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ABSTRACT

Assessing risk and resilience in the built environment requires a comprehensive understanding of the dynamic interactions between physical spaces and their users across multiple scales. The study aims to develop a framework to support such assessments by identifying and structuring quantitative Key Performance Indicators (KPIs) for evaluating risk and resilience in the built environment.

Abbreviations: (BIM), Building Information Modelling; (DSS), Decision Support systems; (DNSH), Do Not Significance Harm; (EWS), Early Warning Systems; (EEA), European Environment Agency; (ESRM20), European Seismic Risk Model; (EU), European Union; (GIS), Geographic Information System; (GBRSs), Green Building Rating Systems; (IPCC), Intergovernmental Panel on Climate Change; (KPIs), Key Performance Indicators; (MULTICLIMACT), MULTI-faceted CLIMate adaptation ACTions; (PGA), Peak Ground Acceleration; (RRSs), Resilience Rating Systems; (UNFCC), United Nations Framework Convention on Climate Change.

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Resilience
Risk

The study combines expert engagement and desk review to identify key factors influencing risk and resilience. It considers a wide range of hazards—both climate-related (e.g., floods, droughts, heat waves) and non-climate-related (e.g., earthquakes)—and examines their impacts on people, buildings, infrastructure, cultural heritage, and urban and territorial systems. Grounded in international guidelines and validated by experts, the proposed set of KPIs enables systematic assessment across scales, user groups, and systems. The KPIs cover risk components such as hazard, exposure, sensitivity, and adaptive capacity, as well as resilience qualities including robustness, rapidity, resourcefulness, and redundancy.

Furthermore, the framework incorporates multiple resilience dimensions—environmental, economic, physical, digital, organisational, and human health and well-being—addressing critical gaps in existing assessment tools. By measuring both vulnerability characteristics and resilience qualities of built environment assets, the framework provides actionable insights to inform policies, planning strategies, and project design.

This study contributes to advancing integrated and evidence-based approaches for disaster risk reduction and climate resilience, offering a tool to support decision-makers, designers, and practitioners in evaluating current conditions and shaping future development or regeneration pathways.

1. Introduction

The built environment plays a central role in the socio-economic landscape, providing spaces for people to live, work and engage in social and leisure activities [1]. It is highly vulnerable to hazards of different nature that threaten its integrity and, consequently, the well-being of society as whole [1,2].

The first European Climate Risk Assessment (EUCRA) report [1] has identified key climatic hazards affecting the built environment. Buildings are particularly vulnerable to extreme weather events leading to structural damage and reduced thermal comfort, with marginalised communities disproportionately affected due to less adaptive capacity (EC, 2020). Urban heat islands exacerbate heatwaves, increasing health risks such as heatstroke and respiratory illnesses [3,4]. Additionally, flooding and landslides – intensified by reduced infiltration capacity, soil sealing, and outdated infrastructure – pose severe threats to built environment systems (IPCC, 2022). Public and commercial facilities are directly affected by floods and heatwaves and indirectly by supply chain disruptions [5]. Meanwhile, transport and energy infrastructures face heat-induced deformations, flooding, and efficiency losses, with costs projected to escalate dramatically by the 2080s [6]. Beyond these climatic hazards, the built environment may be affected by a range of non-climatic hazards, such as earthquakes, which can cause huge damages. The European Seismic Risk Model (ESRM20) highlights the significant consequences of earthquakes on buildings, infrastructure, and human populations [2]. Vulnerable structures, particularly low-rise unreinforced masonry and mid-rise concrete buildings constructed under outdated seismic codes, contribute approximately to €7 billion in annual economic losses across Europe [2] with Italy, Turkey, and Greece being the most affected. Cultural and historic structures that lack proper seismic retrofitting often suffer irreparable losses. Human impacts are also severe, with an average annual rate of 900 fatalities [2], primarily in Italy and Turkey, alongside widespread injuries and displacement. Finally, infrastructures experienced severe disruptions, delaying recovery efforts, while damages to healthcare facilities hinder disaster response capabilities. These vulnerabilities underscore the urgent need for proactive seismic retrofitting and resilience strategies to mitigate economic losses, protect communities, and reduce the societal burden of earthquake-related disasters.

Implementing strategies, actions, solutions and projects aimed at reducing exposure and vulnerability while enhancing resilience requires a thorough understanding of the physical, social, and environmental conditions of the site where the plan or project will be developed. Future-proofing projects need the use of methods to evaluate and quantify the inherent characteristics of the built environment, despite the challenges involved. For instance, the interconnected nature of the built environment amplifies the need for robust risk assessment, as climate- and non-climate-induced impacts often cascade across sectors, influencing systems, economies, and public health. Numerous studies have highlighted the importance of improving resilience in the design, construction, and operation of built environment systems [7]. From this perspective, assessing and quantifying risk and resilience factors entails defining goals for adaptation against climatic and non-climatic hazards and establishing benchmarks for project development.

Over the years, several climate and seismic assessment frameworks have been developed, mostly focused on either adaptation (IPCC, 2022) or resilience [8]. Recently, the European Union (EU) has introduced the 'Do Not Significant Harm' (DNSH) principle, mandating that strategies, actions, solutions and projects under national Recovery and Resilience Plans must not cause any significant environmental harm. Similarly, sustainability rating systems and certifications have begun incorporating climate change and earthquake considerations into the design of buildings and communities. To this aim, several rating systems have been developed to assess resilience levels at different scales, including the "City Resilience Index" [8], the "Building Resilience Index" [9], the "Resilience Action List" [10], the "REDi™: Resilience-Based Design Guidelines for Earthquake design, Floods and windstorms" [11].

Resilience has become a key focus of national and international initiatives aimed at strengthening the built environment responsiveness and reducing potential losses [12,13]. A resilient built environment can be viewed as an ensemble of structures designed to absorb and recover from shocks through a combination of pre- and post-event measures [14]. Recent studies have underlined the importance of assessing resilience across various qualities and dimensions such as physical, social, organisational, environmental, economic and digital characteristics [15,16]. In particular, the economic and digital dimensions are gaining prominence due to their role in ensuring the sustainability of investments, minimizing damage, and leveraging technologies for planning, design and monitoring. In the realm of economic resilience dimension, research has examined key attributes such adaptation cost, inaction cost, and adaptation benefits [17]. Specifically, Parry et al. (2008) reviewed adaptation costs for the United Nations Framework Convention On Climate Change (UNFCCC); the UK Environment Agency [18], Erlandsen et al. [19], the EFC at Sacramento State (2019), and Biasin et al. [20] assessed the cost-effectiveness of climate adaptation projects in the built environment; finally, Nicklin et al. [21] investigated the cost of inaction representing economic losses incurred when no adaptation measures are implemented, regardless of mitigation efforts. In the realm of digital resilience dimension, emerging technologies, such as the Internet of Things, artificial intelligence and digital twins, can enhance infrastructure resilience by enabling real-time monitoring, predictive analytics, and automated decision-making [22]. However, their potential remains underutilized due to regulatory gaps and fragmented approaches, highlighting the need for holistic policies, standards, and cross-sector collaboration. Machine-learning methods have been increasingly applied to risk assessment for critical infrastructures, with predictive models developed to evaluate potential impacts under different scenarios [23]. While predicting natural disasters remains complex due to uncertainties, machine learning may improve our understanding and prediction capabilities [24].

Enhancing the resilience of the built environment requires a holistic approach [25–27] completing traditional risk assessment frameworks with resilience characteristics. To this end, quantitative Key Performance Indicators (KPIs) may serve as powerful tools to

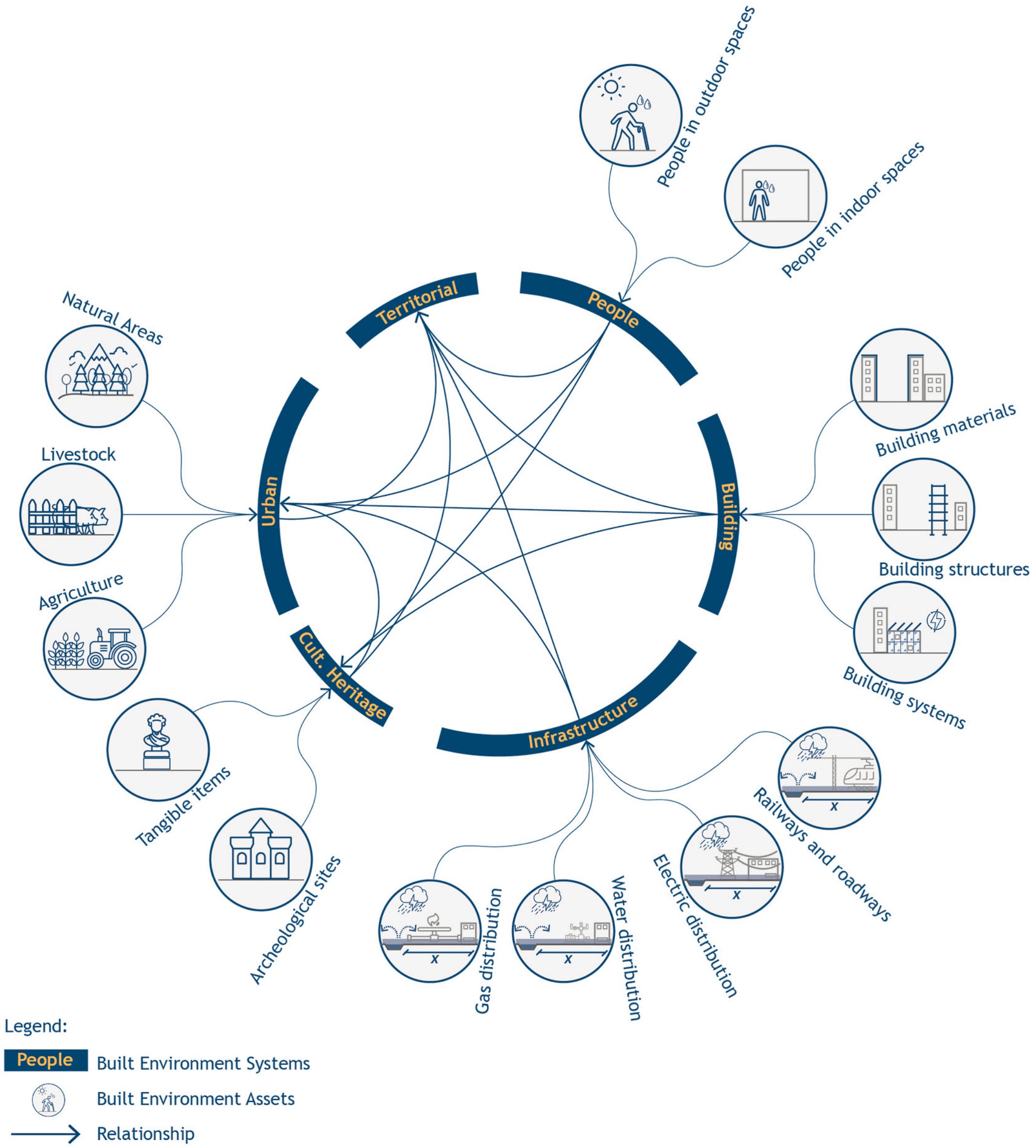


Fig. 1. Built Environment systems and assets considered and their relationship.

monitor progress toward resilience goals [28]. They help operationalize systematic frameworks for assessing risk and resilience, enabling the evaluation of vulnerabilities and performance levels. They also support the prioritisation and monitoring of strategies, actions, solutions, and projects to strengthen the overall preparedness of the built environment [29,30]. Recent studies have exploited KPIs to assess the performance of the built environment under various hazards (e.g. climate change, earthquake, terrorists acts), across different scales (e.g. individual buildings, districts, and metropolitan areas) and for a variety of projects (e.g., new construction and regeneration) [15,31–36]. Other studies have highlighted that using indicators provides a viable alternative to vulnerability and fragility curves for conducting climate change-related risk assessments, particularly at territorial, urban, community and infrastructure scales [4,30,37–40].

