contents. Progress toward an integrated probabilistic design and assessment approach within PBEE has been led by the Pacific Earthquake Engineering Research (PEER) Center. This work forms the foundation of Loss-Based Earthquake Engineering (LBEE) (Krawinkler and Miranda, 2004), which aims to support cost-effective risk management by providing practitioners with tools to implement performance-based design efficiently.

The PEER framework (Cornell and Krawinkler, 2000) establishes a connection between the seismic response of structures and their financial implications. The analytical consequence function, as shown in Eq. 14), quantifies the rate of *C* exceeding threshold *c* (a given consequence, usually identified as the monetary loss):

$$\lambda(C > c) = \int_{DM} \int_{EDP} \int_{IM} P(C>c|DM) f(DM|EDP) f(EDP|IM) |d\lambda(IM > im)| dEDP\ dDM \tag{14)}$$

where:

$\lambda(C>c)$ is the rate of *C* exceeding the threshold *c*; *DM* is a vector damage measure indicating the discrete damage states of each component in the building; *EDP* is a vector of engineering demand parameters; *IM* is a ground-motion intensity measure; $d\lambda(IM > im)$ is the ground-motion hazard curve derivative and $f(A|B) = f(A = a|B = b)$ is the conditional probability distribution function for *A=a*, given *B=b*. The framework assumes conditional independence at each stage of the calculation (i.e. *C* is independent of *EDP* when *DM* is known).

Another metric of common interest is the annual failure rate. As this metric quantifies the level of safety of a structure. This metric can be computed by combining the ground motion hazard curve with the fragility function:

$$\lambda(F) = \int_{IM} P(F|IM = im)|d\lambda(IM > im)|$$

15)

when fragility is lognormal and the hazard curve is log-linear (Eq. 17) the above integral can be computed analytically (Jalayer and Cornell, 2003):

$$\lambda(F) = k_o \theta^{-k} e^{\frac{1k^2\beta^2}{2}}$$

16)

where the equation has been evaluated by the IM-based approach with the ground-motion hazard curve, Eq. (17) expressed by the the power-law relationship:

$$\lambda(IM > im) = k_o im^{-k}$$

17)

with k_o and k parameters defining the shape of the hazard curve and θ and β the parameters of the fragility function, related to the failure of the structure.

Performance assessment implies that the structural, non-structural, and content systems are given and that consequences, (e.g. expected annual loss, mean annual frequency of collapse) are computed and compared to specified performance targets. Performance-based design is different by virtue of the fact that the building and its components and systems first have to be created. The process developed in (Krawinkler et al., 2006) permits design decision making based on constraints imposed by multiple performance objectives, considering trades between different structural system choices and between strength, stiffness, and ductility characteristics. The proposed process also permits a consistent evaluation of the costs and benefits derived from the use of innovative technologies, such as base isolation and internal energy dissipation devices.

Urban center seismic risk assessment

Applications of procedures for estimating seismic risk, whether in the context of single-risk or multi-risk assessments at an urban scale, can be found in the literature.

One such application is presented in (Romis et al., 2021), which examines the medieval city of Campi Alto di Norcia, located in Valnerina (Italy). This study evaluates the reliability of common seismic risk assessment approaches by analyzing actual seismic damage observed in masonry buildings.

As part of the rehabilitation of the historic city center of Coimbra, (Vicente et al., 2011) conducted a comprehensive identification and inspection survey of old masonry buildings. In this study, building vulnerability assessment plays a crucial role, not only due to the physical consequences of a potential seismic event but also because it represents one of the few areas where engineering research can actively contribute to risk mitigation.

In (Cara et al., 2018), a tool for large-scale seismic risk assessment and mitigation in urban areas is presented. This methodology serves multiple objectives, including identifying the most vulnerable buildings whose collapse could obstruct strategic urban roadways during an earthquake and recommending targeted interventions to improve their resilience. The methodology is applied to the "Antiga Esquerra de l’Eixample" neighborhood in Barcelona, where a critical route to a hospital is analyzed.

(Ferreira et al., 2020) introduces a simplified methodology for assessing the seismic vulnerability of reinforced concrete buildings. This method is applied to several buildings affected by recent earthquakes of varying macroseismic intensities. It evaluates key parameters related to factors influencing a building’s seismic response, including structural characteristics and foundation conditions. The formulation of each parameter, along with its assigned weight, is derived from post-earthquake damage observations and expert judgment. This methodology is subsequently applied to the city center of Faro, the capital of Portugal’s Algarve region.

Despite advancements in seismic performance analysis, structural retrofitting remains a technically challenging task. In (Gusella et al., 2025), a framework is developed to identify suitable fragility curves and retrofitting strategies aimed at reducing seismic risk. The study can be applied to the structural typologies as defined in the European Macroseismic Scale (EMS-98), with the goal of facilitating international seismic risk analysis at large scale.

Systemic vulnerability assessment plays a crucial role in analyzing urban districts exposed to multiple hazards. In (Arrighi et al., 2023), a multi-risk workflow for seismic and flood hazards is presented, specifically designed for urban scale applications in historical cities. The workflow provides estimates of expected annual losses for buildings within a coherent multi-exposure and multi-vulnerability framework. This method is applied to the historic city center of Florence

(Italy), where expected seismic damage to buildings is assessed using the macroseismic model (Lagomarsino and Giovinazzi, 2006).

Effective disaster risk management requires analyzing and comparing different risks that may impact a given region, while also accounting for potential interactions between hazards, such as cascading effects. Although multiple risk assessments are often conducted independently, they frequently employ different methodologies and impact metrics, making direct comparisons difficult. To address this issue, (Polese et al., 2024) propose a harmonized multi-risk assessment methodology, focusing on seismic and flood risks. While each risk is evaluated separately, the assessment procedures are standardized to ensure comparability. This methodology has been successfully applied in two cross-border regions spanning Italy, Slovenia, and Austria, demonstrating its effectiveness.

A comprehensive multi-risk evaluation should not only prioritize the analyzed risks but also estimate their combined impact, including potential interactions between hazards and vulnerabilities. However, such interactions are often overlooked due to the complexity of modeling them. As a result, risks from different sources are typically assessed independently. Furthermore, variations in risk assessment methodologies and impact metrics complicate direct comparisons. To overcome this challenge, (Tocchi et al., 2023) present an approach that facilitates the comparison and ranking of risks. This approach is demonstrated through its application to the Veneto region in Italy, where earthquakes and floods are the hazards under investigation.

3.1.5 Tsunami hazard

3.1.6 Volcanic hazard

3.2 Hydraulic hazards

3.2.1 Coastal vulnerability in urban areas

3.2.2 Fluvial floods

3.2.3 Pluvial floods

3.3 Meteorological hazards

3.3.1 Extreme wind events under climate change

3.3.2 Extreme precipitations

3.4 Climate hazards

3.4.1 Urban heat waves characterization

Urban heatwaves are prolonged periods of extreme heat that significantly affect the health of urban populations and the resilience of infrastructure (Nawaro et al., 2023 and Cheng et al., 2019). These events are characterized by elevated daytime and nighttime temperatures and are exacerbated in urban areas due to the Urban Heat Island (UHI) effect, where built environments absorb and retain heat more effectively than surrounding rural areas. This intensification leads to a range of cascading impacts that span health, structural, and systemic challenges, disproportionately affecting vulnerable populations and poorly prepared urban systems.

Cascading Impacts of Urban Heatwaves

Heatwaves create systemic risks across multiple dimensions of urban systems:

1. **Health Impacts**:
    - Increased heat stress among vulnerable populations, such as the elderly, children, and low-income households.
    - Exacerbation of indoor air pollution, including elevated levels of formaldehyde, driven by higher indoor temperatures.
    - Higher morbidity and mortality rates, particularly among populations lacking access to adequate cooling mechanisms.
2. **Structural Risks**:
    - Accelerated deterioration of building facades due to sustained heat exposure, compromising structural integrity and increasing maintenance costs.
    - Reduced effectiveness of poorly insulated buildings, resulting in significant indoor overheating and discomfort.
3. **Systemic Challenges**:
    - Power outages triggered by heightened energy demand for cooling systems, leading to disruptions in essential services.
    - Strain on emergency response systems, delaying healthcare and compounding the health impacts of extreme heat.

Contributing Factors

Urban heatwave vulnerability arises from a combination of physical, social, and systemic factors:

- **Poor Building Stock**: Outdated and inadequately insulated residential buildings lack shading and thermal resilience, amplifying heat exposure.
- **Social Vulnerabilities**: Populations with limited coping capacity—such as elderly residents, children, and low-income families—are disproportionately affected.
- **Behavioral and Systemic Issues**: Limited access to cooling options and reliance on energy-intensive systems compound these challenges.

Case Study: Casette Inglesi, Bolzano

The **Casette Inglesi** neighbourhood in Bolzano exemplifies the cascading impacts of urban heatwaves. This social housing district, managed by the local social housing institute (IPES), comprises poorly insulated buildings with limited cooling solutions. During heatwaves, residents experience:

- **Health risks**, such as heat stress and heightened exposure to indoor air pollutants due to sealed windows and high indoor temperatures.
- **Structural vulnerabilities**, including rapid building degradation from sustained heat exposure.
- **Systemic disruptions**, such as blackouts and delayed emergency responses, which amplify the impacts on health and safety.

The Casette Inglesi case study provides valuable insights into the interplay of physical, social, and systemic vulnerabilities under heatwave conditions. A detailed analysis of this neighbourhood, including proposed mitigation and adaptation strategies, is presented in the following.
The **Casette Inglesi** neighbourhood in Bolzano serves as a critical case study for assessing systemic vulnerability to heatwaves within urban settings. This densely populated district, managed by the local social housing institute (**IPES**), features **344 residential units** housing over **800 residents**, predominantly **low-income families**, **elderly individuals**, and **persons with disabilities**. These demographic and structural characteristics highlight its heightened susceptibility to cascading risks triggered by heatwaves.

__Figure 19__. Casette Inglesi Neighbourhood – Map and Building View

Urban Context and Hazard Description

The **urban configuration** of Casette Inglesi significantly amplifies its vulnerability:

- **Structural Characteristics**:
    - Residential buildings are outdated and lack adequate insulation or shading mechanisms.
    - High **soil impermeability** due to underground parking and narrow road networks exacerbates heat retention.
- **Socioeconomic Profile**:
    - Vulnerable populations, including elderly and low-income households, have limited coping capacities, such as access to air conditioning or energy-efficient infrastructure.

Hazard Context: During heatwaves, the neighbourhood experiences:

1. **Health Risks**:
    - Increased exposure to **indoor air contaminants**, such as formaldehyde, due to high indoor temperatures and limited ventilation.
    - Sustained heat stress, particularly for populations with pre-existing health conditions.
2. **Structural Challenges**:
    - Prolonged heat exposure accelerates the deterioration of building facades, further reducing their thermal efficiency.
3. **Systemic Risks**:
    - Blackouts caused by excessive energy demands disrupt essential services, including healthcare and emergency responses.

These interconnected hazards create a **compound heatwave multi-hazard scenario**, where systemic vulnerabilities intensify the cascading impacts of extreme heat.

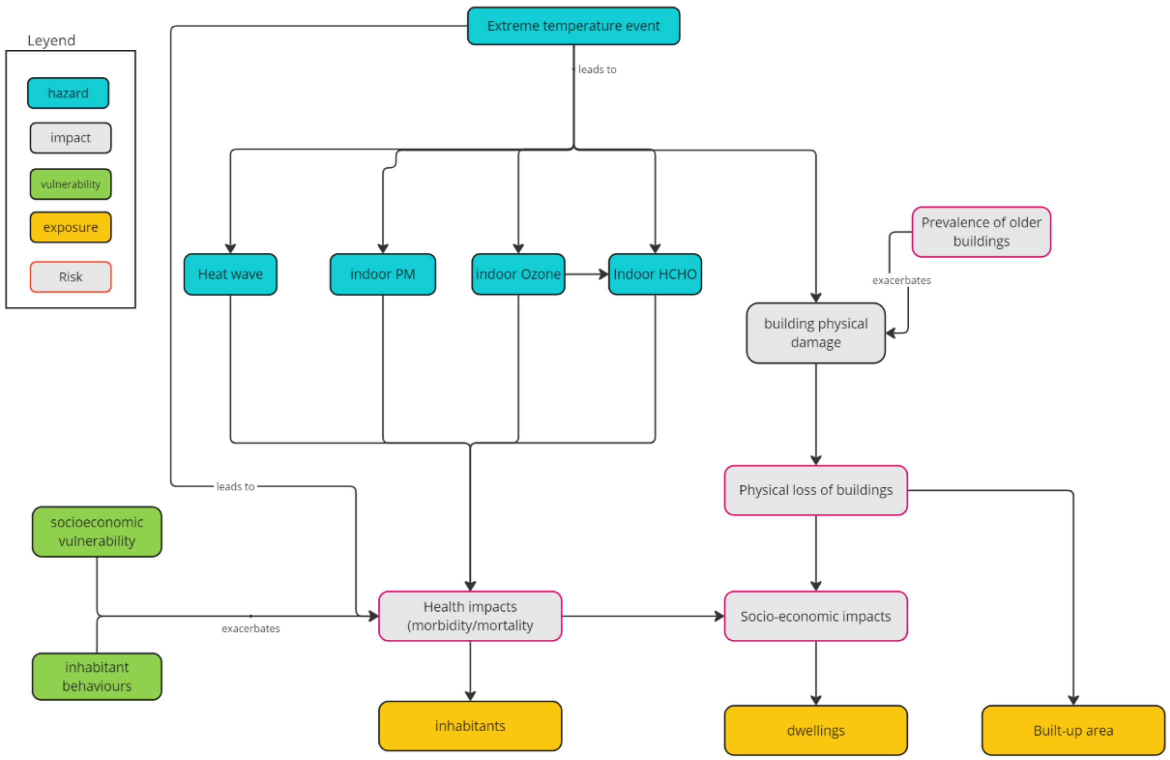


Figure 20*. Risk Storyline impact chain: Bolzano, Casette Inglesi.*

Methodologies

A comprehensive assessment of systemic vulnerability in Casette Inglesi incorporates the following:

1. **Monitoring**:
   - Indoor temperature and humidity trends during heatwaves are observed, providing critical data on microclimatic conditions.
   - Indoor air quality monitoring evaluates pollutant levels, correlating exposure with heatwave intensity and behavioral factors.
2. **Modeling**:
   - Building energy simulations identify vulnerabilities in insulation and ventilation systems, informing potential mitigation strategies.
3. **Health Metrics**:

   - The impact of indoor heat exposure is quantified using a preliminary framework based on the Disability-Adjusted Life Years (DALYs) metric. This framework integrates epidemiological evidence, temperature profiles, and population health data to estimate the cumulative health burden during extreme heat events. Initial findings highlight:
      - Greater health impacts among elderly residents, with significant harm occurring when indoor temperatures exceed minimum risk thresholds (e.g., 24.4°C).
      - A measurable burden of 0.005 to 0.022 DALYs/day for the neighborhood population, emphasizing the need for targeted interventions.
4. **Stakeholder Engagement**:
   - Focus groups and surveys capture resident behaviors and vulnerabilities during heatwaves, ensuring that recommendations align with community needs.
   - Collaboration with IPES and municipal authorities supports actionable strategies for resilience-building.