To address the complexity of assessing risk and resilience across the built environment, this study formulates the following research question: *"What quantitative indicators can be integrated into risk and resilience analyses to account for different climatic and non-climatic hazards, systems and assets, project scales, and users of the built environment?"*.

In response, the study proposes a structured and replicable six-step methodology that disaggregates the built environment into key systems and assets and aligns them with risk and resilience assessment factors. Grounded in established international standards and recent scientific literature, the approach supports the identification and validation of a comprehensive set of quantitative KPIs [30]; ISO 14091:2021[40,41]; Directorate-General for Climate Action [4,39,42]; United Nations Office for Disaster Risk Reduction [37, 43–49].

The novelty of this work lies in the integration of both risk components (hazard, exposure, sensitivity, adaptive capacity) and resilience qualities (robustness, rapidity, resourcefulness, redundancy) within a unified operational framework. Furthermore, resilience is assessed across multiple dimensions—physical, environmental, economic, digital, organizational, and human well-being—ensuring a holistic perspective.

This indicator-based framework enables consistent evaluation of current conditions ("AS IS") and potential future scenarios ("TO BE") across diverse built environment systems and assets. It also fills critical gaps in existing frameworks by providing a scalable tool that supports decision-making in planning, design, and policy development through measurable and actionable metrics for different scales and users.

The paper is structured as follows: Section 2 draws the Methodology for KPIs identification grounded in a holistic assessment framework for risk and resilience assessment, Section 3 presents the final list of quantitative KPIs for each component, and Section 4 discusses the findings, compares them with existing literature, and draws conclusions with future research prospects.

2. Methodology

2.1. Built environment systems and assets

According to the OECD [50], the built environment *"refers to human-made structures, which includes housing, parks, workplaces, transport facilities and digital infrastructure. It plays an important role in driving the well-being of people and communities, affecting their health, learning, mobility, their social interactions and their participation in public life*". Based on this definition, the built environment has been disaggregated into systems and related assets (see Fig. 1). Systems encompass people, buildings, infrastructure, cultural heritage, as well as urban and territorial contexts. They are not entirely independent of one another. While people, buildings, and infrastructure function as standalone systems, buildings, for instance, are integral to cultural heritage and extend across both urban and territorial contexts. Each system is characterized by a set of assets, with interconnected systems naturally sharing common assets. For instance, cultural heritage includes assets related to buildings (e.g., materials, structures, and systems) while also having its specific assets, such as historical materials, tangible items, and archaeological sites. Similarly, the urban context shares assets with buildings, people, infrastructure, and cultural heritage but also has unique assets, such as natural areas, agriculture, and livestock.

2.2. Risk and resilience assessment factors

This study adopts an indicator-based methodology for risk assessment, derived from the Fifth Assessment Reports (AR5) of the Intergovernmental Panel on Climate Change (IPCC). The methodology evaluates the level of risk for each system as a combination of hazard, exposure and vulnerability, using appropriate KPIs. It complies with the ISO 14091:2021[41], a systematic and replicable risk assessment standard allowing for qualitative and quantitative analyses for climate change-related risks. The methodology also aligns with the ARUP universal taxonomy [8], a recent advancement toward the integration of risk and resilience concepts and hazard of diverse nature (climatic and non-climatic) into a unified framework.

Hazard refers to the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihood, service provision, ecosystems and environmental resources. This study account for both climate-related hazards, such as extreme heat, extreme precipitation and storms, and drought, as well as non-climatic hazards, such as earthquakes. Exposure represents the presence of people, livelihoods, ecosystems, infrastructure, and socio-economic or cultural assets in areas at risk. In this study, exposure is linked to the assets that constitute each system. Finally, vulnerability refers to the susceptibility of systems to adverse effects. It encompasses the concepts of sensitivity and adaptive capacity. Sensitivity represents the degree to which a system is directly or indirectly and positive or negative affected by climate variability or change; adaptive capacity refers to the ability of systems, institutions, humans and organisms to adjust to potential damage, take advantage of opportunities or respond to consequences. This study explicitly considers the concepts of sensitivity and adaptive capacity.

While risk assessment relies on a well-referenced methodology, there is no standardised international approach for assessing the resilience of the built environment [16,25]. Indeed, Shamout et al. [51] noted a lack of consensus in defining built environment resilience, emphasizing that resilience goes beyond vulnerability to disasters. In line with this view, this study distinguishes between vulnerability and resilience, defining resilience specifically as the capacity to anticipate, prevent, absorb, and recover from shocks and stresses. This definition aligns with the ICLEI's Montréal Commitment and Strategic Vision 2018–2024 (2018) and Holling's [52] conceptualization of resilience as the persistence and adaptability of systems under change.

Resilience accounts for the concepts of quality and dimension. Quality reflects the effectiveness, strength, and sustainability of a system in withstanding, adapting to, and recovering from shocks. High-quality resilience enables recovery and enhances future adaptability, emphasizing robustness, flexibility, and long-term stability. On the other hand, dimension refers to the various aspects or domains that contribute to resilience. These dimensions provide a comprehensive framework for understanding resilience in different sectors.

To identify quality factors of resilience for the built environment, this study conducted a systematic literature review using the PRISMA flow diagram approach [53]. A SCOPUS search with the keywords "built environment," "natural hazard," and "resilience" yielded 256 studies, of which 15 were deemed relevant and included in the review (see Fig. 2).

Based on the definitions provided by Al-Humaiqani & Al-Ghamdi et al. [16], nine out of fifteen papers commonly converge on four main qualities, which are applied in this study.

- **Robustness:** *"the capacity to buffer climate related disturbances and reduce or prevent the associated impacts, measuring the system's performance level and maintaining the acceptable level of services"*.
- **Rapidity:** "*the speed of the affected system or facility to recover to its full operational function*".

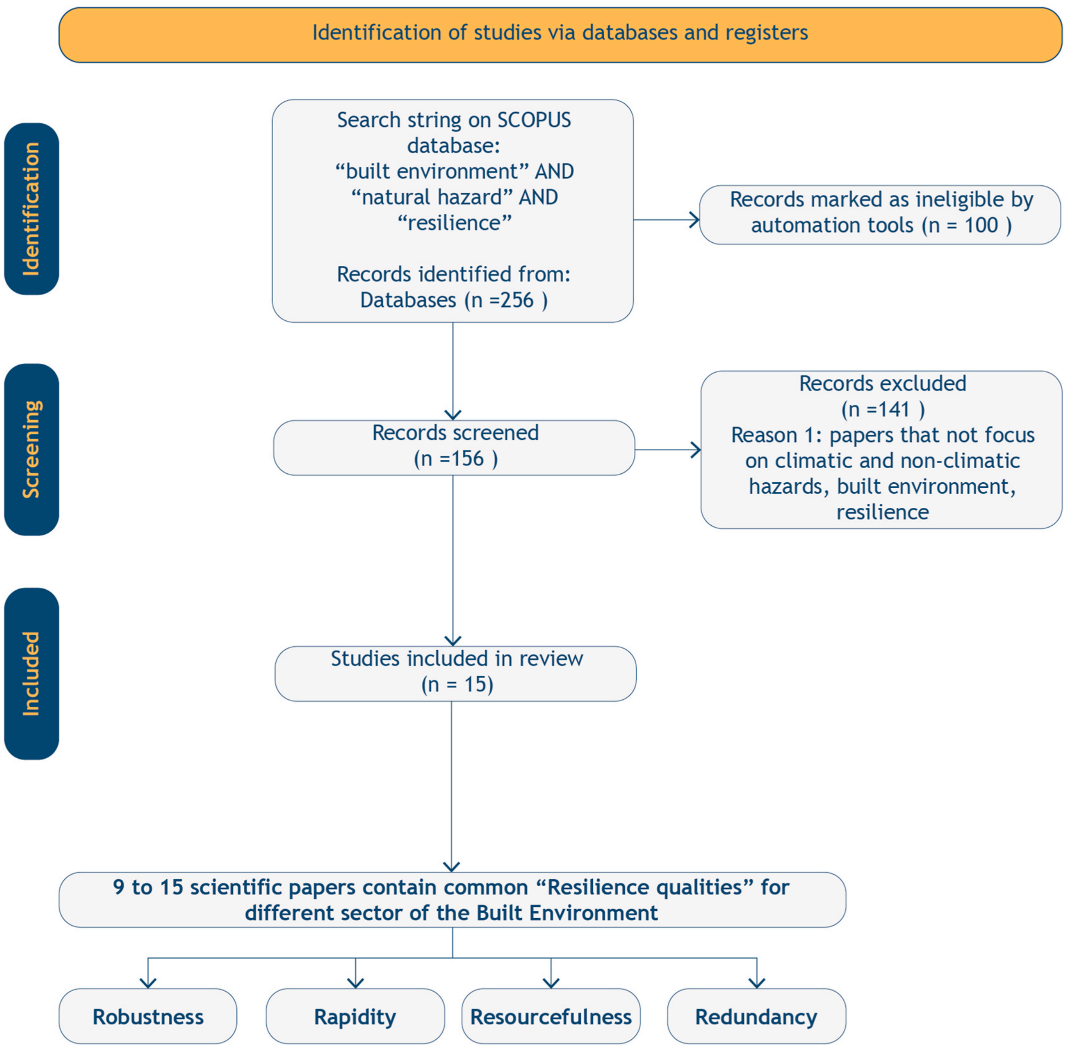


Fig. 2. Scientific literature review based on PRISMA method [53].

- **Resourcefulness:** *"the capacity to identify problems accompanying a disaster event, establishing priorities and mobilizing resources following the event".*
- **Redundancy:** *"Redundancy in public resources and services management provisions, and governance roles functions".*

The resilience dimensions used in this work adjusting what has been proposed by Fuggini et al. [45] as follows.

- **Physical Resilience:** The physical dimension of resilience focuses on the tangible aspects of the built environment, emphasizing the robustness and durability of structural elements.
- **Human health, well-being and quality of life:** Beyond mere survival, resilience entails maintaining and enhancing overall health, safety, and satisfaction. This dimension encompasses various factors, including social cohesion, community engagement, mental and physical health, education, and cultural well-being. A resilient community fosters strong social bonds, supports access to healthcare and education, and promotes a sense of belonging and purpose among its residents.
- **Digital Resilience:** The digital resilience dimension refers to the ability of digital technologies and systems to maintain functionality and support the built environment during and after extreme weather events. This dimension emphasizes the role of digital solutions in providing continuous and reliable data, communication, and decision-making capabilities that enhance the resilience of the built environment. In the present work, we have considered the most common digital enabling technologies in the built environment, based on the experts engaged, to support planning, design and monitoring the projects. These digital technologies are Early Warning Systems (EWS), BIM, real monitoring systems, Geographic Information System (GIS), and Decision Support Systems (DSS), assessing their ability to monitor, detect, respond to, and enhance resilience against floods, heat waves, drought and earthquakes for each built environment asset considered.
- **Economic Resilience:** Economic stability and social structures are essential for fostering resilience, enabling communities to recover and thrive in the face of adversity. This dimension emphasizes the importance of diverse economic sectors, equitable access to resources, and social support systems that empower individuals and businesses to withstand shocks and adapt to changing circumstances. The economic resilience dimension aims to identify KPIs for evaluating the cost-benefit performance, construction, and operational costs of interventions in the built environment.
- **Environmental Resilience:** Environmental resilience focuses on maintaining ecological balance, protecting natural resources, and minimizing negative environmental impacts.

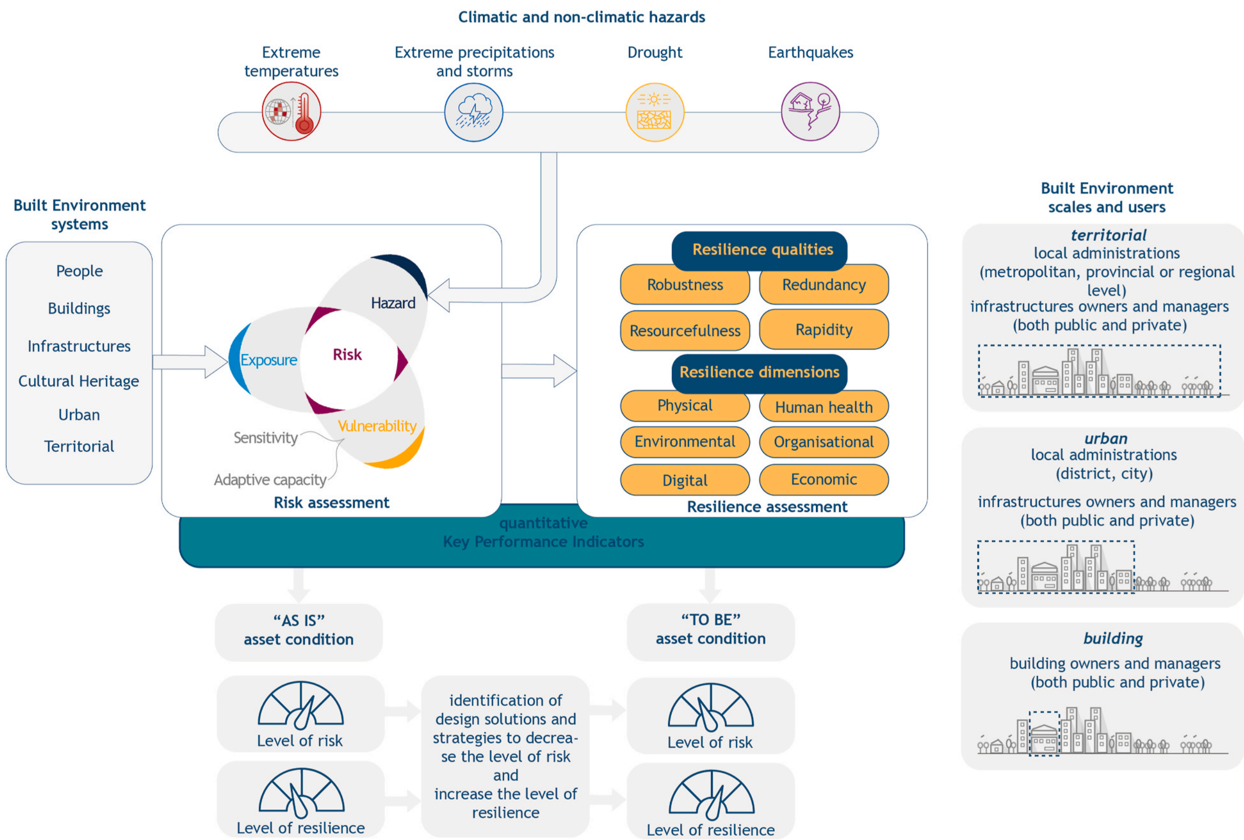


Fig. 3. General framework adopted to identify the quantitative KPIs, in particular for risk section, AR5 IPCC framework has been adopted.

- **Organisational Resilience:** Organizational resilience hinges on adaptive governance, efficient decision-making processes, and collaboration among stakeholders. Effective coordination within institutions, governance structures, and community organizations is crucial for a coordinated and effective response to challenges. By fostering transparency, accountability, and inclusivity, communities can strengthen their capacity to anticipate and address emerging threats, ensuring resilience in the face of uncertainty.

The proposed framework, illustrated in Fig. 3, comprises three main components: built environment systems and assets, risk factors, and resilience qualities and dimensions. Fig. 3 also highlights the interrelationships among these components.

The framework begins with the identification of climatic and non-climatic hazards. Risk assessment can be conducted by integrating climatic and non-climatic hazards, exposure and vulnerability factors of built environment systems and assets. The exposed assets identified through this process are further considered to assess resilience qualities and dimensions. The framework allows for the evaluation of both current and future scenarios by adjusting climatic and non-climatic hazard inputs. The built environment scales and their associated users considered in the analysis are also depicted in Fig. 3.

To operationalize the framework, this study focuses on defining quantitative KPIs for both risk factors and resilience qualities and dimensions. Risk factor KPIs are derived from climatic and non-climatic hazards in relation to the built environment systems, while resilience KPIs are based on climatic and non-climatic hazards in relation to the built environment assets.

This study proposes a replicable framework for KPI identification, independent of specific measures, enabling standardized assessments across different contexts. While most KPIs associated with resilience qualities align with dimensions such as physical, human health, well-being and quality of life, environmental, and organizational resilience, specific KPIs have been identified for economic and digital resilience dimensions.

2.3. A step-by-step process to identify the KPIs

The process to identify KPIs for each factor of the risk and resilience assessment includes the following main steps, and it is synthesized in Fig. 4.

- Step 1: through an expert engagement process, 10 institutions coming from different fields related to the built environment (infrastructure engineering, decision support systems developments, healthy living spaces research, data-driven software to support decision makers development, nature-based solutions management, BIM development, cultural heritage research, urban and territorial planning, building seismic structure engineering, building energy management and climate risk assessment) were involved in identifying the KPIs. Through the experts involved, the climatic and non-climatic hazards impact chains development has been carried out in order to identify the main factors in terms of climatic and non-climatic hazards, exposure, sensitivity,

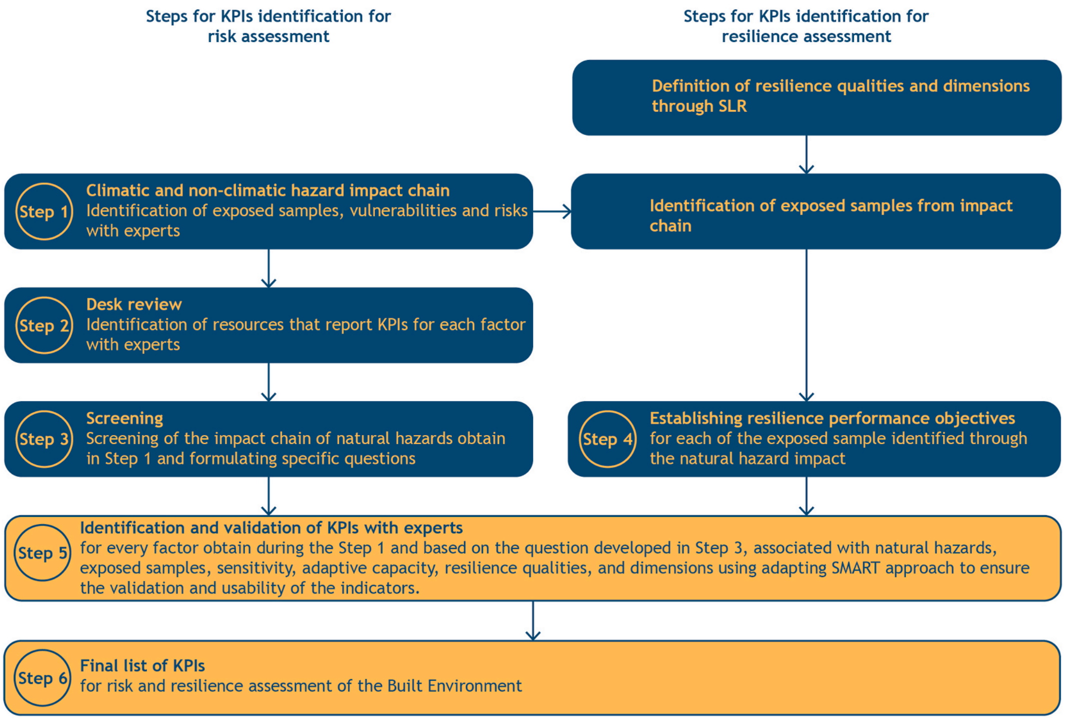


Fig. 4. Methodology adopted to identify KPIs for risk and resilience assessment. The SMART approach based on Doran [54] and D'Amico et al. [34] has been adapted to this work to ensure the validation and usability of the indicators.