Insights and Implications

This case study underscores the critical interplay of physical, social, and systemic factors in urban heatwave vulnerability. The application of the indoor heat-harm metric provides a novel, standardized approach to quantifying health impacts, offering actionable insights for enhancing urban resilience. These findings inform targeted measures, such as retrofitting buildings for better insulation and ventilation, while contributing to broader frameworks for systemic vulnerability assessment.

3.4.2 A Heatwave vulnerability and impact assessment GIS based framework in urban areas

Heatwaves are becoming increasingly frequent and intense due to climate change, posing significant threats to cities. Densely populated urban areas are especially vulnerable to extreme heat events. As climate hazards become more pressing, researchers have focused on developing decision-support tools to assess risk levels and identify critical urban areas where climate-resilient solutions must be adopted (D'Ambrosio et al., 2023a).

It is in this context that, as a part of the "PLANNER-Piattaforma per LA GestioNe dei rischi Naturali in ambiEnti uRbanizzati" (Platform for managing natural risks in urbanised environments; Participating Subjects: ETT spa [lead subject], Genegis GI, STRESS S.c.a.r.l.-Sviluppo Tecnologie e Ricerca per l'Edilizia Sismicamente Sicura ed ecosostenibile, DiARC – UNINA [Scientific Responsible for DiARC: V. D' Ambrosio]) research project, a heatwave vulnerability and assessment model was developed. The research project focuses on improving climate adaptation and digitizing urban design processes. It includes four research outputs and results in a decision-support tool that maps vulnerability to environmental risks like seismic hazards and heatwaves. The project also offers a comprehensive set of tools, technologies, and methodologies for risk evaluation, management, and mitigation to enhance urban resilience (Bassolino et al., 2021).

Conceptual framework of the model

The model proposed for the assessment of the heatwave impact is based on the general risk/impact model proposed in the AR5 report of the IPCC (2014), which assesses the impacts of climatic phenomena as a result of the combination of vulnerability, hazard and exposure. The model defined and tested within the research to assess the distribution of the impact of a climate hazard scenario on an urban system takes into account the vulnerability of the urban system and a specific exposure (D'Ambrosio et al., 2023a; Di Martino et al., 2017).

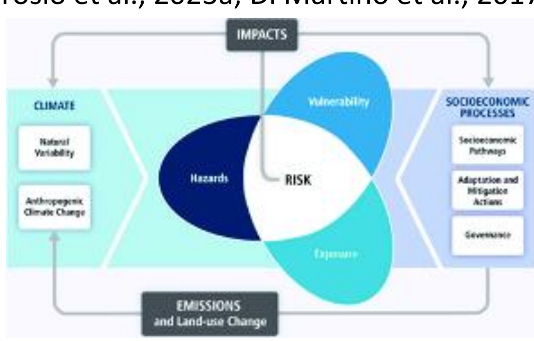


Figure 21. *Risk conceptual framework of IPCC AR5 (Source: IPCC, 2014).*

In the proposed model, the **heatwave hazard scenarios** refer to 3 different periods:

- Short-term scenario: 2020-2040
- Medium-term Scenario: 2041-2070

- Long-term Scenario: 2071-2100

The three periods were associated with different intensities of the heatwave, which tends to worsen over time, estimated based on the Greenhouse G as (GHG) emission time trend scenarios defined in the IPCC AR5 report as Representative Concentration Pathway (RCP) scenarios. Representative Concentration Pathways (RCPs) are climate scenarios expressed as GHG concentrations rather than emission levels. The number associated with each RCP refers to the Radiative Forcing (RF) expressed in units of Watts per square meter (W/m2) and indicates the magnitude of anthropogenic climate change by 2100 compared to the pre-industrial period: for example, each RCP shows a different amount of additional heat stored in the Earth system as a result of GHG emissions. Specifically, RCP scenario 4.5 ('Strong mitigation') assumes the implementation of certain initiatives to control emissions. Stabilization scenarios are considered: by 2070, CO2 emissions fall below current levels, and atmospheric concentrations stabilize at about double pre-industrial levels by the end of the century (Di Martino et al., 2017).

The impact scenario analysis conducted as part of the PLANNER research project focuses on **heatwave hazards associated with the RCP 4.5 scenario**.

The **impact scenario** is generated by referencing a specific hazard scenario of a heatwave phenomenon affecting an urban system. This involves assessing the system's vulnerability to the phenomenon as well as its combined vulnerability. The impact scenario **is linked to exposure**, which determines the value at risk from the climatic hazard.

The vulnerability model applied in PLANNER research is based on the acknowledgement of the need for the detailed analysis of the urban context concerning the characteristics that make it more sensitive to the climatic phenomena to have a complete vulnerability assessment. Specifically, a division of the urban system into subsystems is proposed to more effectively model the complexity of the urban area studied and separately analyse the vulnerability of each subsystem to the climate event.

The assessment of the vulnerability of the urban fabric is made through a hierarchical model. In the research project, the vulnerability to the heatwave of the buildings subsystem is assessed using four intermediate indicators: thermal lag, thermal decremention factor, building volume, and solar exposure of building envelope. Instead, for the outdoor spaces subsystem, the intermediate indicators are: Albedo, Sky View Factor, Solar Exposure of Outdoor Spaces, Normalized Difference Vegetation Index (D'Ambrosio et al., 2023b).

In PLANNER, the testing was carried out taking into consideration three types of assets exposed to risk:

- resident population (given by the density of total population residing in the census area),

- disadvantaged population of the weakest segment (given by the population density of weak range - age < 5 years and age > 65 years - per census area),
- fuel poverty (refers to fuel poverty population density -residents who are non-income earners, unemployed, and in households with more than 5 members - by census area).

The purpose was to analyse the distribution of impact scenarios in the urban fabric of the study, not only in relation to the total resident population, but also to the weak population only, i.e. children and the elderly, who are the categories most at risk from a health point of view, and the unemployed or low-income population, who may not have the necessary economic resources to purchase and use energy consumption goods, such as air conditioners, to mitigate the discomfort of heat wave phenomena in their homes (Bassolino et al., 2021; D'Ambrosio et al., 2023a).
The **combination of exposure and the vulnerabilities of the physical system** with which it interacts forms a specific indicator labelled as "Combined vulnerability"[1]. This indicator measures the joint intensity of the value of the asset exposed to risk and the vulnerabilities of the subsystems it interacts with. Finally, the **impact indicator** is measured as a combination of the combined vulnerability and the considered hazard scenario (Di Martino et al., 2017).

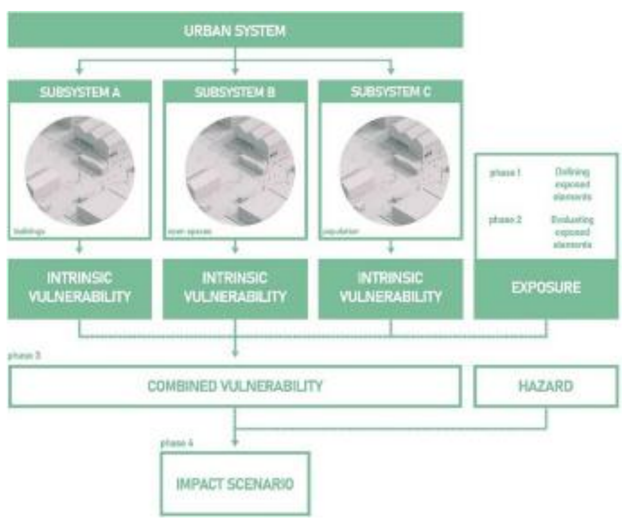


Figure 22. *Diagram of the hierarchical model for the assessment of heatwave impact scenario. Source: D'Ambrosio et al., 2023a.*

The model was realized with the support of Geographic Information System (GIS) tools. It integrated a hierarchical approach for estimating urban vulnerability and heatwave impacts and

1 It represents an indicator of vulnerability associated with the element of the subsystem in which the value exposed to damage is located, integrating the intrinsic vulnerability of the elements of the subsystems that interact with the exposure and the vulnerability itself.

optimizes adaptation and mitigation actions for residential buildings to enhance comfort and reduce CO_2 emissions, with resilience measured by reduced vulnerability and impacts (D'Ambrosio et al., 2023b).

Case of application

The model was tested in the area of the municipality of Naples (Italy). The selection of these urban settlements was driven by their complexity and the variety of their urban forms. Naples exemplifies a dense urban fabric with a range of settings, from well-established historical areas to newly developed zones.

The city is divided into 4301 census tracts, and for each residential tract, the Italian National Institute of Statistics (ISTAT) offers comprehensive data on the resident population and the built environment.

To implement the impact assessment model, the following datasets have been used (D'Ambrosio et al., 2023b):

- Light Detection and Ranging (LIDAR) high-resolution Digital Terrain Model (DTM) and Digital Surface Model (DSM) raster datasets of the study areas with a cell size of 1 m × 1 m provided by the Italian Ministry of Environment;
- A topographic database of the study areas on a spatial scale of 1:5000;
- An ISTAT last-census dataset on a spatial scale of 1:10,000;
- The satellite NDVI, albedo and sky-view factor in raster format with a cell size of 1 m × 1 m;
- Satellite soil temperature data measured in day and night hours during a heatwave period in raster format with a cell extension equal to 1 m × 1 m.

In the model, the census section[2], as defined by the 15th Census of Population and Housing conducted by ISTAT in 2011, was identified as the spatial reference unit for heatwave impact analysis.

Methodological approach

As previously indicated, the impact assessment model is based on the conceptual framework defined by the IPCC's AR5 report, which states that the impact in the field of climate risks results from the interaction between hazard, vulnerability, and exposure. Within the research project, an automated calculation model for assessing the impact of heatwaves in urban areas has been

2 The census sections represent well-defined territorial units, homogeneous in terms of geography and administration, that collect socio-demographic and structural information about the population and the built environment. The data collected for the 15th General Census by the National Institute of Statistics refers to October 9, 2011. ISTAT provides geographic data related to the territorial base systems for the years 1991, 2001, and 2011, covering the entire zoning of the Italian territory. The geographic information of the census sections has been merged at the national level and is accessible in two different geographic projections (the ED 1950 UTM Zone 32n reference system and the WGS 84 UTM Zone 32n, which was used in the proposed process) in shapefile format.

developed. To this end, the model was created using GIS-based tools and consists of a series of algorithms that perform the calculation process.
The **impact scenario maps** on residents in the presence of heatwaves were produced following these steps:

1. Calculation of the Exposure value by estimating the resident population in individual residential buildings.
2. Calculation of the combined vulnerability indicator, considering exposure, the intrinsic vulnerability [3]of buildings, and the intrinsic vulnerability of surrounding open spaces.
3. Calculation of the impact indicator, considering combined vulnerability and a heatwave hazard scenario.

The **heatwave hazard scenarios** were defined according to the RCP 4.5 GHG emissions scenario as described by AR5 report of the IPCC. The RCP 4.5 scenario was chosen in the framework of the research as the one most probable at the current state. The extraction of characteristics that determine a hazard scenario caused by a heatwave considered the following daily climatic parameters (D'Ambrosio et al., 2017):

- daily maximum temperature;
- daily minimum temperature;
- daily heat index;
- daily gradient of surface temperature between day and night.

To establish a hazard scenario, it's crucial to determine the number of consecutive days each of the previously described parameters surpasses a specified threshold. For each parameter, a risk characteristic is defined by setting a threshold value and a minimum consecutive days criterion for surpassing it. When all four parameters exceed their thresholds for a consecutive number of days exceeding the predetermined minimum, a heatwave phenomenon is triggered (D'Ambrosio et al., 2017). Based on the values of daytime temperature and temperature gradient, and the period during which the heatwave is expected (short, medium, or long term), the hazard indicator value has been estimated and divided into 5 thematic classes.
The study of the impacts of the heatwave climatic phenomenon focused on assessing risk-**exposed values** associated with the resident population, which is subject to discomfort and potential health damage caused by the occurrence of the phenomenon. The exposure is measured by computing the number of residents living in each residential building (D'Ambrosio et al., 2023a).