adaptive capacity and related risks (Appendix A from Figs. 1–10). This stage has been conducted following the method reported by Zebisch et al. [30] and adapted to the paper context considering also earthquakes as non-climatic hazard.
- Step 2: The expert engagement process has supported a desk review of existing technical documents and scientific literature, legislation, and standards that provide quantitative KPIs for climatic and non-climatic hazards in the built environment. This step has been crucial to identify some references to support the KPIs identification. The criteria used to collect each resource are reported in Appendix B – Table 1. The desk review analysed 26 references, encompassing technical reports, scientific papers, and Green Building Rating Systems and Resilience Rating Systems, as detailed in Appendix B – Table 1. These sources span diverse geographical regions and sectors, with a primary focus on buildings and territories exposed to hazards such as earthquakes, floods, and multi-hazards.
- Step 3: After the identification of factors that compose the climatic and non-climatic hazards impact chain, a screening process has been conducted in order to avoid any overlapping or merge the common factors identified among different systems and formulating specific questions (Appendix C – from Tables 1–3) to aid the experts in the identification of KPIs.
- Step 4: Resilience performance objectives have been established for each of the exposed asset identified through the climatic and non-climatic hazards impact that are considered as assets of built environment systems (Appendix D – Table 1);
- Step 5: KPIs were identified for every factor obtained during Step 1 and based on the question developed in Step 3, associated with climatic and non-climatic hazards, exposed asset, sensitivity, and adaptive capacity for risk assessment. In addition, identification of KPIs for each factor based on Step 4, associated to performance goals, resilience qualities, and dimensions for resilience assessment. This step has been carried out with the support of experts engaged for each built environment asset. Furthermore, a validation process was conducted adapting the SMART approach [34,54] to the objective of the present work (Appendix E, from Table 1 to Table 11), considering the following parameters:
  - o Validity: assesses if the indicator accurately captures at least one of the resilience dimensions (physical, human health, digital, economic, environmental, and organizational) with clarity.
  - o Simplicity: refers to the ease with which decision-makers and other stakeholders can comprehend and effectively use the indicator.
  - o Measurability: refers to the ability to quantify a KPI with objective, numerical data. This characteristic is essential for monitoring progress, identifying trends, and making informed decisions. The KPI must be expressible in numbers. For example, the percentage of reduction in risk incidents, the number of mitigated risks, or the financial savings from reduced risk.
  - o Specific: means that the KPI should focus on a clearly defined and narrow aspect of hazard that pertains to the built and natural environment, such as buildings, infrastructure, and their interactions. This specificity ensures that the KPI addresses particular risks or combinations of risks that are significant to the safety, sustainability, and efficiency of the built environment.
  - o Realistic: refers to the practicality and attainability of the objectives set by the KPI. It ensures that the goals are achievable given the current resources, constraints, and conditions within the built environment. This involves establishing objectives related to behavioural issues or specific actions that can be realistically accomplished. The objectives should be based on realistic assessments of the current situation, including any constraints or limitations that may affect the achievement of the goals.
- Step 6: The final list of KPIs for risk and resilience assessment of the built environment has been compiled. The list is reported in the Excel file provided as Appendix F [55], where each KPI is categorized with the following rule: related factor in the impact chain; name of indicator; description of indicator; formula for calculation; unit; data sources; type and range of results; potential users of the KPI; reference standard regulation (ISO, number of law or regulation); technical or scientific reference; resilience dimension. In addition, to provide additional information and support the adequate selection in the future by different type of users, KPIs for exposure, sensitivity and adaptive capacity have been categorized introducing some additional criteria such as name of system, type of natural hazard, type of impacts, type of exposure sample, name of "sensitivity (negative qualities)", name of risk and related scale such as building, urban and territorial. For KPIs selected for resilience have been introduced some columns based on the specify on the information required by this group of KPIs such as name of reference exposed sample, hazard type and type of resilience quality, type of digital technology and type of capacity of each digital technology.

3. Results & discussion

This section presents the results of the study, following the step-by-step process outlined in the Methodology. It synthesizes the key findings for each step and provides links to the Appendices for a more detailed exploration of the complete information.

3.1. Step 1- Climatic and non-climatic hazards impact chain

This work has identified the climatic and non-climatic hazards impact chain of the built environment, focusing on the key systems—people, buildings, infrastructure, cultural heritage, urban, and territorial—and identifying critical exposure, sensitivity and adaptive capacity factors. Detailed climatic and non-climatic hazards impact chains for each built environment subsystem are available in Appendix A from Figs. 1–10.

3.1.1. People

Human systems in hazard-prone areas, including those exposed to extreme heat, flooding, drought, and earthquakes, share common vulnerabilities. These include older adults, individuals with pre-existing health conditions, socially isolated populations, and socio-economically disadvantaged groups. Specific stressors—such as thermal discomfort, dehydration, and malnutrition—further exacerbate these vulnerabilities, particularly for outdoor workers and those without access to green spaces during extreme heat events. Flooding heightens psychological stress and social isolation, while drought can lead to resource conflicts and displacement. Adaptive capacities encompass behavioral adaptations, access to green infrastructure, and psychological resilience strategies, including community support and coping mechanisms. In the case of earthquakes, risks are particularly pronounced for older adults and individuals with disabilities, underscoring the need for resilience-building through social and psychological support systems (Fig. 1 – Appendix A).

3.1.2. Buildings

Buildings are highly exposed to hazards such as extreme heat, flooding, drought, extreme winds, and earthquakes. Key exposure factors include proximity to hazard zones and structural vulnerabilities. Sensitivity drivers vary by hazard: for extreme heat, risks are heightened by non-insulated structures and high cooling demands; for floods, low-elevation locations and non-water-resistant materials are critical concerns. Unreinforced and poorly maintained buildings face increased risks of structural failure during earthquakes and extreme winds. Adaptive capacities include the use of thermal- and water-resistant materials, green spaces for heat mitigation, passive design strategies, reinforced construction for wind and seismic resilience, and regular maintenance. Efficient drainage systems and renewable energy solutions further enhance overall resilience (Figs. 2 and 3 – Appendix A).

3.1.3. Infrastructure

Infrastructure systems—including transportation networks, water and gas pipelines, and electrical grids—face distinct risks across various hazard scenarios. Exposure is determined by factors such as location, land cover, and usage intensity, with flood-prone areas and unstable soil conditions exacerbating vulnerabilities. Sensitivity drivers vary by infrastructure type: for pipelines, material properties, joint types, and soil resistivity are critical; for transport and power networks, aging or poorly maintained structures increase risk. Adaptive capacities include flood- and earthquake-resistant designs, regular maintenance, and efficient backup systems. Integrated adaptation planning enhances resilience, reducing service disruptions and structural damage while ensuring continuity during hazard events (Fig. 4 – Appendix A).

3.1.4. Cultural heritage

Cultural heritage assets—including historic buildings, archaeological sites, and protected natural areas—share vulnerabilities with buildings but also face unique risks due to their intangible value and the assets they contain. Exposure is influenced by geographical location and environmental conditions, while sensitivity is heightened by natural aging and material degradation, particularly under extreme events such as heat, flooding, and wildfires. Ecosystem vulnerabilities, including soil degradation and deforestation, further exacerbate these risks. Adaptive strategies focus on preventive and proactive maintenance, fire prevention, and structural reinforcement. Additionally, ecosystem management practices—such as reforestation and fire-resistant designs—are essential for preserving the integrity of cultural heritage (Figures 5 and 6 – Appendix A).

3.1.5. Urban and territorial

Urban systems concentrate risks associated with people, buildings, infrastructure, and cultural heritage, further exacerbated by land use changes and ecosystem degradation. Key sensitivity factors include soil sealing, biodiversity loss, and ecosystem fragmentation. Adaptive capacities involve sustainable land use planning, flood-resistant crops, and community-based resilience strategies. Urban green infrastructure, reforestation, and buffer zones help mitigate flooding and drought risks while enhancing overall urban adaptation.

At a broader scale, territorial systems exhibit similar dynamics, with vulnerabilities aggregated across regions. Integrated management strategies prioritize the coordination of urban and rural adaptation efforts to effectively address spatially distributed hazards (Figs. 7, 8, 9 and 10 – Appendix A).

3.2. Step 2 - Desk review of tools

The references collected through the desk review are reported in Appendix B – Table 1, most of the references collected include quantitative indicators, with all references contain risk metrics underscoring their critical role in resilience assessments. Sensitivity metrics were the most represented (24 references), followed by adaptive capacity metrics (16 references). However, only 12 references provided exposure metrics, highlighting a gap in comprehensive data.

While 20 references prioritized risk assessment, few integrated broader resilience factors, revealing an opportunity for advancing resilience-focused frameworks.

3.3. Step 3 - Questions developed to identify the KPIs for risk assessment factors

For each factor identified for exposure, sensitivity, and adaptive capacity, a question has been formulated to support the identification of KPIs by experts. In this scenario, some obtained factors for sensitivity and adaptive capacity have been removed because they present a more qualitative characteristic rather than quantitative.

Appendix C – Table 1 reports the questions identified for the 15 exposed assets identified through the climatic and non-climatic hazards impact chain. Appendix C – Table 2 displays the questions selected for the 79 sensitivity factors associated with the exposed assets identified. For 14 sensitivity factors, the question focuses on asking the expert if it is possible to quantitatively calculate the factors reported in the table. Appendix C – Table 3 displays the questions selected for the 60 adaptive capacity factors associated

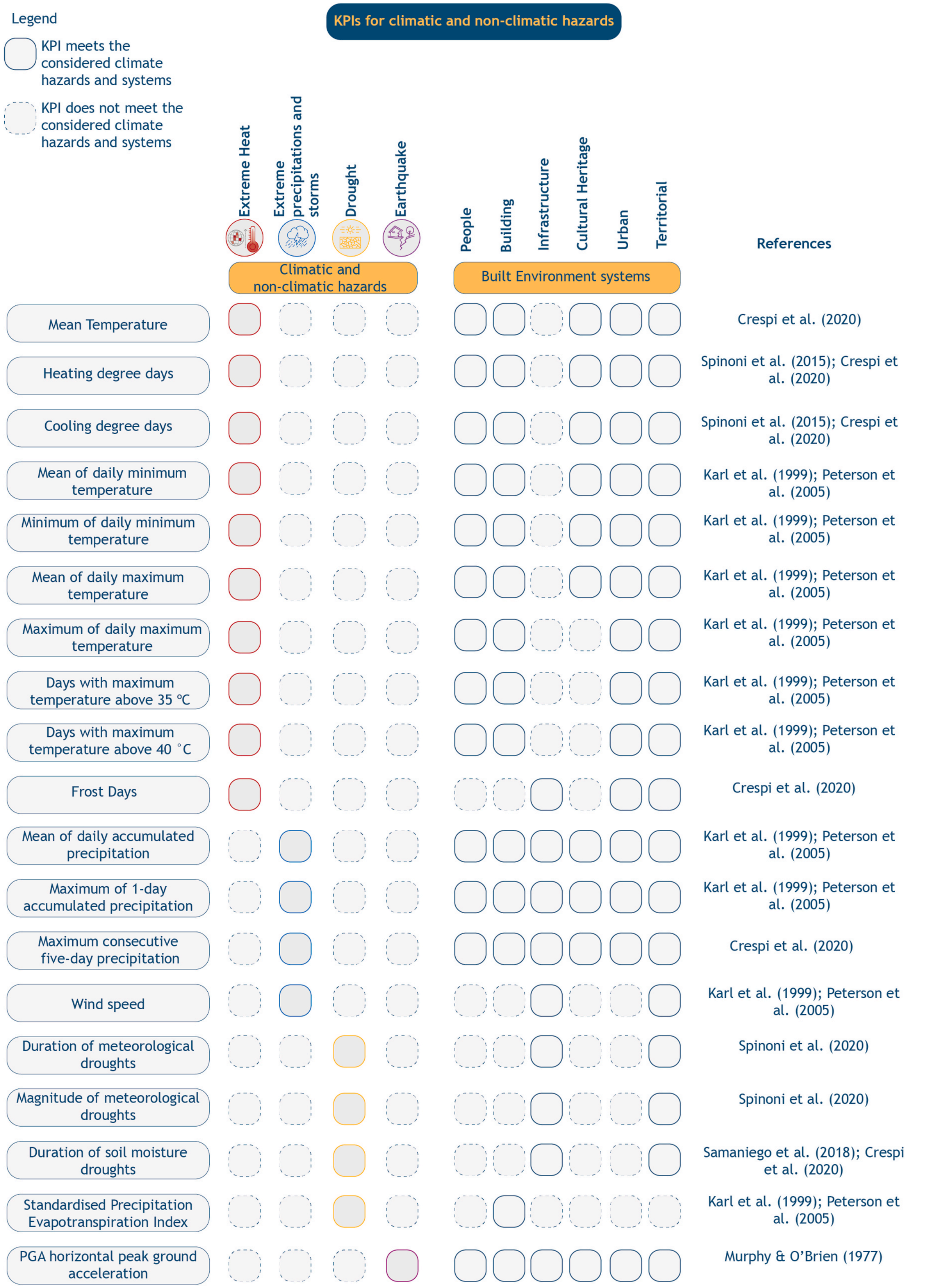


Fig. 5. Final list of KPIs for climatic and non-climatic hazards.[56][57][58][59][60][61][62]

with the exposed assets. For 17 adaptive capacity factors, the question focuses on asking the expert if it is possible to quantitatively calculate the factors reported in the table.