3 It refers to those characteristics that, regardless of the magnitude of the climatic phenomenon considered and the interactions between subsystems, determine the propensity of each individual element belonging to the urban system to suffer negative effects. To assess the intrinsic vulnerability of subsystems, the characteristics of their elements that might influence their response to heatwave events are evaluated. These characteristics pertain to the construction, morphological, technological, and environmental aspects of residential buildings and open spaces. For residential buildings, this includes factors such as construction eras and techniques to evaluate thermal lag and thermal decremention factor, building volume, and solar exposure. For open spaces, it includes the Sky View Factor, solar exposure, albedo, and NDVI (D'Ambrosio et al., 2023a).

The exposed values are (D'Ambrosio et al., 2017):

- resident population (given by the density of total population residing in the census area),
- disadvantaged population of the weakest segment (given by the population density of weak range - age < 5 years and age > 65 years - per census area),
- fuel poverty (refers to fuel poverty population density -residents who are non-income earners, unemployed, and in households with more than 5 members - by census area).

The categories were developed considering the data from the 2011 census territorial databases, calculating for each category the surface population density. To obtain exposure, the population density domain per census area was partitioned into 5 thematic classes.

The **impact scenarios** were generated by first creating a combined vulnerability map of the urban system, which represents the combined contribution of exposure and the vulnerabilities of the subsystems that interact with the value at risk. The combinations of the two indicators, hazard and combined vulnerability, resulted in the generation of 3 impact scenarios for each hazard scenario, one for each of the combined vulnerability thematic maps obtained.

Vulnerability assessment

To assess the **vulnerability** of residential building and outdoor space subsystems, a series of indicators were calculated, taking into account the fundamental features of settlements in terms of type, morphology, and technology. Additionally, consideration was given to the presence and strength of greenery and urban elements that can influence temperature, airflow, and humidity levels during severe climatic events (D'Ambrosio et al., 2023a). The climate vulnerability calculation model is based on a hierarchical architecture suitable for managing the complexity of the physical, technological, environmental, and social components of an urban system at different scales. The process of building the vulnerability assessment model consists of the following activities (Apreda, 2017):

- identification and selection of indicators;
- determination of calculation characteristics;
- acquisition of input data.

The model was constructed by first identifying indicators commonly found in scientific literature and then selecting the ones to be used. The model is structured into five hierarchical levels and was built based on the recognition of three subsystems (buildings, open spaces, and population). Different types of information corresponding to various knowledge levels were assigned to these subsystems (Di Martino et al., 2017). The vulnerability assessment model is structured in different steps (Apreda et al., 2019):

1. *Subdivision of the Urban System*

The urban system is divided into subsystems. The choice of section size is related to the scale of detail for the analysis.

2. *Identification of Influencing Characteristics*

Characteristics that affect each subsystem's response to phenomena are identified.

3. *Selection of Vulnerability Indicators*

A set of vulnerability indicators is selected based on one or more characteristics of each subsystem, then normalized and classified.

4. *Weight Attribution and Calculation*

Weights are assigned to each vulnerability indicator, and a synthetic vulnerability indicator for each subsystem is calculated. This phase involves the use of decision-making approaches and calibration necessary to assign the weight of each indicator, evaluating its contribution to the vulnerability of the investigated subsystem.

The indicators for the assessment of the intrinsic vulnerability of the physical system are:

- Residential Buildings Sub-System
    - Thermal Lag
    - Thermal Decremental Factor
    - Building Volume
    - Solar Exposure of Building Envelope
- Outdoor spaces
    - Albedo
    - Sky View Factor
    - Solar Exposure of Outdoor Spaces
    - Normalized Difference Vegetation Index.

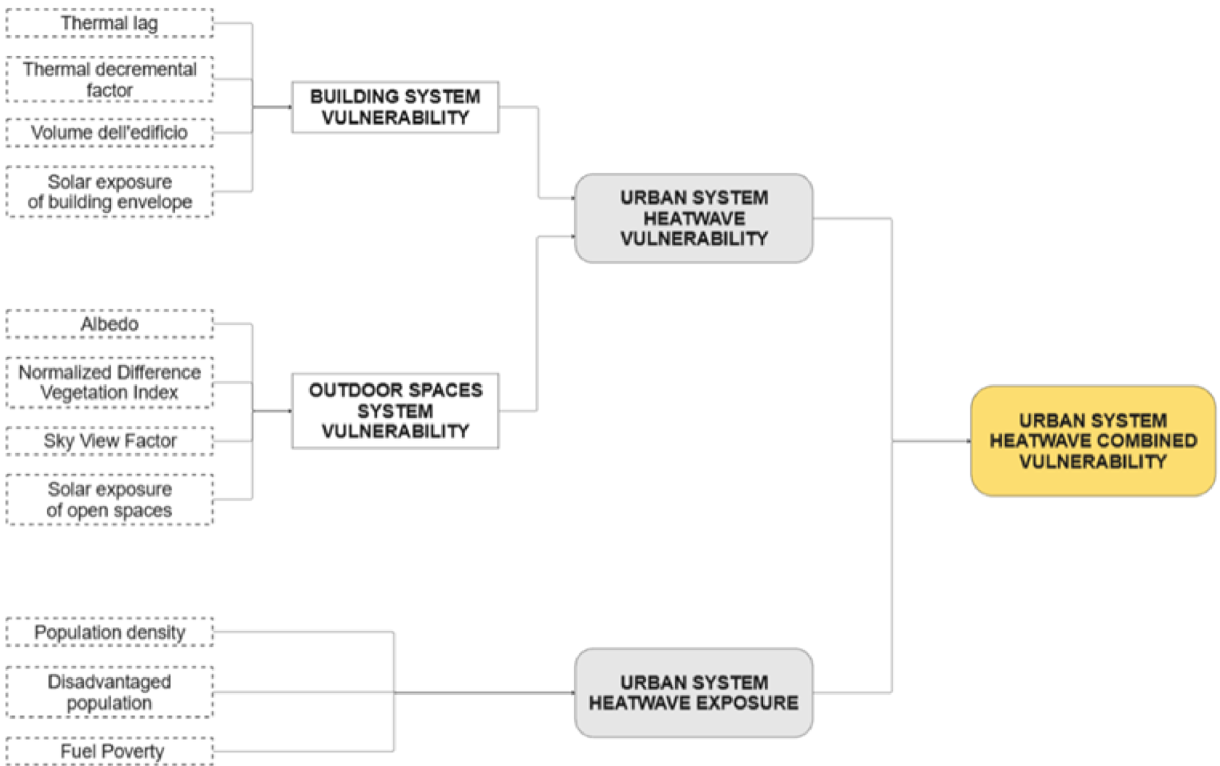


Figure 23. *Set of indicators used for the assessment of vulnerability to heatwave.*

All indicators are subject to a normalisation process by classes.
To effectively use the indicators' contribution in the calculation of the subsystem vulnerability, each indicator is normalised by performing a partitioning into n classes through an appropriate thematic classification method for ranges of values. A thematic classification by value ranges is a partitioning into n classes of equivalence of a set of thematic elements (e.g. building polygons of the Buildings theme), taking into consideration a specific attribute or number field of the theme. Each class is identified by the lower and upper extremes of the attribute's value range, known as breaks. Each class is then assigned a label and a symbol for display on a map. A method of thematic classification by value ranges is a method that appropriately determines the breaks of each class. At the end of the calculation process, each indicator is assigned a particular numerical value. The value domain of the indicator is partitioned into n classes in the normalisation phase. Each indicator is then normalised by partitioning the subsystem elements into n thematic classes according to the numerical value of the indicator. In the research, it was decided to perform a partitioning into 5 classes, assigning a value from 1 to 5 to each class, where a lower value corresponds to a greater contribution to the vulnerability of the subsystem element.

NUMERICAL VALUE	LABEL
1	High
2	Medium-high
3	Medium
4	Medium -low
5	Low

Figure 24. *Indicator values and labels (Source: Di Martino et al., 2017).*

The heatwave impacts are related to the possible thermal discomfort and potential loss of life of the population, which are influenced by the characteristics of buildings and open spaces. Consequently, the proposed indicators aim to characterise in more detail the vulnerability of these sub-systems: the selection presented in the model includes both widely used indicators (NDVI, population density, weak population groups) and indicators specifically constructed to describe at a more detailed scale (1:5000) the characteristics of buildings (phase shift, attenuation, volume, envelope sunshine), outdoor spaces (SVF, albedo, open space sunshine) and population (fuel poverty) (D'Ambrosio et al., 2017).

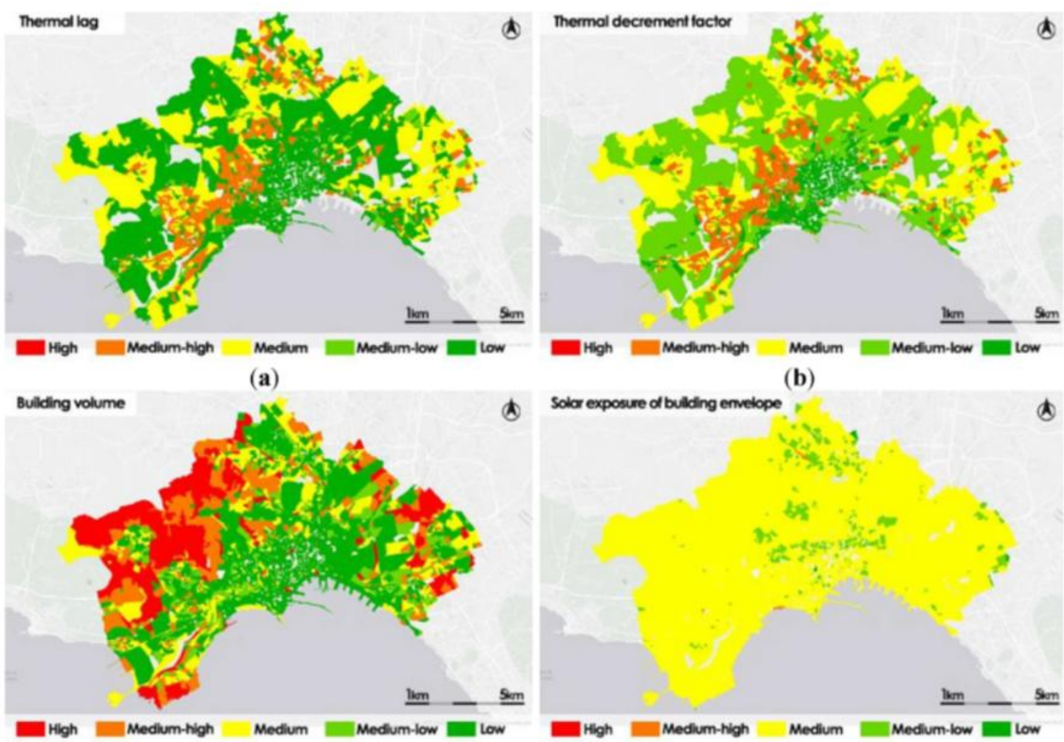


Figure 25. *Residential building subsystem vulnerability intermediate indicators (Source: D'Ambrosio et al., 2023a).*

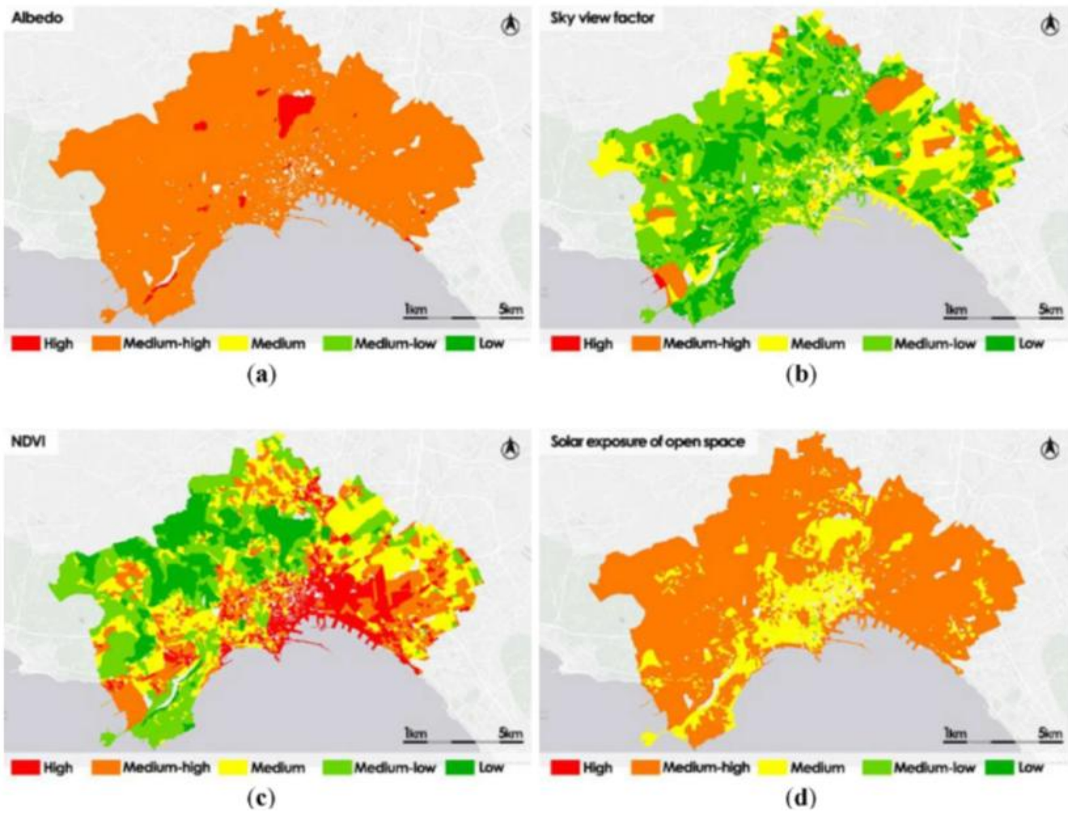


Figure 26. *Outdoor spaces subsystem vulnerability intermediate indicators (Source: D'Ambrosio et al., 2023a).*

3.4.3. A methodological approach to assess pluvial flooding vulnerability and impact

Pluvial flooding, caused by intense rainfall overwhelming urban drainage systems, poses a growing challenge in cities, particularly in coastal and low-lying areas. Areas with rapid urban growth and insufficient drainage, like East Naples suffer from drastic changes in weather due to climate change. This not only makes the area more prone to flooding but also causes extensive damage to the urban infrastructure. In the framework of the METROPOLIS – Metodologie e tecnologie integrate e sostenibili per l'adattamento e la sicurezza di sistemi urbani (Integrated and sustainable methodologies and technologies for the adaptation and safety of urban systems; PONREC 2007/2013 - Coordinator and Scientific Coordinator for the DiARC Research Group: Valeria D'Ambrosio) research project, a methodological approach to assess pluvial flooding vulnerability and its impacts was tested in the East Naples area. It defines a framework of tools and guidelines for climate risk reduction, useful for developing appropriate methodological and operational processes necessary for the performance control of interventions at various scales. This begins with modelling the vulnerability characteristics of the urban system and simulating expected climate impact scenarios.