3.4. Step 4 - Resilience performance objectives for each asset

Based on the exposed assets emerged during the climatic and non-climatic hazards impact chain development in Step 1, this step identified the resilience performance objectives for each of them. The performance objectives for resilience were identified based on the risks emerging from the impact chain. These objectives represent qualitative descriptions of the desired state for each system and asset considered at the end of a specific time period. They define the intended final outcome and are aligned with the overarching strategic choices for each asset, aiming to ensure protection and functionality in the face of climate-related and other hazards. Additionally, these objectives were crucial in enabling experts to determine specific targets for the resilience assessment indicators of each exposed asset of the built environment to climatic and non-climatic hazards. In this scenario, indicators identified for all resilience qualities and resilience dimensions have to take into account the resilience performance goals. Appendix D – Table 1 shows the list of the 15 identified performance objectives.

3.5. Step 5 – Identification and validation of KPIs identified through expert engagement for risk and resilience assessment

As shown in Section 2, the validation process (Step 5) has been crucial in order to identify the final list of KPIs eligible for risk and resilience assessment of the built environment to support "AS IS" asset condition and to "TO BE" future scenarios analysis. In Appendix E from Tables 1–11 are reported all KPIs validated, i.e., all the SMART parameters are achieved, and non-validated, i.e., one or more SMART parameters are not achieved.

3.5.1. Risk assessment indicators

This study validated 19 of 35 climatic and non-climatic hazards indicators based, as outlined in Appendix E – Table 1. These indicators, sourced from Copernicus Climate Atlas, ETCCDI, and EEA, comprehensively evaluate climatic and non-climatic hazards risks to the built environment. All exposure indicators (Appendix E – Table 2) were validated as they are readily measurable and have been applied in prior research projects. Sensitivity indicators (Appendix E – Table 3) encompass diverse factors, but 16 were non-validated due to their qualitative nature, while some were reclassified into resilience metrics. Similarly, adaptive capacity indicators (Appendix E – Table 4) underwent refinement; non-quantifiable metrics were excluded or reassigned to resilience categories.

3.5.2. Resilience assessment indicators

Appendix E – Table 5 highlights gaps in robustness indicators across agriculture, building systems, materials, and ecosystems in hazard-prone areas. Many indicators remain underdeveloped due to high complexity or presence of qualitative metrics. For example, indicators for drought resilience in agriculture and ecosystems are notably absent. Appendix E – Table 6 emphasizes rapidity indicators, focusing on recovery speeds for assets post-disturbance. Agriculture, ecosystems, and building systems lack validated rapidity indicators for hazards like extreme precipitation and drought. Resourcefulness indicators (Appendix E – Table 7) reflect competencies, financial preparedness, and access to critical resources. Despite progress, significant gaps exist for drought resilience, particularly in vulnerable ecosystems and cultural heritage. Appendix E – Table 8 assesses redundancy indicators for ensuring backup systems during disturbances. Even though 26 indicators were validated, redundancy gaps for aridity and drought hazards reveal systemic vulnerabilities, necessitating expanded measures for infrastructure and ecosystems. Economic resilience indicators (Appendix E – Table 9) validate adaptation and construction costs. While standardized KPIs enable robust cost-benefit analyses, gaps persist in assessing ecosystem-related adaptation costs. Digital resilience indicators (Appendix E – Table 10) address robustness, rapidity, redundancy, and resourcefulness through technologies like GIS, BIM, real time monitoring systems and decision support platform. Although 34 indicators were validated, cultural heritage and ecosystems lack sufficient digital monitoring measures, as these technologies are often first applied for design rather than assessment of existing infrastructure.

3.6. Step 6 - Final list of KPIs

The full list of KPIs with the complete description of each indicator is reported in Appendix F [55]. In the figures presented in the following paragraphs, a continuous line and a solid square are used to confirm the consistency of each indicator with the four climatic and non-climatic hazards considered, as well as with the six built environment systems. Conversely, a dashed line indicates the absence of consistency with the aforementioned criteria for each KPI. In Figs. 9–15, related to resilience indicators, the six built environment systems have been replaced with the thirteen built environment assets, as described in the Methodology section.

3.6.1. KPIs to support risk assessment

3.6.1.1. Hazard indicators. Fig. 5 summarizes the validated 19 climatic and non-climatic hazards indicators for understanding the impacts on the built environment systems. Climate-related indicators can be used to assess local climate profile and future expected variations in terms of climate change for extreme heat, extreme precipitations, droughts, fires and extreme winds. In addition, these indicators can be used in different sectors of the built environment to assess energy demand change, impacts on human health and wellbeing, impacts on agriculture production, and on building and infrastructure.

Non-climate-related indicators include Peak Ground Acceleration (PGA). These indicators can have an impact on structural safety and show a direct correlation with the built environment, affecting energy efficiency, structural integrity, and resource management. Increased mean temperatures and degree days influence heating and cooling energy demand, while frost days and extreme temperature days affect building materials structures and human-health, in particular for vulnerable people. Drought indicators (duration and magnitude) highlight water resource challenges, affecting agriculture, flood protection and water supply infrastructure. Extreme events influenced by increase in frequency and intensity for wind speed and PGA are crucial for structural safety, influencing building codes and design standards.

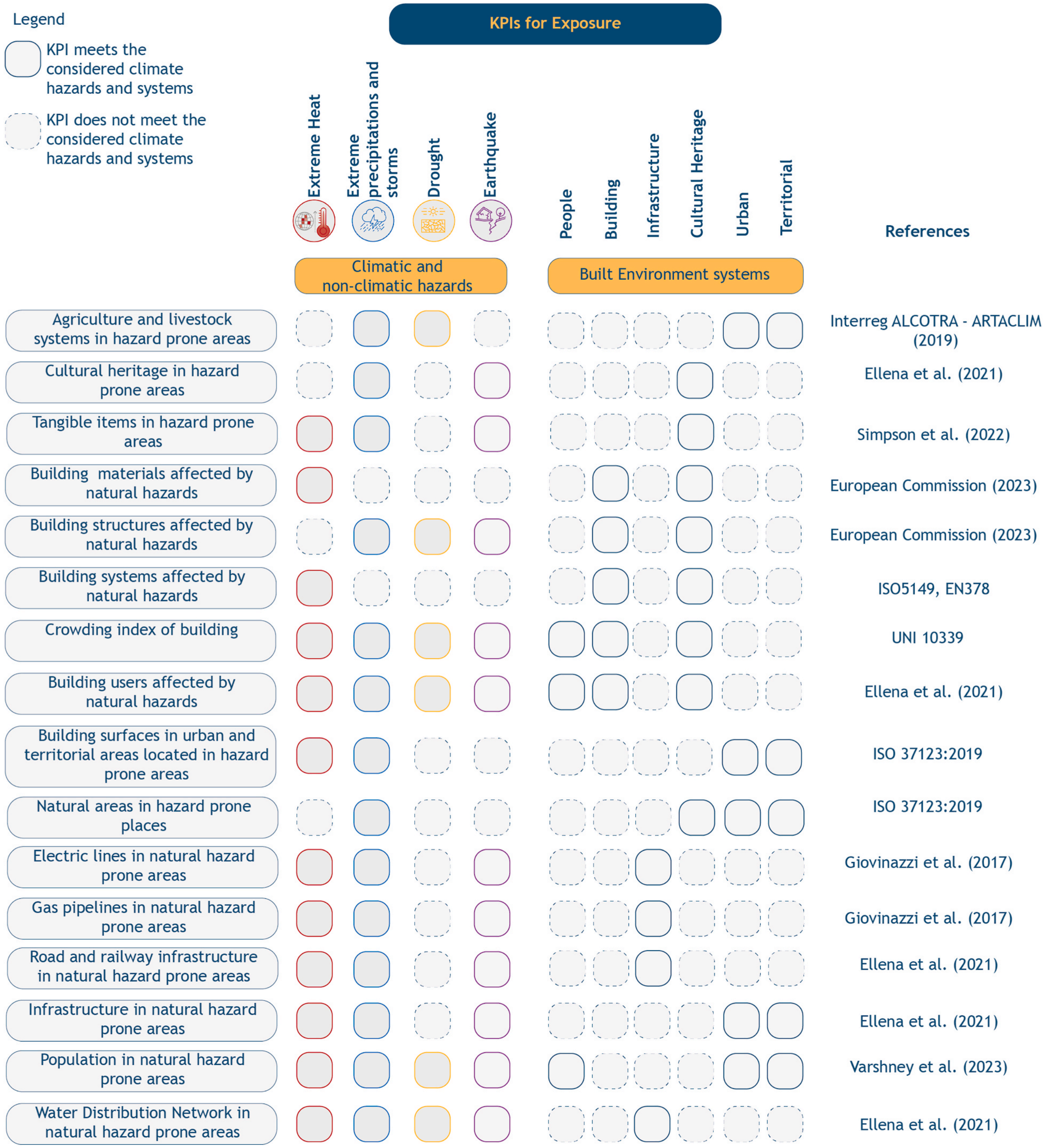


Fig. 6. Final list of KPIs for Exposure.[63][64][65][66][67][68]

3.6.1.2. Exposure indicators. Fig. 6 presents 16 validated exposure indicators for assessing the impacts of climatic and non-climatic hazards on various systems. These indicators evaluate the extent of exposure through various units of measurement such as percentage, count, area, volume, and kilometre's.

For example, the indicators for agriculture, cultural heritage, and natural areas use the percentage of total area to assess exposure. Tangible items, building users, and population indicators use count data to quantify exposure. Indicators for building materials, structures, systems, and surfaces use measurements of area and volume. Infrastructure indicators (electric lines, gas pipelines, roads, railways, and water distribution) use kilometres to determine the amount of exposure.

These indicators highlight the critical connections between climatic and non-climatic hazards and their potential impacts on the built environment. High percentages and numbers in these indicators suggest significant exposure and the need for robust adaptation strategies. Overall, these indicators provide a comprehensive framework for evaluating and addressing the risks posed by climatic and non-climatic hazards to various systems and the built environment.