Conceptual framework of the model

The model proposed for the assessment of the pluvial flooding impact is based on the general risk/impact model proposed in the AR5 report of the IPCC (2014), which assesses the impacts of climatic phenomena as a result of the combination of vulnerability, hazard and exposure. The model defined and tested within the research to assess the distribution of the impact of a climate hazard scenario on an urban system takes into account the vulnerability of the urban system and a specific exposure (Di Martino et al., 2017).

The research endeavours led to the creation of a vulnerability assessment model for heatwaves and pluvial flooding. This model was developed through the examination of data about the characteristics of the social and physical systems gathered from institutional databases, direct analysis, and observations conducted at various scales. The focus of the analysis included intricate urban elements, residential units, buildings, and open spaces. The research methodology involved classifying typologies and sampling based on recurring types/morphologies and building techniques. This ensured a representative selection of urban elements and similar buildings within distinct urban contexts. This approach facilitated integrating point data with databases lacking the depth required for detailed knowledge processes through downscaled analyses. By correlating different categories of data, extensive mapping was achieved, listing urban elements and buildings belonging to the same class based on shared characteristics. The abundance of data allowed for normalizing and saturating data related to urban fabrics according to implemented classifications, thereby providing a broad and consistent foundation for developing the knowledge model (D'Ambrosio et al., 2016).

The analysis of impacts in an urban environment involved data collection through three methods: a) satellite remote sensing and a rapid data processing procedure; b) databases (ISTAT, DPC, Weather Observatory, CMCC, Basin Authority, etc.); c) direct survey (dimensional, thermographic, atmospheric, environmental, and technological data) conducted both in rapid form and in detail (D'Ambrosio et al., 2015).

The assessment of the impact of pluvial flooding in urban settlements is based on the construction of an evaluation model for the climate vulnerability of the urban system to the phenomenon under consideration. The model proposed in the Metropolis project, structured in five hierarchical levels, was constructed based on the recognition of three subsystems, to which different types of information corresponding to the various levels of knowledge were subsequently referenced. The adoption of a systemic approach allowed for viewing the urban reality as a system characterized by multiple overlapping subsystems that interact with one another, in relation to which the model and indicators can be articulated (Apreda, 2017).

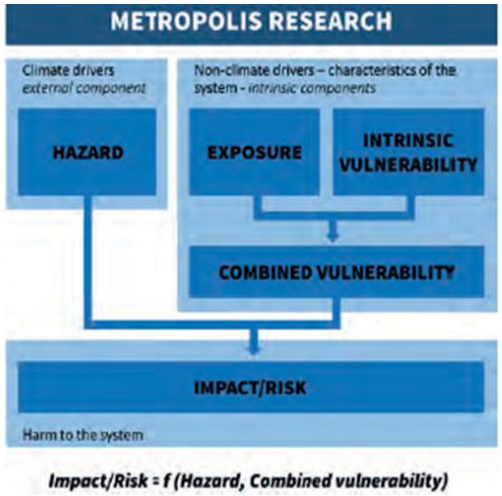


Figure 27. *Diagram of the hierarchical model for the assessment of pluvial flooding impact scenario (Source: Apreda, 2017).*

Case of application

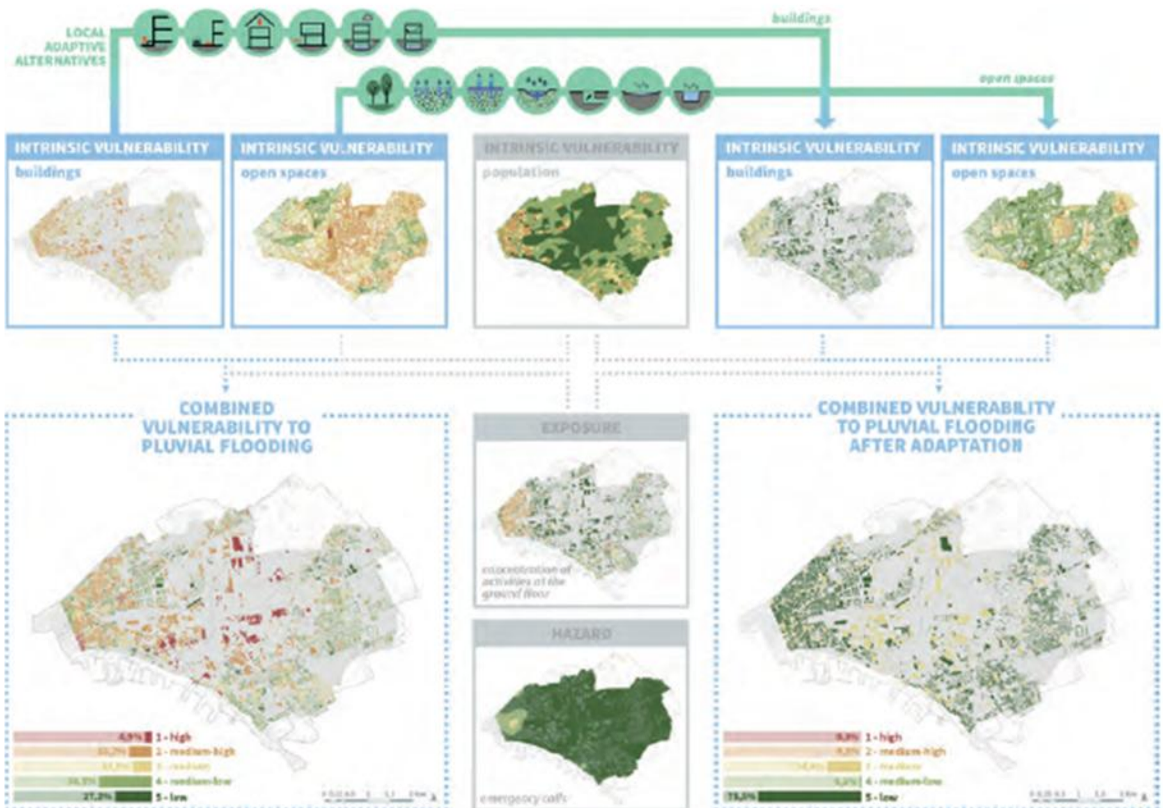
The eastern area of Naples has been chosen as the urban area to test the pluvial flooding vulnerability and impact assessment model. This area consists of nine communities, each with distinct social and physical characteristics, spread across the municipality's three districts. Because of its complexity, the region is a great case study, illustrating diverse degrees of susceptibility influenced by a mix of technological and typo-morphological elements from various historical eras.

About 23.5 km², or 20% of the city's total land area, is covered by the study area. It displays an extensive range of urban, natural, and "human" landscapes, each of which represents a distinct historical era

Methodological approach

The impact scenario maps of pluvial flooding on the ground floors of buildings have been produced for the study area of Eastern Naples. The process of generating impact scenario maps consists of the following steps (D'Ambrosio et al., 2017):

- calculation of the Exposure value by estimating the usable area on the ground floors of the buildings;
- calculation of the integrated vulnerability indicator considering exposure, the intrinsic vulnerability of the buildings, and the intrinsic vulnerability of the surrounding open spaces;
- calculation of the impact indicator, taking into account the integrated vulnerability and the hazard scenario for pluvial flooding.



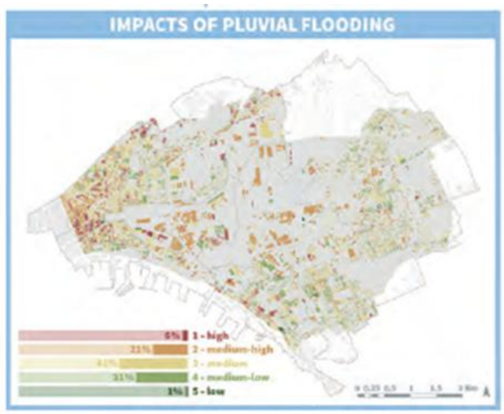


Figure 28. *Diagram of the Calculation Model for the Impact of Pluvial Flooding (Source: Metropolis research).*

The impact scenario maps were obtained by appropriately combining the integrated vulnerability with the climate hazard scenarios regarding pluvial flooding. Since the study area is not subject to significant flooding phenomena, the choice was made to configure a hazard scenario related to the concentration of reports provided by the Civil Protection Office of the municipality of Naples in the study area (D'Ambrosio et al., 2017).

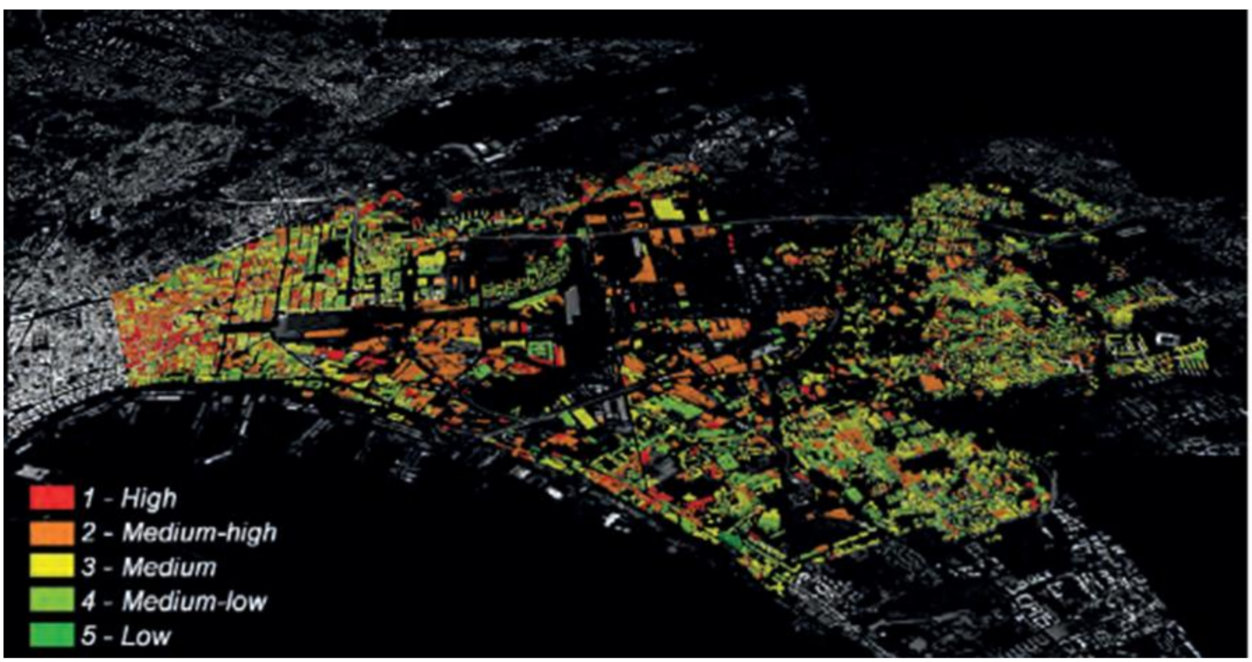


Figure 29. *Pluvial flooding impact scenario (Source: D'Ambrosio et al., 2017).*

The model proposed in the Metropolis project, structured in five hierarchical levels, was constructed based on the recognition of three subsystems, to which different types of information corresponding to various levels of knowledge were subsequently assigned. Adopting a systemic approach allowed for viewing urban reality as a system characterized by multiple overlapping subsystems that interact with one another, providing a framework for articulating the model and the indicators. The 'extrapolation' of the subsystems **Buildings**, **Open Spaces**, and **Population** enabled a minimal characterization of the urban system, necessary for assessing vulnerability, which could be further integrated with other subsystems in relation to new research objectives (Apreda, 2017).

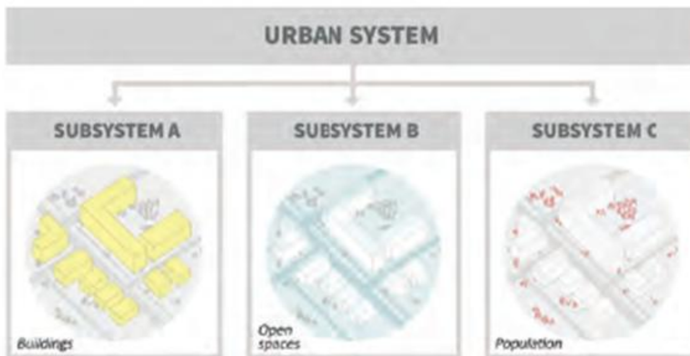


Figure 30. *Urban system subdivision into the 3 subsystems: buildings, open spaces, population (Source: Apreda et al., 2017).*

Vulnerability assessment

The development of the vulnerability assessment model follows these steps (Apreda et al., 2019):

1. **Subdivision of the urban system** into its subsystems.
2. **Identification of key characteristics** that affect the response of each subsystem to the phenomenon.
3. **Selection of vulnerability indicators**, derived from one or more characteristics of each subsystem, which are appropriately normalized and classified.
4. **Assignment of weights** to each vulnerability indicator and calculation of the composite vulnerability indicator for each subsystem.