3.6.1.3. Sensitivity indicators. Seventy-six sensitivity indicators (Fig. 7 part 1, part 2 and part 3) were validated for assessing climatic and non-climatic hazards vulnerabilities across built environment systems. For buildings, KPIs such as Structural Safety, Fire Resistance, and Energy Efficiency evaluate safety, resistance, and energy performance. Cultural heritage systems are characterized by Structural Vulnerability, Material Sensitivity, and Protection Measures, focusing on degradation and protective systems. Infrastructure systems include Network Redundancy, Maintenance Level, and Recovery Capacity, emphasizing service continuity and maintenance practices. Natural ecosystems, evaluated at urban and territorial systems, use KPIs such as Biodiversity Levels, Ecosystem Services, and Land Degradation. Finally, population sensitivity is assessed using Health Status, Socioeconomic Status, and Demographic Characteristics in urban and territorial systems. Common indicators like Structural Vulnerability and Recovery Capacity reveal interconnections between built environment systems in addressing hazards. High vulnerability of buildings amplifies risks in earthquakes and fires, while Poor infrastructure maintenance prolongs disruptions during floods and heatwaves. Ecosystem degradation further exacerbates the environmental and economic impacts of floods and droughts.

3.6.1.4. Adaptive capacity indicators. This study identified 35 validated adaptive capacity indicators to assess the ability of built environment systems to adapt to climatic and non-climatic hazards (Fig. 8 part 1 and 2). For buildings, key indicators include Building Codes and Standards, Insurance Coverage, and Emergency Plans, Measuring Compliance, Financial Preparedness, and Disaster Response strategies. Cultural heritage systems are evaluated through Preservation Plans and Funding for Conservation, focusing on protection strategies and resource allocation. Infrastructure systems rely on indicators such as the presence of Alternative Systems, Regular Maintenance, and Hazard Withstanding Capacity to ensure service continuity during disruptions. Natural ecosystems are evaluated with indicators such as efforts to protect ecosystems, Biodiversity Management strategies to maintain species diversity, and initiatives to rehabilitate degraded areas. Population adaptive capacity is measured through indicators such as Public Awareness and Preparedness Programs, Availability of medical support and Community support systems.

The connection between these adaptive capacity indicators and the impacts of climatic and non-climatic hazards on the built environment is crucial. Strong Building Codes and Insurance Coverage can significantly reduce the damage and financial loss from disasters.

3.6.2. KPIs to support resilience assessment

3.6.2.1. Robustness indicators. Fig. 9 part 1 and 2 present 22 validated robustness indicators for assessing the resilience of built environment systems to climatic and non-climatic hazards. Cultural Heritage are characterized by indicators such as Temperature and Seismic stability which evaluate the ability of archive materials in buildings to maintain stability under temperature changes, withstand earthquakes and floodings.

Assets related to building systems include indicators for structural health assessment and seismic susceptibility, focusing on the structural capacity and earthquake fragility of buildings structures. Infrastructure indicators encompass resilience of service networks and ability to adapt operations under stress. Natural ecosystems are evaluated with indicators like ability of forests to resist from disturbances and overall ecosystem stability.

Validated robustness indicators highlight interconnections between built environment systems, particularly in mitigating hazard impacts. High structural stability reduces cascading failures, while robust maintenance protocols in infrastructure minimize disruptions. Enhanced ecosystem stability, through soil and biodiversity management, mitigates erosion and flood risks.

3.6.2.2. Rapidity indicators. This study validated 14 rapidity indicators (Fig. 10) to evaluate recovery capacities across built environment systems. For archive materials, the Restoration Time Index is consistently applied across hazards, showcasing adaptability for preserving archive materials, books, and artifacts in cultural heritage system.

In building users asset, indicators such as Recovery Time for earthquakes and Recovery Capacity for general functionality offer quantifiable measures of resilience, although metrics for extreme heat remain underdeveloped. For group of buildings localized in hazard-prone areas, specific metrics like the time to recover an adequate level of Land Surface Temperature (LST) and insurance coverage indicate practical and financial aspects of recovery. Infrastructure robustness is gauged using indicators like Mean Time to Repair, effectively standardizing recovery timelines for electric and gas distribution networks, as well as highways and railroads. People in hazard prone areas incorporates physiological and psychological measures, such as Sweat Rate for heat stress and

Legend

KPI meets the considered climate hazards and systems (✓)

KPI does not meet the considered climate hazards and systems (–)

KPIs for Sensitivity

	Climatic and non-climatic hazards				Built Environment systems						
KPI	Extreme Heat	Extreme precipitations and storms	Drought	Earthquake	People	Building	Infrastructure	Cultural Heritage	Urban	Territorial	References
Age of construction of overhead lines	–	–	–	✓	–	–	✓	–	–	–	Giovinazzi et al. (2017)
Air quality at urban and territorial level	✓	–	✓	–	✓	–	–	–	–	–	Saroglu et al. (2024)
Area of land classified as class I and II based on soil capability	–	✓	–	–	–	–	–	–	✓	✓	Interreg ALCOTRA - ARTACLIM (2019)
Aspect ratio (H/L)	–	–	–	✓	–	✓	–	✓	–	–	EN 1994-1-1 :2004
Average Daily Traffic	–	✓	–	–	–	–	✓	–	✓	✓	U.S. Department of Transportation (2018)
Bridges and Overpasses in natural hazard prone areas	–	✓	–	–	–	–	✓	–	✓	✓	Ellena et al. (2021)
Building systems interruptions	✓	–	–	–	–	✓	–	✓	–	–	Dong (2021)
Buried power lines	✓	–	–	–	–	–	✓	–	–	–	Calcara et al. (2018)
Burned area percentage	–	✓	✓	–	–	–	–	✓	✓	✓	Wei et al. (2021)
Classification of Flood Damage-Resistant Materials	–	✓	–	–	–	✓	–	✓	✓	✓	FEMA (2008)
Daily physical activity	✓	–	–	–	✓	–	–	–	–	–	Martin-Conty et al. (2020)
Density of buildings within an urban area	–	✓	–	–	–	–	–	–	✓	✓	Rafiei-Sardooi et al. (2021)
Ductility Index	–	–	–	✓	–	✓	–	✓	✓	✓	Imanzadeh et al. (2021)
Effect of urban form to indoor thermal comfort	✓	–	–	–	–	✓	–	✓	–	–	Zheng et al. (2022)
Effective seismic bracing	–	–	–	✓	–	✓	–	✓	–	–	Hilti (2022)
Electrical and mechanical systems above the maximum flood level recorded	–	✓	–	–	–	✓	–	✓	✓	✓	Internation Finance Corporation (2024)
Elevation above sea level	–	✓	–	–	–	–	✓	–	–	–	Internation Finance Corporation (2024)
Energy class of the building	✓	–	–	–	–	✓	–	✓	–	–	Thullner (2010)
Ethnic minorities coming from poor countries with high migration pressure	–	–	✓	–	✓	–	–	–	–	–	Ellena et al. (2023)
Extension of River Pebbly Shores	–	✓	–	–	–	–	–	–	✓	✓	Interreg ALCOTRA - ARTACLIM (2019)
Extent of Reduced Natural Areas	–	✓	–	–	–	–	–	–	✓	✓	Interreg ALCOTRA - ARTACLIM (2019)
Farms with Operators Aged 65 and Above	–	✓	–	–	–	–	–	–	✓	✓	Interreg ALCOTRA - ARTACLIM (2019)
First-floor elevations (FFEs)	–	✓	–	–	–	✓	–	✓	✓	✓	Diaz et al. (2024)
Habitat provision	–	✓	–	–	–	–	–	–	✓	✓	Gonzalez-Ollauri et al. (2021)
Hourly urban albedo of building façades	✓	–	–	–	–	✓	–	–	✓	✓	Yuan et al. (2021)

Fig. 7. Final list of KPIs for Sensitivity (part 1).[69][70][71][72][63][73][74][75][64][76][77][78][79][80][81][82][83][84]
Fig. 7Final list of KPIs for sensitivity (part 2). [85][86][87][88][89][90][91][64][92][93][94][95][96][97][68]
Fig. 7 Final list of KPIs for Sensitivity (part 3).[98][99][100][101][102][103][104][105][106][76][107]

Psychological Distress for earthquakes. Ecosystem recovery is evaluated through indicators addressing land surface temperature and rehabilitation of degraded areas.

Common indicators, including Recovery Time and Recovery Capacity, underline the interconnectedness of built environment systems, highlighting the cascading impacts of prolonged disruptions.

3.6.2.3. Resourcefulness indicators. Six resourcefulness indicators have been identified for assessing the capacity of built environment systems to manage resources effectively during disasters (Fig. 11).

Archive materials asset in cultural heritage system employs the Qualified Staff Index across multiple hazards, ensuring skilled personnel manage items like archive materials and artifacts. However, gaps exist for aridity/drought metrics, limiting preparedness for this hazard. For building users, building structures and group of buildings, indicators like Fundamental Access to First Aid, Emergency Supplies, Water, Food, and Communication address multiple hazards, except aridity/drought and earthquakes. Similarly, Available Budget for Building Refurbishment focuses on heat impacts for building materials, buildings systems and group of buildings but neglects other hazards, revealing gaps in financial preparedness. Infrastructure systems, such as electric and gas networks, and transportation rely on Local Resourcefulness across hazards, though these measures lack specificity. Ecosystems and landscapes have no defined resourcefulness indicators, highlighting significant gaps in managing natural landscapes during hazards.

This interconnected framework reveals gaps in preparedness, particularly for aridity/drought, and emphasizes the need for tailored indicators to enhance built environment resilience comprehensively.

3.6.2.4. Redundancy indicators. This work validated 12 redundancy indicators (Fig. 12) to assess the capacity of built environment systems to maintain functionality during disruptions.

For archive material asset in cultural heritage system, the Backup Protection Redundancy Index ensures preservation across extreme heat, flooding, and earthquakes, highlighting robust protective measures. However, no indicators address aridity/drought for this asset. Building users rely on Generators or Photovoltaic Systems for extreme heat and Pumping Backup Systems for flooding, yet lack redundancy metrics for aridity/drought and earthquakes. Building materials, structures, and systems have limited indicators, such as Peer Review for flooding and Long-Term Adaptability Design for aridity/drought, leaving gaps for other hazards. Infrastructure systems exhibit varying levels of redundancy. The Electric and Gas Distribution Networks and Water Distribution Systems employ comprehensive indicators, such as Structural Robustness and Redundancy, across heat, flooding, and earthquakes. Similarly, Highways and Railroads utilize a Network Redundancy Index, offering standardized resilience.

Despite these metrics, ecosystems, landscapes, and people in hazard-prone areas lack adequate redundancy indicators, underscoring critical gaps in preparedness for certain hazards like aridity/drought.

3.6.2.5. Cost-benefit analysis and operational and construction costs indicators. This study validated 15 economic indicators (Fig. 13) to assess adaptation costs, operational expenses, and the benefits of avoided damages across built environment systems.

For archive materials asset in cultural heritage system, the Cost of Inaction Index quantifies the economic consequences of inaction, while the Adaptation Protection Cost Index and Adaptation Benefit Index evaluate the costs and benefits of protective measures. This trio provides a comprehensive economic framework for adaptation planning.

Building users are assessed using injury and casualty count as the Cost of Inaction, with adaptation costs and avoided injuries measured by corresponding indices. Agriculture and livestock asset use crop yield loss per hectare as the Cost of Inaction, paired with adaptation costs and avoided losses to provide specific, actionable metrics.

Building users, structures, materials, systems and group of buildings, infrastructure, and utility networks—such as electric, gas, and water systems—follow a consistent structure: Damage Costs for inaction, Adaptation Protection Cost Index for adaptation expenses, and avoided damages as adaptation benefits. Highways and railroads apply the same indicators, ensuring comparability across infrastructure categories.

Additionally, the Maintenance Cost Efficiency Index and General Construction Cost Index are uniformly applied to operational and construction costs, streamlining financial assessments across built environment systems.

3.6.2.6. Capacity of digital technologies to enhance the resilience of built environment indicators. This study validated indicators to assess the capacity of digital technologies in enhancing the resilience of the built environment against climatic and non-climatic hazards (Fig. 14). Digital tools such as BIM, DSS, EWS and Real-Time Monitoring System play a critical role in quantifying resilience dimensions across built environment systems.

Building users benefit from BIM and DSS, with indicators such as Hours Outside Comfort Temperature and Occurrence Probability of Consequences measuring robustness and rapidity. For agriculture and livestock systems, DSS uses Floodwater Depth to assess robustness. Building materials and systems employ BIM and DSS with indicators like Thermal Transmittance, Seismic Resistance, and Fire Resistance Rating to evaluate robustness.

Infrastructure systems such as electric and gas networks, highways, and railroads leverage DSS, BIM, and Real-Time Monitoring systems with indicators like Seismic Resistance, Surface Temperature of Pavements, soil moisture content, and Floodwater Depth.

Legend

KPI meets the considered climate hazards and systems (●)

KPI does not meet the considered climate hazards and systems (blank)

KPIs for Sensitivity

KPI	Climatic and non-climatic hazards: Extreme Heat	Extreme precipitations and storms	Drought	Earthquake	Built Environment systems: People	Building	Infrastructure	Cultural Heritage	Urban	Territorial	References
Loss of resistant cross-section				●				●	●	●	EN1990, EN1991, JRC (2014)
Normalized strength parameter				●		●		●			Harrington & Liel (2021)
Number of outdoor workers	●	●			●				●	●	Habibi et al. (2021)
Number of tourists potentially affected by Urban Heat Islands	●								●	●	Pede et al. (2022)
Older population in buildings	●	●			●	●		●			Varshney et al. (2023)
Older population in urban areas	●	●	●	●	●				●	●	Varshney et al. (2023)
Outdoor Thermal comfort (PET)	●				●						Kotharkar et al. (2023)
Percentage of buildings structurally vulnerable		●		●		●			●	●	Ohenhen & Shirzaei (2022)
Percentage of land area dedicated to Orchards and Vineyards		●							●	●	Interreg ALCOTRA - ARTACLIM (2019)
Percentage of River Stretches Aligned with Buffer Strips		●							●	●	Interreg ALCOTRA - ARTACLIM (2019)
Permanent grasslands		●							●	●	Interreg ALCOTRA - ARTACLIM (2019)
Pipe diameter				●			●				Pollino et al. (2021)
Population density in hazard prone areas	●	●	●	●	●				●	●	Ellena et al. (2023)
Presence of households in bad conditions	●	●		●		●		●			Directive—2010/31—EN - EUR-Lex. (n.d.)
Rate of Change in Water Salinity		●								●	Al-Shammiri (2002)
River infrastructures density		●					●		●	●	Interreg ALCOTRA - ARTACLIM (2019)
Sealed openings		●				●		●	●	●	Internation Finance Corporation (2024)
Sealed roof		●				●		●	●	●	Internation Finance Corporation (2024)
Settlement dispersion index		●		●					●	●	Interreg ALCOTRA - ARTACLIM (2019)
Shapes and orientation of buildings	●	●				●		●			Commonwealth of Australia and States and Territories (2019)
Skew angles				●			●				FEMA (2022)
Social isolation	●			●	●				●	●	Ellena et al. (2023)
Socioeconomic status (Nutritional status)			●		●						Few (2007)
Soil sealing in natural and urbanized context	●	●						●	●	●	Ellena et al. (2021)
Solar Heat Gain Coefficient (SHGC)	●					●		●			International Energy Conservation Code (IECC) (2001)
Solar Reflectance Index	●					●		●			LEED v4.1 Building Design and Construction Beta Guide | U.S. Green Building Council. (n.d.)

Fig. 7. (*continued*).

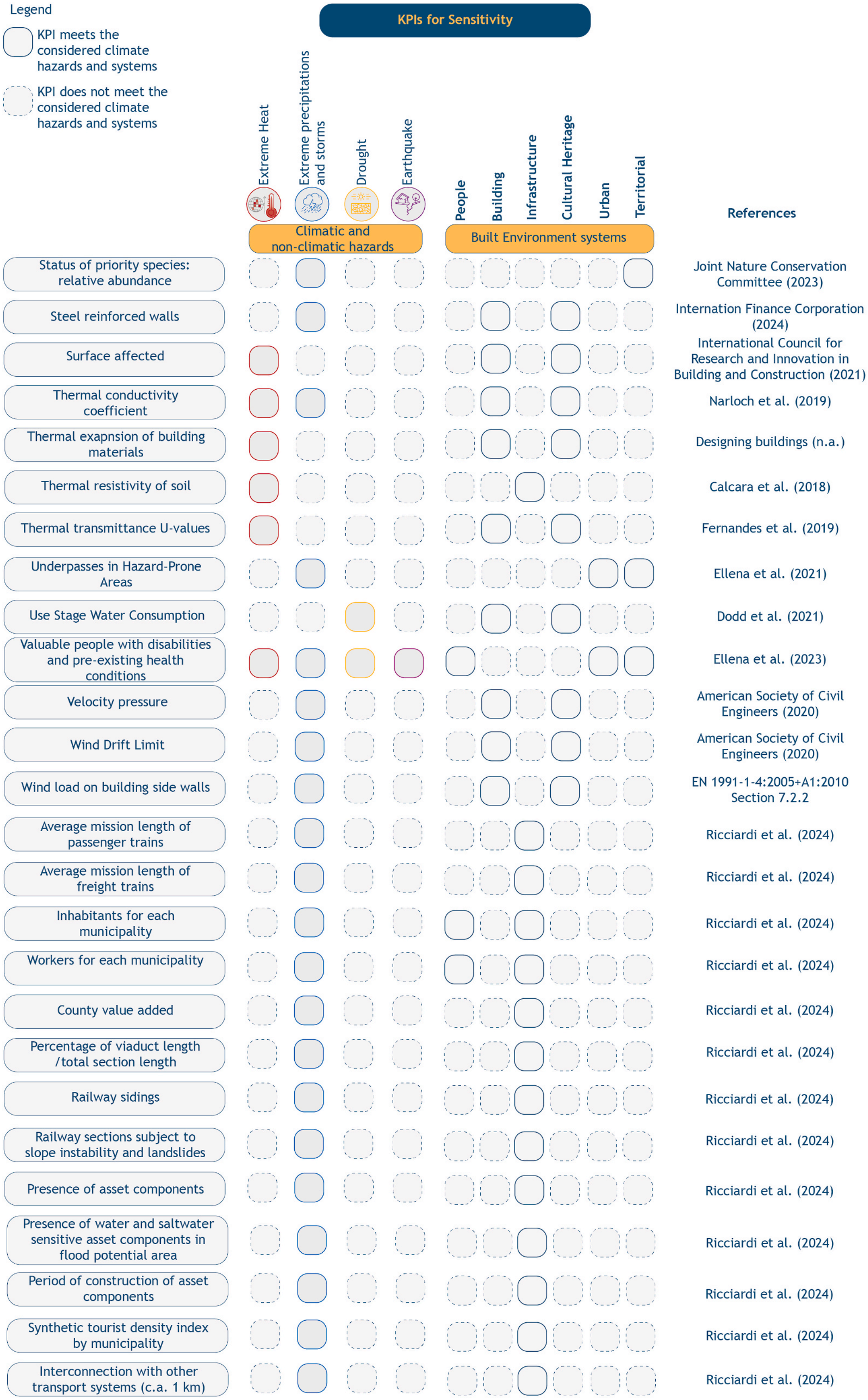


Fig. 7. (*continued*).