The indicators - recurring in the scientific literature - were selected according to specific criteria. Once the set of indicators and their corresponding calculation formulas were identified, the necessary characteristics for the calculations were determined, which were then elaborated from input data acquired from official databases. This allowed for the search for data sources, which involved redefining some characteristics and indicators in cases where reliable and/or accessible sources were lacking (Di Martino et al., 2017).

The indicators selected for the assessment of the intrinsic vulnerability of the urban sub-systems are:

- Residential buildings
  - Building coverage ratio
  - Percentage of building on the sidewalk
  - Ground floor activities
  - Roof typology
- Outdoor spaces
  - Open spaces area
  - Soil permeability
  - Flow capacity of storm drainage system
  - Maintenance of storm drainage system.

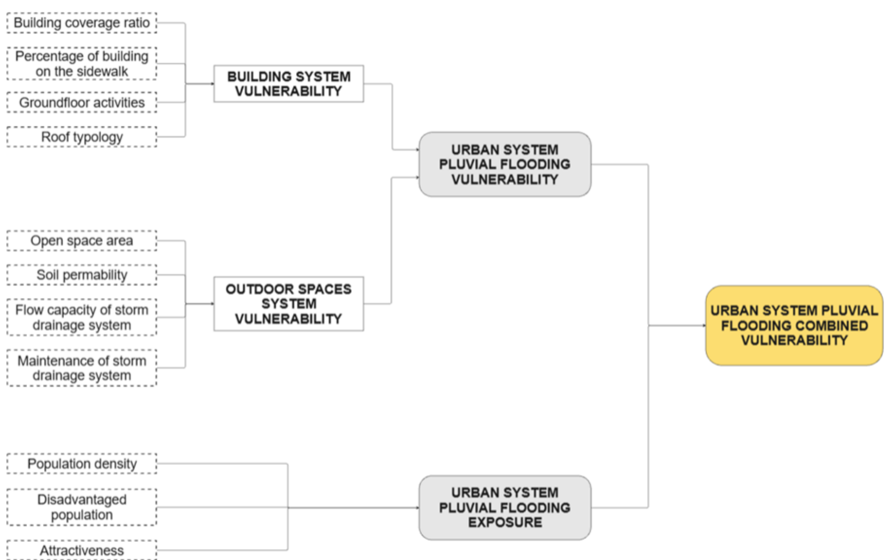


Figure 31. *Set of indicators used for the assessment of vulnerability to pluvial flooding.*

The indicators for evaluating the vulnerability of buildings to pluvial flooding focus on various factors, including the area covered by buildings and the presence of uncovered internal areas that could lead to flooding on ground floors. Key indicators include the building coverage ratio, which compares the covered area to the total building area, and the percentage of building on the sidewalk, determined by the ratio of the perimeter adjacent to sidewalks to the total perimeter. Additionally, vulnerability is assessed based on ground floor activities and the roof's ability to facilitate rainwater runoff, categorized by roof type (flat or sloped).

For open spaces, vulnerability is measured by analyzing areas potentially exposed to flooding and their physical characteristics, such as soil permeability and the effectiveness of the storm drainage system. This system's flow capacity is calculated by comparing the drainage pipes' discharge to the runoff discharge, considering factors like geometry and slope. Maintenance of the storm drainage system is also assessed by evaluating the percentage of clogged inlets.

Population exposure to pluvial flooding is analyzed using indicators such as population density and the presence of disadvantaged groups. An additional indicator evaluates the concentration of specific populations, such as students and employees, which can impact mobility and safety during flooding events (Apreda et al., 2019).

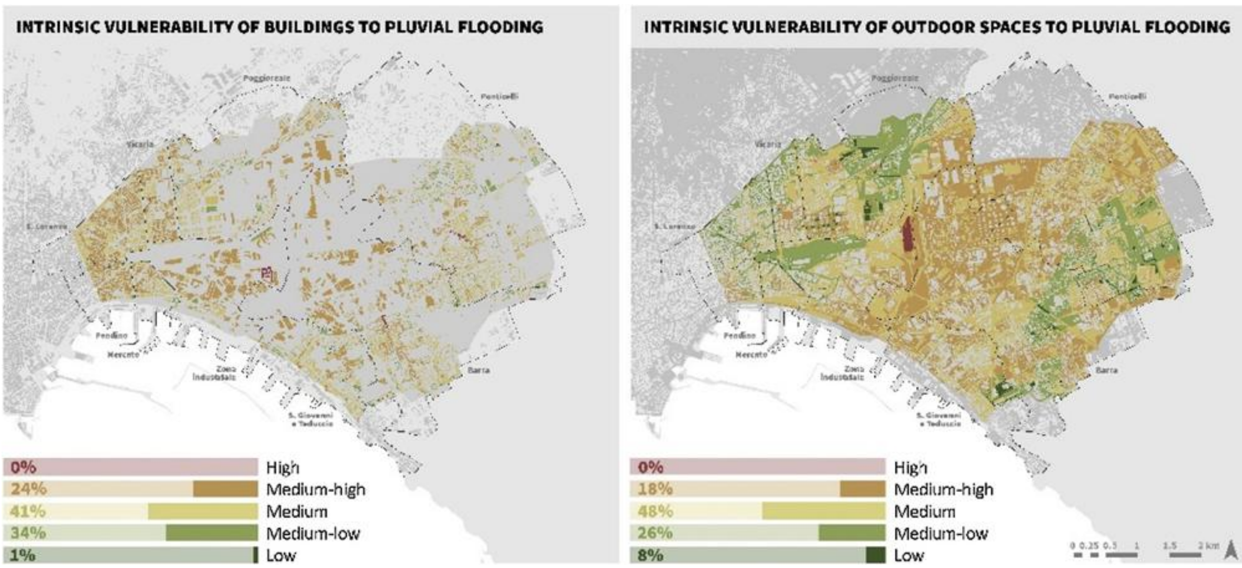


Figure 32*. Intrinsic vulnerability of residential buildings and open spaces to pluvial flooding (Source: Apreda et al., 2019).*

3.4.4 Assessing systemic vulnerability: a climate vulnerability index

The concept of vulnerability is inherently complex and dynamic, encompassing both the susceptibility of a system to external hazards and its capacity to cope with them. Rather than being solely defined by the presence of climate-related stressors, the vulnerability of the urban systems results from the interaction between environmental hazards, socio-economic conditions, institutional capacities and characteristics of the built environment (Lankao & Qin, 2011). Due to the complexity of urban systems, an integrated and holistic approach to vulnerability requires advanced knowledge systems to understand and assess the climate vulnerability of the cities. According to the previously discussed dimensions and the conceptual framework of systemic vulnerability (DV 5.3.3, paragraph 2.2), as well as the literature review on assessments, models, tools (DV 5.3.3, paragraph 2.2.1), and indexes and indicators (DV 5.3.3, paragraph 2.2.3), an exploratory analysis has been conducted to develop a climate vulnerability index for studying heat stress vulnerability and supporting evidence-based adaptation planning.
Commonly, the climate vulnerability of cities is studied through indicator-based vulnerability assessments (Tapia et al., 2017), that often involve aggregating multiple dimensions of vulnerability into composite indices or scores to facilitate comparison and decision-making

(Adger, 2006; Birkmann et al., 2013; Füssel, 2010; Hinkel, 2011). At the urban scale, the studies typically focus on either specific geographic areas exposed to climate hazards (Carter et al. 2014; Depietri et al. 2013; El-Zein & Tonmoy 2015) or the vulnerability of social groups and critical infrastructure components within the built environment (Maldonado & Moreno-Sánchez, 2014; Mitchell & Borchard, 2014; Friedrich & Kretzinger, 2012). Indicators serve as essential tools for operationalizing theoretical concepts of vulnerability, allowing complex and multi-dimensional factors to be synthesized into measurable metrics (Apreda et al., 2019). If designed with rigor - ensuring reliability, credibility, and policy relevance - indicators can support decision-making by providing clear, comparative insights into urban climate risks (Fritzsche et al., 2014; Kalisch et al., 2014). Composite indicators, in particular, facilitate the normalization and aggregation of diverse vulnerability factors, enabling cities to develop targeted adaptation strategies (Schneiderbauer et al., 2017).

A major challenge in urban climate vulnerability assessments lies in capturing the multiple dimensions of urban systems, which require an integrated knowledge framework that considers their socio-spatial complexity (Boeing, 2018). The methodology proposed here assumes that to study climate vulnerability at the city and district scale, it is necessary to consider and integrate the interactions between spatial and physical components with ecological, social and economic ones. The proposed experimentation focuses on heat vulnerability in urban areas.

In the climate risk framework, heat vulnerability in urban settlements refers to the susceptibility of urban areas and their populations to the adverse effects of extreme heat, often exacerbated by the urban heat island (UHI) effect. It is influenced by several factors such as demographic and socioeconomic characteristics, health conditions, building features and environmental factors.

Heat vulnerability in urban areas is a multifaceted issue that requires comprehensive assessment methods to inform effective urban planning and policy development. Several methodologies have been developed to assess heat vulnerability, often combining spatial data with socio-economic indicators. Some of them include the use of indicators and data, such as demographic and socioeconomic data, health conditions, and environmental factors that are often gathered from remote sensing, GIS, and socio-economic surveys (Fei Li et al., 2022; Inostroza et al., 2016). There are also different modelling approaches, such as heat vulnerability indexing, principal component analysis (PCA), and machine learning (Inostroza et al., 2016; Fei Li et al., 2024).

One of the main challenges in developing heat vulnerability indices is the lack of standardized criteria for selecting indicators and validating models. For instance, a methodology tested in Padova, Italy, uses high-resolution spatial information and crowdsourced data to create indicators of sensitivity, adaptive capacity, vulnerability, exposure, and risk, which are crucial for local adaptation strategies (Maragno et al. 2020). Similarly, in Santiago, Chile, a heat vulnerability index was developed using GIS-based spatial information, incorporating exposure, sensitivity, and adaptive capacity levels derived from remote sensing and socioeconomic data (Inostroza et al., 2016). Furthermore, in Montpellier, France, a methodology was developed to assess urban heat island (UHI) vulnerability by integrating urban planning policies with exposure and sensitivity indicators (Técher et al., 2023) and in Birmingham, UK, an open-access approach was used to incorporate heat vulnerability into local authority decision-making, focusing on areas with compact urban forms, limited green space, and high deprivation (Ferranti et al., 2023).

3.4.4.1 Methodology

The climate vulnerability index to heat stress provides a framework to assess the potential impact of heat stress on urban populations by considering three key dimensions: socio-environmental, socio-economic, and socio-spatial (Edmonds et al., 2020; Young, 2019; Campos et al., 2022). These dimensions encompass various factors that contribute to vulnerability, and the use of Principal Component Analysis (PCA) helps in reducing the complexity of the data while maintaining meaningful insights for each component.

Considering the theoretical premises of our work, i.e. that to study climate vulnerability at city and district scale, it is necessary to consider and integrate the interactions between spatial and physical components with ecological, social and economic ones. In the study, an evaluation methodology was elaborated, based on the identification of criteria and indicators capable of expressing the factors that influence or can potentially influence (positively or negatively) the systemic vulnerability of urban systems.

The identification of criteria derives from the factors most widely recognised in the literature for their influence on the systemic vulnerability of urban systems. For each criterion, the relevant indicator was identified considering the availability of local data from official statistical sources (ISTAT 2011 and 2021 censuses) and results from previous studies and experiments conducted by some of the authors of this deliverable.

In the experimentation, the proposed evaluation model has been structured as follows: dimensions and criteria identification, indicator selection, data collection, Principal Component Analysis (PCA) for synthesising variables, homogenisation of components polarity, standardization, aggregation, vulnerability index development (Figure 33).

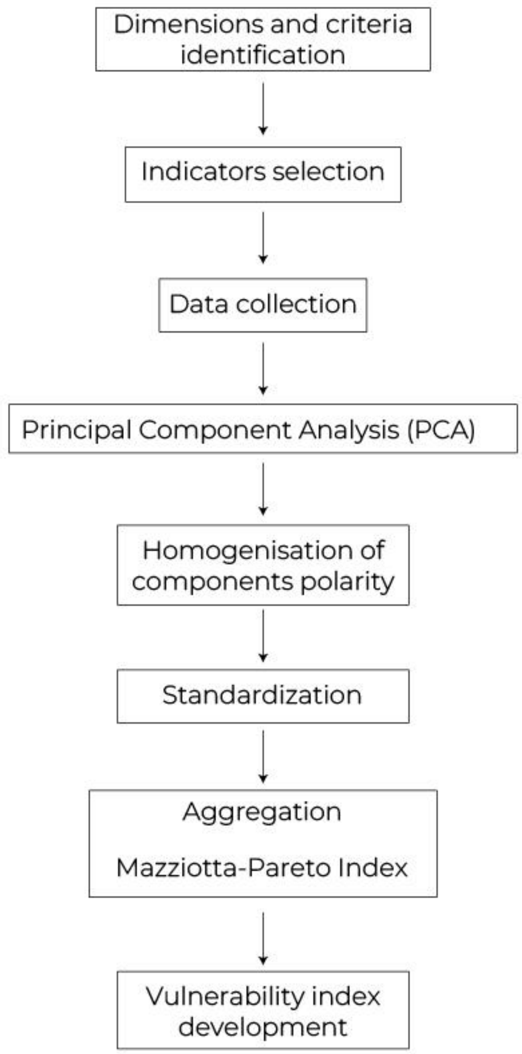


Figure 33. *Principal Component Analysis (PCA)*

Dimensions and criteria identification

1. Socio-environmental Dimension: this dimension examines the environmental and physical aspects that contribute to heat stress vulnerability. The criteria include:

- **Green Spaces: a** variability and quality of parks, trees, and vegetation that help cool the environment and provide shade.
- **Population Density:** higher density often correlates with reduced access to green spaces, increased built-up areas, and more exposure to heat.

- **Open Spaces Discomfort:** public spaces or areas lacking shade, which are more exposed to direct sunlight and higher temperatures, leading to discomfort and increased heat vulnerability.

The more densely populated areas are, the greater the risk when there is a lack of green spaces and thermal discomfort increases due to limited shaded open spaces and reduced evaporative cooling from vegetation. High population density often means less access to cooling areas and open spaces, exacerbating heat-related stress.

2. Socio-economic Dimension: this dimension focuses on the social and economic characteristics of populations that influence their ability to cope with heat stress. The criteria include:

- **Level of Income:** lower-income populations may live in poorly insulated homes, lack access to air conditioning, or have limited resources to mitigate heat exposure.
- **Level of Education**: individuals with lower levels of education might lack knowledge about heat risks and the importance of cooling strategies.
- **Immigrants:** immigrant populations, particularly those unfamiliar with local climate conditions, may have less access to resources or support networks.
- **Family Members:** larger families might be at a higher risk as they may reside in smaller or overcrowded living spaces, which can intensify heat stress.
- **Building Conservation:** older or poorly maintained buildings may lack modern cooling systems or insulation, making them more vulnerable to heat.

The most vulnerable groups in this dimension are those with lower income, lower educational attainment, immigrant populations, large families, and those living in buildings with poor conservation. These groups often face challenges in coping with high heat due to limited resources and poor housing conditions.

3. Socio-spatial Dimension: this dimension examines the spatial and social factors that influence heat stress vulnerability, especially focusing on the built environment and demographic factors. The components include:

- **Age of Population:** older adults and young children are more susceptible to heat stress due to reduced ability to regulate body temperature.
- **Fuel Poverty:** households struggling to afford heating or cooling systems are more vulnerable during heatwaves, especially if they cannot afford air conditioning or adequate cooling.

- **Indoor Discomfort:** poorly ventilated or insulated homes increase indoor discomfort, heightening the risk of heat-related illnesses.

Vulnerable groups in this dimension include the elderly, children, and individuals experiencing fuel poverty. Additionally, people living in poorly insulated homes or those unable to afford cooling systems are more exposed to heat stress indoors.
Furthermore, the following criteria are analyzed within this dimension:

- **Age of Buildings:** older buildings are likely to have poor insulation and outdated construction standards, making them less energy-efficient and more vulnerable to heat stress.
- **Construction Technique:** the materials and methods used in building construction play a significant role in a building's thermal efficiency. Buildings constructed with poor insulation or using materials that retain heat can increase vulnerability.
- **Gender of Population:** women, especially those in specific socio-cultural contexts, may have different access to cooling resources or be more likely to stay at home during extreme heat, which can heighten their vulnerability.
- **Income:** low-income populations are more likely to live in substandard housing with poor insulation and lack access to air conditioning, further increasing their vulnerability to heat.

Older buildings and those constructed with outdated techniques or inadequate insulation are particularly vulnerable to heat stress. These buildings tend to retain heat during the day and fail to cool down at night, creating a "heat island" effect indoors. In such environments, residents are exposed to prolonged periods of high indoor temperatures, which can lead to increased risks of heat-related illnesses like heat exhaustion or heat stroke. Certain construction techniques, due to the lack of proper insulation or energy-efficient envelopes, further exacerbate these issues, as these buildings are unable to regulate internal temperatures effectively. This vulnerability can be particularly pronounced in densely populated areas or where there is a concentration of older, poorly maintained buildings.

From these dimensions, the model identifies specific factors that increase vulnerability:

- **Socio-environmental:** vulnerability in this dimension arises from densely populated areas with limited green spaces and outdoor discomfort due to lack of cooling resources like trees and shaded areas.

- **Socio-economic:** vulnerable groups include low-income individuals, those with lower education levels, immigrants, large families, and those living in poorly maintained buildings.
- **Socio-spatial:** vulnerabilities highest among certain age groups (elderly and young children), people experiencing fuel poverty, and those with poor indoor thermal comfort.

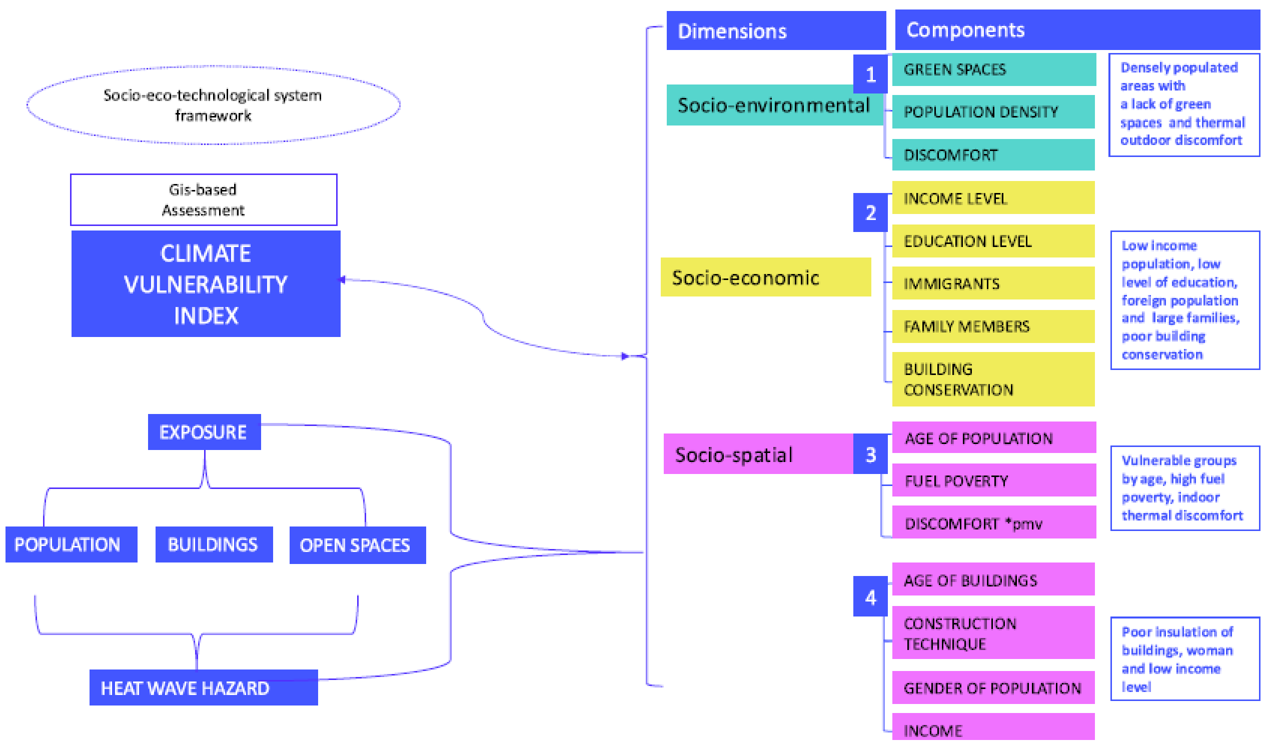


Figure 34. *Framework for climate vulnerability index development*

Indicators selection

The Italian municipality of Naples in Campania region was chosen as case study, and it has been analysed considering only one level of territorial depth, namely the Census Area level, which details information at the scale of neighbourhoods or aggregates of neighbourhoods.

The choice was conditioned by the desire to read phenomena increasingly at the micro scale and, of course, by the availability of data (D'Ambrosio et al., 2023).

In the choice of the level of detail at the census section scale, the lack of an adequate and homogeneous database at municipal and sub-municipal level of soft data on complementary information of absolute relevance for human-centred urban planning (such as, for example, issues relating to inhabitants' perceptions of risk) is very clearly reduced. Therefore, indicators measurable by objective, quantitative data at census section level were taken into account in the selection process.

Table 13 presents the evaluation matrix proposed for the development of the climate vulnerability index based on dimensions, criteria, indicators and related description, the scale of application and the data source for populating each indicator.

Table 13. Evaluation Matrix

Dimensions	Criteria	Indicators	Description	Scale	Source
Socio-Environmental	Green Spaces	NDVI (Normalized Index Vegetation Index)	The NDVI (Normalized Difference Vegetation Index) is an index used to assess the presence and health of vegetation based on the reflectance of light in the red (Red) and near-infrared (NIR) bands	Census area	Planner
	Population Density	Population Density	Ratio of the number of inhabitants to the surface area of the territory (number of inhabitants per square kilometre)	Census area	Istat census (2021)
	Discomfort	Thermal outdoor discomfort	The perception of thermal discomfort in outdoor spaces, influenced by climatic parameters such as temperature, humidity, wind and solar radiation	Census area	Planner
Socio-Economic	Income level	Equivalent household income	A system of correction coefficients used to standardise heterogeneous units of analysis (e.g. consumption and household income). In the household consumption survey, coefficients are used to determine the poverty line when households have more than two members	Census area	Istat census (2021)
	Education Level	Number of residents with the lowest educational level	Number of residents with the lowest educational qualification obtained in any school, public or private, Italian or foreign	Census area	Istat census (2021)
	Immigrants	Foreign immigration rate	Ratio of the number of people registered in population registers from abroad to the average amount of the resident population, multiplied by 1,000	Census area	Istat census (2021)
	Family Members	Average number of members per household	The average household size, calculated by dividing the total number of household residents by the number of households	Census area	Istat census (2021)

	Building Conservation	State of buildings conservation	The state of buildings conservation expressed through a qualitative judgment: excellent, good, poor and very poor	Census area	Istat census (2021)
Socio-Spatial	Age of population	Average age of the population	Average age of the resident population on a certain date, expressed in years and tenths of a year. It is obtained as a weighted average with weights equal to the amount of the population in each age group	Census area	Istat census (2021)
	Fuel Poverty	Energy demand	The condition in which a household spends an excessive share of its income on essential energy needs, such as heating, cooling and the use of household appliances	Census area	Planner
	Discomfort (pmv)	PMV (Predicted Mean Vote) at the time of evaluation	The PMV (Predicted Mean Vote) is an index used to assess the thermal comfort perceived by humans in a given environment and is based on a model that considers the thermal equilibrium between the human body and the environment	Census area	Planner
	Age of buildings	Residential buildings by age of construction	Number of residential buildings (absolute values) from the following construction periods: 1918 and earlier, 1919-1945, 1946-1960, 1961-1970, 1971-1980, 1981-1990, 1991-2000, 2001-2005, 2006 and later	Census area	Planner
	Construction techniques	Type of use of the building (or complex of buildings)	Constructive characterisation of a building according to its intended use	Census area	Planner
	Gender of population	Resident population	Population constituted in each Commune by the persons having their usual residence in that Commune. Persons temporarily residing, in another commune or abroad, for the exercise of seasonal occupations or for reasons of limited duration, do not cease to belong to the resident population	Census area	Istat census (2021)
	Income level	Equivalent household income	A system of correction coefficients used to standardise heterogeneous units of analysis (e.g. consumption and household income). In the household consumption survey, coefficients are used to determine the poverty line when households have more than two members	Census area	Istat census (2011)

Data collection

In the context of the spatial analysis of the Campania region, the integration of geographical and tabular data was fundamental in order to obtain a comprehensive and detailed view of the indicators. The methodological sub-steps into which the first phase is divided are illustrated below:

- *Data Collection and Import into GIS*
- *Linking the datasets through Join and Verifying the correctness of the integration*

Two main data sources were used: the spatial databases contained in a shapefile from ISTAT (2021), which includes population and housing indicators for the Campania region (R15). These data were selected because they complement each other: the spatial bases provide the spatial component, while the shapefile contains the associated statistical attributes.
The linking between the spatial geometries and the tabular data was carried out using the Join function of GIS. This step was necessary to transform qualitative data into georeferenced quantitative data. Thanks to this integration, it was possible to analyse and interpret the indicators within a spatial context.

Table 14 provides a clear and detailed overview of the spatial and tabular data collection and integration process, highlighting the care taken to ensure the quality and compatibility of the datasets.

Table 14. Outline of process steps

Step	Description	Main Actions
Data collection and import into GIS	Collection of complementary spatial and tabular datasets.	- Use of ISTAT shapefiles for census section geometries. - Import of an Excel file with population and housing indicators for Campania.

	Verification of data structure and quality. Loading of datasets into QGIS for integration of spatial and tabular data.	- Check of the common identification field (e.g. census section code). -Importing the shapefile to display the geometries. - Importing the Excel file as a separate table. - Verification of correspondence between the identification fields of the two datasets
Linking of datasets via Join and Verification of Integration Correctness	Association of tabular data with spatial geometries via the common identifier field. Control to ensure correct linking between databases.	- Use of QGIS Join function. - Transfer of indicators from Excel file to shapefile layer. - Elaboration of an integrated dataset for spatial analysis. - Visual check: comparison between map and tabular data. - Spot check: verification of random data samples between Excel and shapefile. - Correction of any discrepancies.

This step represented a fundamental step for the subsequent use of the data in Principal Component Analysis (PCA), allowing for geo-referenced and properly integrated data, essential for accurate model calibration.

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) (Jolliffe, 2002) was applied as a tool to reduce the dimensionality of the data and identify the main factors that explain the variance between indicators (i.e. how far the values of the indicators considered deviate from or, conversely, concentrate around the mean value), by integrating components of different natures (e.g. social, environmental, economic). The objective of PCA is to reduce the dimensionality of the data set by eliminating the redundancy of information resulting from n highly correlated variables and by replacing these with a smaller number h (h < n) of new, uncorrelated variables that are linearly related to the source variables. PCA simplifies the analysis by identifying the 'principal components' that capture most of the variance in the data, thus reducing the number of variables to be considered without losing fundamental information. Thus, PCA (Figure 35) transforms the original dataset into a space in which the new variables (the principal components) are uncorrelated and effectively summarise the information contained in the original dataset. In addition to being uncorrelated, the new variables are ordered with respect to the percentage of variability in the original data.

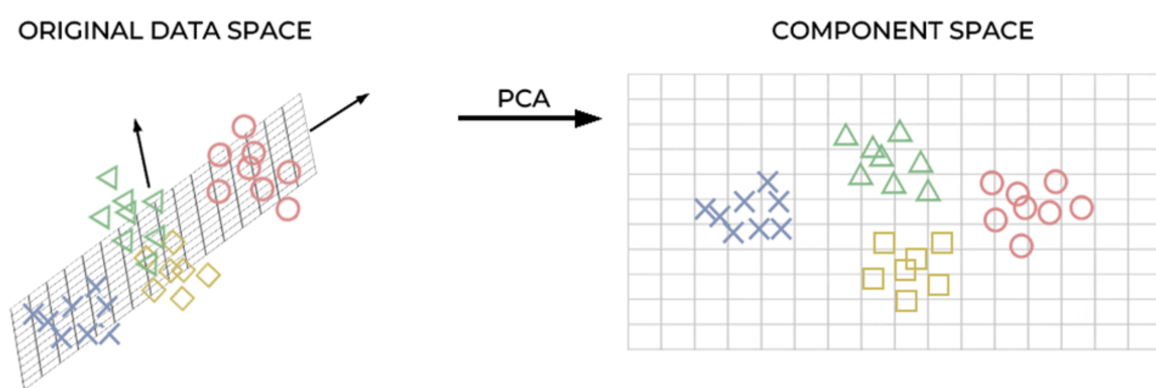


Figure 35. *Spatial transformation of the original dataset in principal components*

Table 15 gives a clear and detailed overview of the PCA process.

Table 15. Outline of the steps in the PCA process

Step	Description	Main Actions
Database pre-processing	Collection and verification of raw data to ensure completeness and consistency. Standardisation of formats and units (conversion from shapefile to raster and homogenisation of classes into five categories) to eliminate discrepancies.	- Data collection and verification - Standardisation of formats and units of measurement

	Reduction of dataset dimensionality through PCA. The covariance (or correlation) matrix is calculated, eigenvectors and eigenvalues extracted, and components selected according to the explained variance (cumulatively 70-80%).	- Conversion of shapefiles to raster - Homogenisation of classes - Cleaning and correction of errors, missing data and inconsistencies
Principal Component Analysis (PCA)	Collection and verification of raw data to ensure completeness and consistency. Standardisation of formats and units (conversion from shapefile to raster and homogenisation of classes into five categories) to eliminate discrepancies. Reduction of dataset dimensionality through PCA. The covariance (or correlation) matrix is calculated, eigenvectors and eigenvalues extracted, and components selected according to the explained variance (cumulatively 70-80%).	- Calculation of the covariance/correlation matrix - Extraction of eigenvectors and eigenvalues - Selection of components based on explained variance

Homogenisation of components polarity

After obtaining the principal components, it became necessary to change the direction (or polarity) of some of them to facilitate the interpretation of the results. The 'polarity' (or 'direction') of an elementary indicator is a sign of the relationship between the indicator and the phenomenon being measured. This becomes important when, by convention or for specific interpretative needs, higher values are considered to indicate a 'positive' (or, conversely, negative) effect. This reversal of polarity is not a mere formality, but has a direct impact on the clarity and consistency of data interpretation. Changing the direction of the components facilitates the alignment and comparability of the values they express, making the subsequent transformation step into pure, dimensionless numbers through normalisation more intuitive. In this way, the resulting components clearly show the relationships between the variables, explicitly distinguishing between indicators of a different nature, such as urbanisation versus socio-demographic indicators.

Table 16 shows the initial polarity assigned to each indicator, where the sign '+' means that a high value of the indicator contributes to a high vulnerability (positive correlation) while the sign '-' means that a high value of the indicator contributes to a vulnerability mitigation (negative correlation). Only for two indicators does the polarity depend on qualitative considerations that are not related to the intensity of the indicator value but to the type of information: Indeed, the indicators related to the type of use of the building (or building complex) and resident population respectively refer to the fact that the materials and methods used in the construction of buildings play a significant role in the thermal efficiency of a building (buildings constructed with poor insulation or using materials that retain heat may increase vulnerability), while women, especially those in specific socio-cultural contexts, may have different access to cooling resources or be more likely to stay at home during extreme heat, which may increase their vulnerability.

Table 16. Outline of the steps in the PCA process

Criteria	Indicators	Polarity
Green Spaces	NDVI (Normalized Index Vegetation Index)	+
Population Density	Population Density	+
Discomfort	Thermal outdoor discomfort	+
Income level	Equivalent household income	-
Education Level	Number of residents with the lowest educational level	-
Immigrants	Foreign immigration rate	+
Family Members	Average number of members per household	+
Building Conservation	State of buildings conservation	-
Age of population	Average age of the population	+
Fuel Poverty	Energy demand	+
Discomfort (pmv)	PMV (Predicted Mean Vote) at the time of evaluation	+
Age of buildings	Residential buildings by age of construction	+
Construction techniques	Type of use of the building (or complex of buildings)	/

Gender of population	Resident population	/
Income level	Equivalent household income	-

Standardisation

The standardisation procedure is a key step to ensure the comparability and homogeneity of the indicators. In this step, we reported each indicator by eliminating differences resulting from different units of measurement and ranges of values, thus facilitating an integrated and comparative analysis.

Aggregation

An aggregation of the data from the previous matrix has then been created, carried out by rows (i.e. per census parcel) instead of by columns. In this way, each census parcel is considered together with all the indicators that characterise it. The aggregation method used by ISTAT, known as the Mazziotta-Pereto Index (MPI) (Mazziotta & Pareto, 2022), is adopted to carry out this aggregation by rows.

Vulnerability index development

The final step to obtain the index involves applying the arithmetic mean or weighted mean of the values of the main components. The arithmetic mean can be used in the case where all components are considered to have the same weight, while the weighted mean is applied in the case where consultation with a group of experts is envisaged in order to attribute a different weight to each of the components, thus obtaining a hierarchy of importance. The weighting can be obtained by applying different methods among which emerges the Simos method (Simos, 1990), also called the 'card method' because of its ability to be able to consider several variables at the same time and not to necessarily compare them in pairs (as is the case with other comparative methods such as AHP).

The procedure for developing the index can be applied to all the principal components in order to obtain a single vulnerability index. Similarly, the principal components can be traced back to the three dimensions of vulnerability identified at the outset and the procedure for developing the index can be applied for the components belonging to each of the dimensions thus obtaining three different indices.

3.5 Chemical hazards

Climate change directly or indirectly impacts on the environmental quality (e.g., on air and water quality), in different ways. First of all, climate change can alter chemical reaction rates that lead to the formation of air pollutants. Higher temperatures can accelerate the chemical reactions that produce ground-level ozone, a major component of smog. This effect is particularly significant for ozone formation, which depends on temperature, sunlight, and the presence of precursor pollutants (Ebi and McGregor, 2008). Moreover, changes in weather patterns associated with climate change can significantly impact air pollution levels, via (i) stagnation events (climate change may increase the frequency of stable anticyclonic conditions with little boundary layer ventilation, leading to more air pollution episodes (Ebi and McGregor, 2008); (ii) reduced cyclone frequency (Mickley et al., 2004), and (iii) changes in mixing depths (while mixing depths may increase in some areas, it may not be enough to compensate for increased stagnation (Mickley et al., 2004). Climate change can also indirectly affect air pollutant concentrations by altering emissions: changes in human behavior in response to climate change, such as increased energy use for cooling, can indeed lead to higher emissions of air pollutants (Ebi and McGregor, 2008). Moreover, climate change may affect air pollution, for example introducing particles or contaminants throughout the increase of extreme weather events (Bolan et al., 2024).

As said, climate change is expected to significantly impact also water quality: changes in precipitation patterns may lead, for example, to increased volatilization of persistent organic pollutants (POPs) and pesticides in drier regions, while areas with increased rainfall could experience greater surface deposition and runoff of these chemicals (Noyes et al., 2009; Whitehead et al., 2009). More frequent extreme weather events may result in severe chemical contamination of water bodies (Noyes et al., 2009). Moreover, climate change is also expected to exacerbate eutrophication by increasing nutrient concentrations in water bodies, potentially leading to harmful algal blooms (Sharabian et al., 2018).

Focusing on human health, human interactions with exogenous agents would become more frequent over years, as highlighted by recent works analyzing the particles/fibers/pollutants presence in human tissues and their potential health impact (Peters et al., 2020; Visonà et al., 2021; Krause et al., 2024). Thus, reliable and validated procedures are needed to quantitatively detect pollutants and contaminants in human tissues. To quantify and analyze the chemical nature of pollutants a digestion protocol has been developed, enabling the extraction of the exogenous substances from the organic matrix, allowing their investigation using advanced microscopy techniques. Customizing the solvent and container depending on the pollutants under investigation (asbestos fiber, microplastics, talc, aluminum, …), it proved to be strongly versatile and compatible for diverse tissues (lungs, ovary, bladder, lymph node, placenta, …).

3.5.2 Pollution: regulated and emerging substances

Air pollution

Among the several potential pollutants, the well-know asbestos is one of the most studied and characterized. Asbestos is a natural mineral (durable, fireproof and resistant to heat and chemicals) made of fibers commonly used in many industries for decades: the asbetsos fibers are know to provoke respiratory system diseases such as asbestosis, mesothelioma and lung cancer [Belluso et al., 2006]. Another natural mineral is the crystalline silica, highly abundant in the α-quartz form. It is highlighted as a human carcinogen - Group 1, manifesting fibrotic lung diseases pathologically-known as silicosis, and mainly related to occupational exposure [McLean et al., 2017]. Recent studies have also reported the correlation of mineral talc, having the following chemical formulation $Mg_3Si_4O_{10}(OH)_2$, with ovarian cancer [Fletcher at al., 2019], for example upon talcum baby-powder (hydrous magnesium silicate, with small amounts of aluminum silicate) intensive use [Johnson et al., 2020]. Inorganic pollutants have been monitored using Scanning Electron Microscopy coupled with Energy Dispersive X-Ray (EDX) chemical analysis, for a quantitative analysis in terms of dimensions, shape/morphology and concentration per milligrams of dried biological tissue, as exemplified for the 11µm-long asbestos fiber in Figure 36**.**

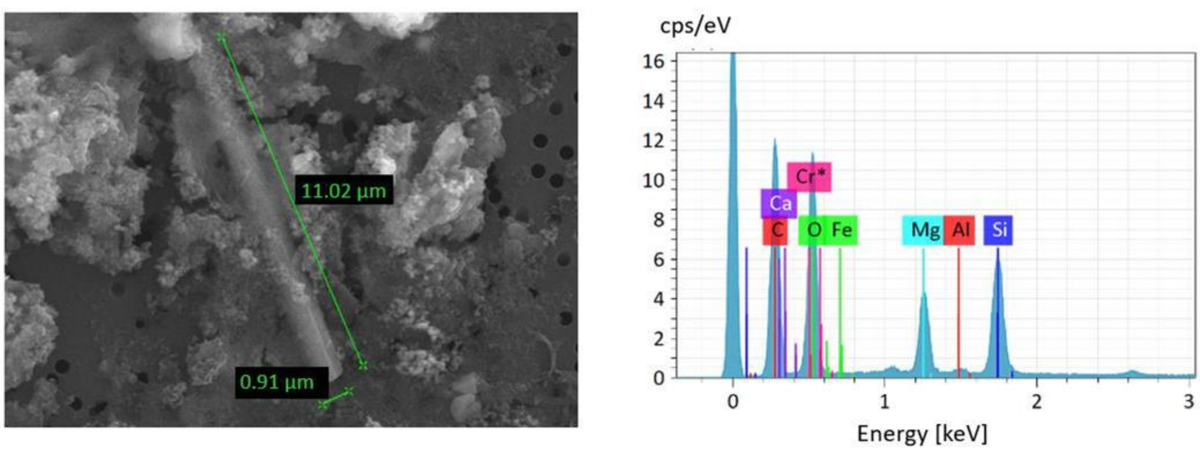


Figure 36. *Asbestos fiber on a polycarbonate membrane filter that is visible despite small biological tissue residuals (left) and its chemical x-ray spectrum (right) confirming the Magnesium and Silicon peaks, typical of asbestos-like contaminant.*

It is finally worth noting that also microplastics are now investigated as nocive atmospheric pollutants and particulates, as recent studies have demonstrated the existence of microplastics in the area of urban, rural and remote atmosphere and atmospheric deposition (Zhang et al., 2020). Microplastics are detailed in the following sub-section (Water pollution).

4.5.2.2 Water pollution

Microplastics are an emerging concern worldwide (PlasticsEurope, 2018). Microplastics have been discovered in several media, from soils to aquatic systems (including oceans, rivers, shorelines, and swamps); moreover, they have been found in digestive tracts of both vertebrates and invertebrates (Auta et al., 2017; Li et al., 2018; Prata et al., 2019; Rochman, 2015).
Microplastics might directly or indirectly trigger inflammations, for example enhancing the prevalence or severity of non-communicable diseases or influencing the uptaking of other environmental pollutants. Owing to the present knowledge gap on microplastics effects (either inhaled or via ingestion), they are currently under study and represent a hot-topic nowadays (Krause et al., 2024).
Raman spectroscopy is currently one of the most powerfull and reliable techniques employed for the detection, quantification and chemical characterization of microplastics. Microplastic investigaiton is currently carried on placenta and kidney tissues by means of Raman analysis, aiming at the evaluation of the influence of microplastic particles on cell metabolomics or as "Trojan horse" for other environmental pollutants and contaminants, respectively.

3.6 Biological hazards

3.6.1 Climate-change effects on the general and the occupationally exposed population

As reported in the literature, climate change may affect human health through both direct and indirect mechanisms. Specifically, the increase in global temperatures and in extreme weather events (in terms of frequency and intensity), coupled with alterations in ecosystems and the redistribution of infectious diseases, are exerting an impact on health and safety outcomes both on the general and on the occupational populations.

Vulnerable population
Certain groups of population are particularly vulnerable to the effects of climate change due to their increased exposure and sensitivity. Among the general population, elderly, children, and those with chronic conditions such as cardiovascular and respiratory diseases are disproportionately affected, as they exhibit reduced capacity to adapt to environmental changes and extreme events. Elderly, for example, face diminished thermoregulation abilities and frequently coexist with chronic illnesses, which are exacerbated by extreme heat or secondary effects of climate change, such as air pollution. Similarly, children, whose immune and respiratory systems are still developing, are more vulnerable to airborne pollutants and vector-borne infections. Chronic disease patients experience exacerbated preexisting conditions due to climate change, leading to higher mortality rates.

In the occupational context, outdoor workers (i.e., farmers, construction workers, fishers, and forestry workers) are at significant risk of heat stress, leading to heat strokes, cognitive decline, and higher workplace injury rates. These risks are exacerbated by inadequate infrastructure, lack of appropriate personal protective equipment, and working conditions unadjusted to the intensifying climatic extremes.
Finally, from a socioeconomic perspective, economically disadvantaged communities suffer the most severe consequences of climate impacts due to limited resources, insufficient access to resilient infrastructure, and inadequate healthcare support, restricting their ability to cope and adapt.

General Population
As previously mentioned, elderly, children, and marginalized communities are among the groups most vulnerable to climate change effects. The elderly face significant risks due to reduced thermoregulation capacities and the frequent presence of chronic diseases, such as cardiovascular and respiratory disorders, which are further aggravated by extreme heat. Children, with their developing immune and respiratory systems, are more susceptible to airborne pollutants and vector-borne infections such as malaria and dengue. Marginalized communities, often lacking adequate economic and infrastructural resources, experience disproportionate exposure to extreme climatic events such as floods and heatwaves, exacerbating social and health inequities.

The general population is thus exposed to a wide range of health risks associated with climate change. Heatwaves, increasingly frequent and intense, have been linked to higher mortality rates, particularly among the elderly and individuals with preexisting conditions. Besides causing heat strokes and dehydration, extreme heat exacerbates chronic conditions, increasing the burden on healthcare systems. Moreover, rising temperatures contribute to elevated concentrations of atmospheric pollutants, such as ozone and particulate matter, worsening respiratory diseases like asthma and chronic obstructive pulmonary disease. The expansion of vector habitats driven by global warming also facilitates the spread of infectious diseases like malaria, dengue, and West Nile virus.

Occupational Population
Focusing on the occupational population (Table 17), workers in sectors such as agriculture, construction, and fishing are among the most vulnerable to climate change effects. Prolonged exposure to high temperatures is linked to heat stress, heat strokes, and dehydration. Chronic conditions like renal insufficiency and cardiovascular diseases disproportionately affect workers

in tropical and subtropical regions. Additionally, outdoor workers face increased risks of vector-borne diseases, highlighting the need for targeted preventive measures. Recent studies have documented significant declines in productivity and increased sick leaves during periods of extreme heat.

More in detail, agricultural workers, for example, experience dual risks: direct exposure to extreme climatic conditions, such as heatwaves and droughts, and indirect effects like reduced agricultural productivity and crop yields. Construction workers frequently experience heat stress, which not only reduces productivity but significantly increases the risk of workplace injuries. Forestry workers face unique challenges, including the risk of wildfires, which pose life-threatening dangers and expose them to hazardous smoke and particulate matter, increasing the likelihood of long-term respiratory diseases. Similarly, fishers contend with marine ecosystem changes and extreme weather events that heighten the risk of accidents and economic losses. Across all these sectors, the absence of adequate protective equipment and insufficient adaptation policies exacerbate vulnerability.

Urban Environment

In urban settings, both the general population and workers face specific challenges associated with climate change. Cities often experience the urban heat island effect, with temperatures significantly higher than surrounding rural areas. This phenomenon increases the risk of heat stress, particularly for vulnerable groups such as the elderly, children, and individuals with chronic illnesses like asthma and chronic obstructive pulmonary disease. Furthermore, urban areas with high pollutant concentrations, exacerbated by rising temperatures, contribute to worsening respiratory conditions and higher hospitalization rates.

Urban workers, such as those employed in public transportation, logistics, and construction, are exposed to various risks. Construction workers, for instance, face heat stress during peak hours and a higher incidence of injuries due to reduced concentration. Logistics and transport workers are vulnerable to sudden weather changes, such as storms and urban flooding, which cause delays, infrastructure damage, and physical hazards. The scarcity of green spaces and shaded areas in cities limits opportunities to mitigate heat effects. Targeted interventions, including the implementation of green infrastructure, reflective surfaces, and effective ventilation systems, are crucial. Urban planning must integrate strategies to enhance resilience for both residents and workers.

Prevention and Mitigation Measures

Addressing the impacts of climate change requires an integrated, multidimensional approach that considers the diverse vulnerabilities of both the general and occupational populations. Adaptation policies are essential to safeguard high-risk groups. For workplaces, mandatory breaks during peak heat hours, guaranteed access to hydration, and the provision of cooling infrastructure, such as shaded areas and ventilation systems, are fundamental. For high-risk workers, such as agricultural and construction employees, providing personal protective equipment and adopting specific safety protocols is critical. Moreover, education and awareness campaigns are equally important. Public initiatives can raise awareness about climate risks and promote practical adaptation strategies, such as recognizing early symptoms of heat stress and staying hydrated.

Table 17. Effects of climate change on the occupational population

Reference	Outcomes
Adam-Poupart et al., 2013	▪ Heat stress ▪ Respiratory disorders ▪ Cardiovascular disorders ▪ Allergies ▪ Skin diseases ▪ Injuries
Amoadu et al., 2023	▪ Productivity: Absenteeism; Reduced work efficiency; Interpersonal conflicts ▪ Heat-related illness: Profuse sweating; Fatigue/ dizziness/ tiredness; Dehydration/thirst/dry mouth; Heat cramps; Headache; Reduction in urine quantity; Changed in urine color; Skin rashes/itche; Dry skin; High core body temperature; Nausea/vomiting; Heatstroke/sunstroke; Heat exhaustion; Nose bleeding; Fainting; Loss of coordination; Spasm; Prickly skin; Heat edema ▪ Kidney diseases: Acute kidney injury; Reduced kidney function; Kidney stones; Chronic/kidney disease ▪ Cardiovascular: Tachycardia; Heart disease; Cardiac strain; Racing heart; Hypertension ▪ Respiratory: Respiratory diseases; Difficulty breathing; Chest tightness; Asthma

	■ Injury: Falls, slips, trips; Burns/wound/ lacerations; Brain injury; Spinal cord injury; Bone fracture; Musculoskeletal pains ■ Liver: Liver diseases ■ Reproductive health: Vaginal infections; Fetal deaths; Fetal discomfort; Fetal heart race ■ Diabetes ■ Eye diseases: Eye irritation; Poor vision; Eye damage ■ Digestive Gastrointestinal diseases: Indigestion ■ Cancer ■ Mortality ■ Mental health: Anxiety/ irritation; Depression; Confusion; Loss of concentration; Suicide; Hallucination; Delirium; Psychological distress ■ Water/Vector borne: Malaria; Cerebrospinal meningitis; Dengue; Lyme; Fever; typhoid; Cholera; Diarrhea ■ Others: Poor heath; Difficulty sleeping; Poor social life; Stomach ache; Loss of appetite
Ansah et al., 2021	■ Health: Heat stroke; Dehydration; Kidney diseases; Respiratory issues; Reproductive health problems; Mental health conditions ■ Productivity: Absenteeism; Reduced efficiency; Increased work-related conflicts
Chandra and Xu, 2024	■ Health: Heat-related illnesses (e.g., dehydration, heat stroke); Cardiovascular disorders; Kidney disorders; Mental health effects ■ Productivity: Reduced work capacity; Increased risk of occupational injuries
Donnan et al., 2021	■ Executive functions (e.g., working memory)
D'Ovidio et al., 2016	■ Respiratory diseases (e.g., occupational asthma, rhinitis) and skin conditions caused by allergens

	■ Amplified allergenic effects due to climate-driven changes in pollen and spore dynamics
Ebi et al., 2021	■ Cardiovascular and respiratory illnesses are leading causes of heat-related mortality ■ Chronic kidney disease associated with dehydration in outdoor workers ■ Heat exacerbates mental health disorders, leading to increased hospitalizations
Fatima et al., 2021	■ Higher risks of injuries such as slips, trips, falls, cuts, and burns in extreme heat
Flouris et al., 2018	■ Heat strain ■ Kidney disease or acute kidney injury ■ Productivity loss ■ Occupational heat strain during or at end of a work shift ■ Average core temperature during work shift in heat stress conditions ■ Change in urine specific gravity due to a work shift in heat stress conditions
Foster et al., 2020	■ Fatigue ■ Injury
Freidin et al., 2024	■ Dehydration ■ Nephrolithiasis ■ Acute interstitial nephritis
Garcia et al., 2022	■ Neurological symptoms such as delirium, convulsions, and coma ■ Systemic inflammatory response syndrome (SIRS), coagulation disorders, and organ failure
Gibb et al., 2024	■ Heat exhaustion ■ Acute kidney injuries

	■ Chronic kidney disease ■ Cardiovascular impairments
Gubernot et al., 2014	■ Heat-related illnesses (e.g., heat exhaustion, heat stroke) ■ Cardiovascular strain ■ Kidney damage ■ Workplace accidents
Habibi et al., 2021	■ Heat exhaustion ■ Heat stroke ■ Kidney damage ■ Dehydration ■ Impaired cognitive and physical performance
Habibi et al., 2024	■ Fatigue ■ Dehydration ■ Heat cramps ■ Heat exhaustion ■ Impaired cognitive performance ■ Mental health effects
Habibi et al., 2024	■ Heat exhaustion ■ Heat stroke ■ Productivity loss ■ Long-term health impacts
Herath et al., 2018	■ Chronic Kidney Disease of Unknown Etiology
Ioannou et al., 2022	■ Heat exhaustion ■ Heat stroke ■ Dehydration ■ Reduced cognitive and physical performance
Levi et al., 2018	■ Kidney diseases and urinary diseases

	• Mental health • Cardiovascular diseases • Heat-related cardiorespiratory symptoms • Allergies • Respiratory diseases • Injuries • Vector-borne diseases • Productivity
Lundgren et al., 2013	• Heat exhaustion • Dehydration • Kidney problems • Cardiovascular stress • Work efficiency
Mac and McCauley, 2017	• Heat exhaustion • Heat stroke • Dehydration • Reduced work capacity
Marchetti et al., 2016	• Heat exhaustion • Dehydration • Cognitive decline • Impaired motor performance
Moda et al., 2019	• Heat exposure: Heat Stress/Stroke; Fatigue; Dehydration and Kidney Disease; Cardiovascular Disease; Respiratory Distress; Death; Increase morbidity and fatality • Air Pollution: Respiratory Distress; Respiratory Track Irritation; Asthma Attack; Increased Respiration due to Heat exposure; Exposure to carcinogens • Unbalanced Physiological Function leading to decrease in work capacity

	■ Extreme weather and sea level rise: High risk of flooding causing displacement; Injury; Resource disruption e.g., water supply ■ Psychological effects on Workers Mental health
Paterson and Godsmark, 2020	■ Mortality related to cardiovascular, respiratory issues; increased prevalence of dehydration, heat exhaustion, and occupational injuries
Roncal-Jimenez et al., 2016	■ Chronic kidney disease linked to tubular damage, hyperosmolarity, and uric acid crystal deposition
Ronda et al., 2018	■ Mortality ■ Productivity losses
Santurtún and Shaman, 2023	■ Heat exhaustion ■ Heat stroke ■ Increased accident severity during heatwaves ■ Psychological stress leading to reduced concentration and increased risk of errors
Schulte and Chun, 2009	■ Heat exhaustion, heat stroke, dehydration ■ Increased exposure to air pollution-related illnesses (e.g., asthma, respiratory diseases) ■ Higher prevalence of vector-borne diseases among outdoor workers
Shanmugam et al., 2023	■ Congenital anomalies linked to prolonged heat exposure during early pregnancy ■ Reduced productivity among working pregnant women
Spector and Sheffield, 2014	■ Heat-related illnesses: Heat exhaustion, heat stroke, dehydration ■ Increased chemical absorption and metabolism risks under heat stress

	▪ Chronic kidney disease linked to heat stress and dehydration
Varghese et al., 2018	▪ Specific injuries include cuts, burns, fractures, slips, trips, and falls
Vonesch et al., 2016	▪ Expansion of vector habitats to higher altitudes and latitudes ▪ Increased cases of diseases like Lyme borreliosis, tick-borne encephalitis, dengue, and malaria in previously unaffected areas ▪ Economic impacts on sectors dependent on outdoor labor
Wuersch et al., 2023	▪ Heat exhaustion ▪ Dehydration ▪ Mental health impacts ▪ Cardiovascular strain ▪ Productivity losses
Xiang et al., 2014	▪ Heat-related illnesses: Heat exhaustion, dehydration, heat stroke, kidney damage ▪ Behavioral effects: Fatigue, irritability, impaired concentration, reduced motor performance ▪ Increased accident rates due to heat-related cognitive impairments

3.6.2 Exposure to contaminants in various biological tissues

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