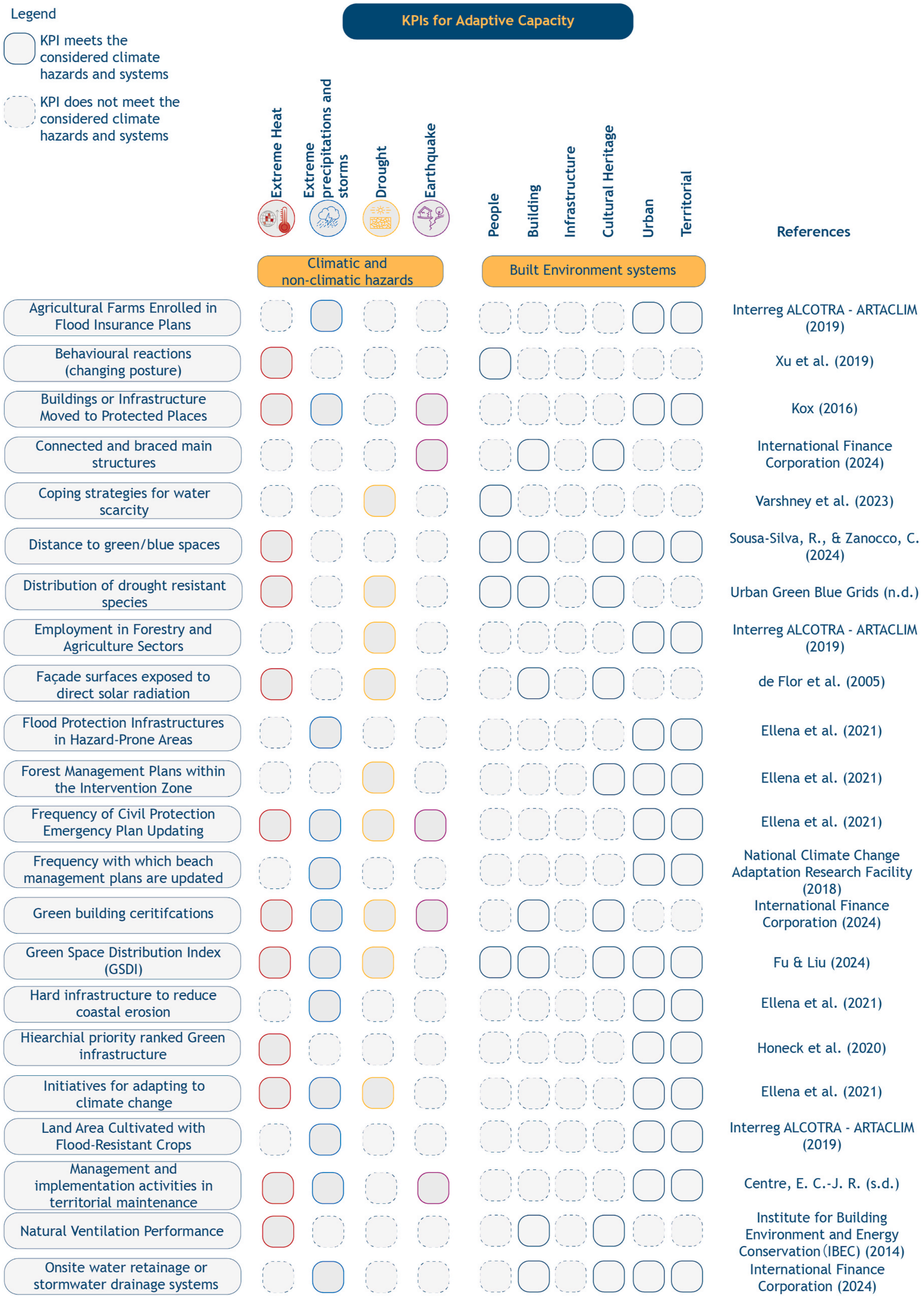

Legend
KPI meets the considered climate hazards and systems
KPI does not meet the considered climate hazards and systems
KPIs for Adaptive Capacity
Extreme Heat
Extreme precipitations and storms
Drought
Earthquake
People
Building
Infrastructure
Cultural Heritage
Urban
Territorial
References
Climatic and non-climatic hazards
Built Environment systems
Agricultural Farms Enrolled in Flood Insurance Plans
Interreg ALCOTRA - ARTACLIM (2019)
Behavioural reactions (changing posture)
Xu et al. (2019)
Buildings or Infrastructure Moved to Protected Places
Kox (2016)
Connected and braced main structures
International Finance Corporation (2024)
Coping strategies for water scarcity
Varshney et al. (2023)
Distance to green/blue spaces
Sousa-Silva, R., & Zanocco, C. (2024)
Distribution of drought resistant species
Urban Green Blue Grids (n.d.)
Employment in Forestry and Agriculture Sectors
Interreg ALCOTRA - ARTACLIM (2019)
Façade surfaces exposed to direct solar radiation
de Flor et al. (2005)
Flood Protection Infrastructures in Hazard-Prone Areas
Ellena et al. (2021)
Forest Management Plans within the Intervention Zone
Ellena et al. (2021)
Frequency of Civil Protection Emergency Plan Updating
Ellena et al. (2021)
Frequency with which beach management plans are updated
National Climate Change Adaptation Research Facility (2018)
Green building ceritifcations
International Finance Corporation (2024)
Green Space Distribution Index (GSDI)
Fu & Liu (2024)
Hard infrastructure to reduce coastal erosion
Ellena et al. (2021)
Hiearchial priority ranked Green infrastructure
Honeck et al. (2020)
Initiatives for adapting to climate change
Ellena et al. (2021)
Land Area Cultivated with Flood-Resistant Crops
Interreg ALCOTRA - ARTACLIM (2019)
Management and implementation activities in territorial maintenance
Centre, E. C.-J. R. (s.d.)
Natural Ventilation Performance
Institute for Building Environment and Energy Conservation (IBEC) (2014)
Onsite water retainage or stormwater drainage systems
International Finance Corporation (2024)

Fig. 8. Final list of KPIs for Adaptive Capacity (part 1).[108][109][110][111][112][64][113][114][115][116][68][117]
Fig. 8Final list of KPIs for Adaptive Capacity (part 2).[118][119][120][103][104][65][113][121][122][123][124]

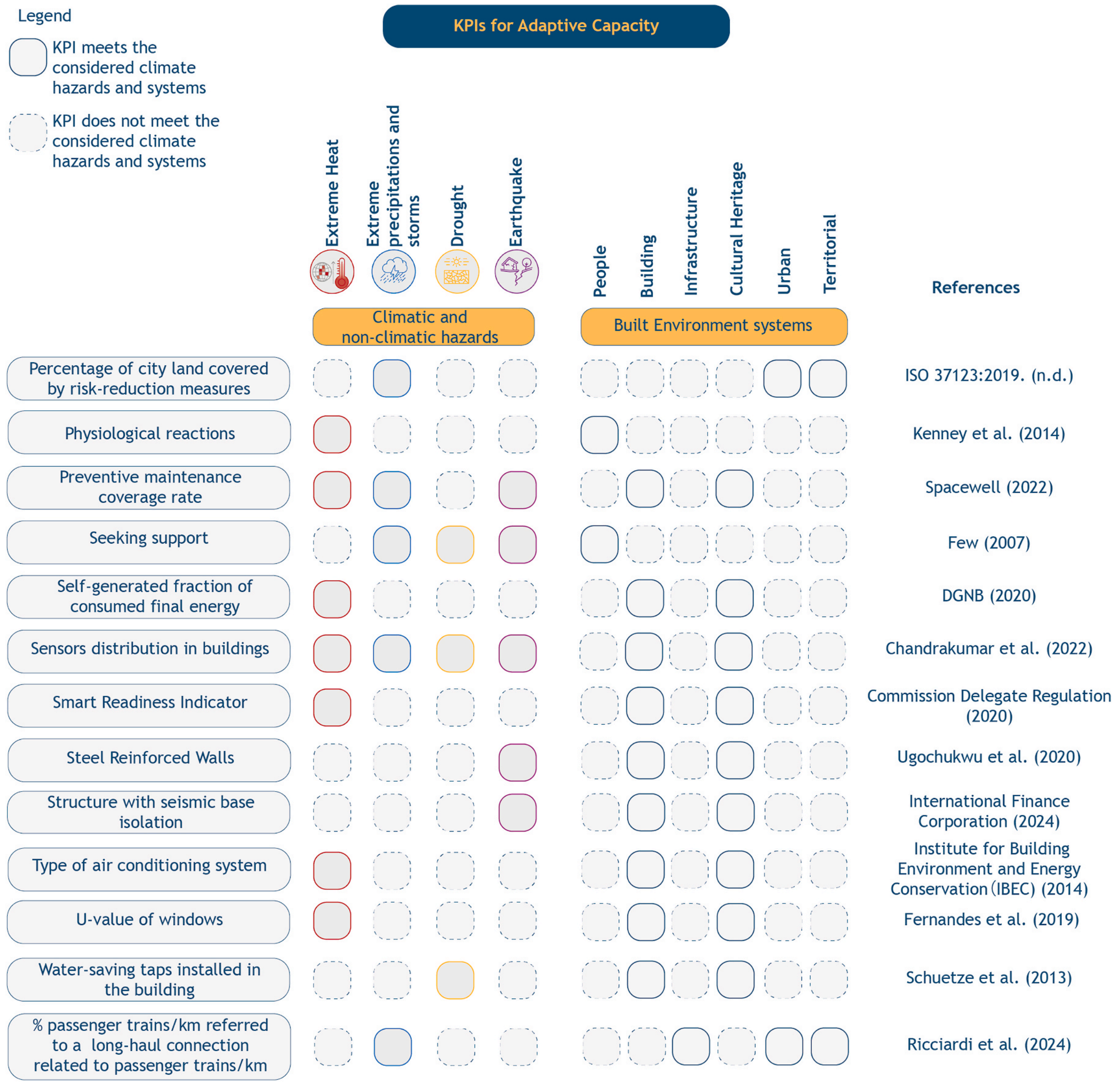


Fig. 8. (*continued*).

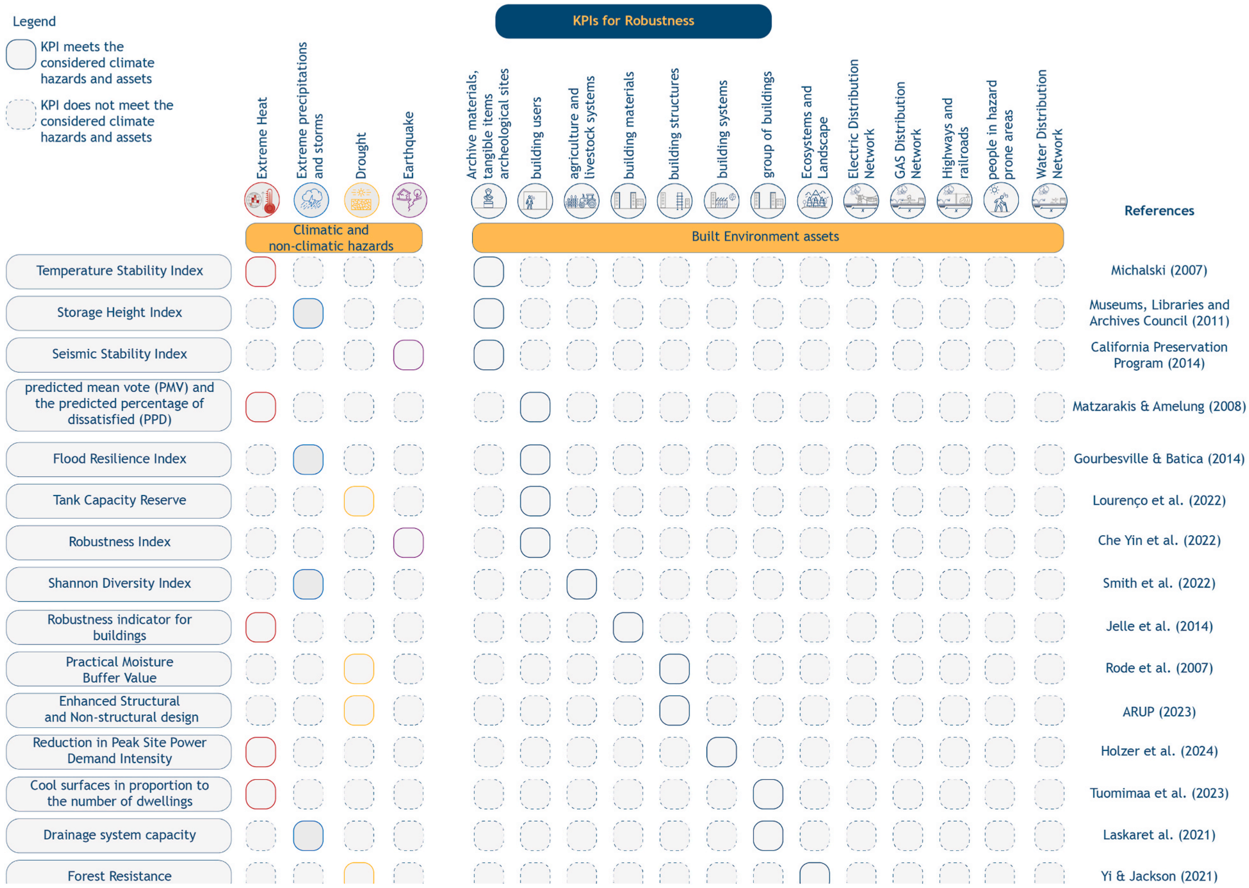
Water networks use DSS with Occurrence Probability of Consequences for robustness, while Early Warning Systems and DSS are used to measure Operational Continuity, Mean Time of Recovery, Mean time for mitigation and Structural Redundancy.

Gaps remain for archive material asset in cultural heritage systems and ecosystems, highlighting opportunities to expand digital resilience metrics, especially related to the capability of storing large databases of information for performance prediction.

3.6.2.7. Capacity of digital technologies to monitor, detection and response during extreme events indicators. This study validated seven indicators to assess the capacity of digital technologies for monitoring, detection, and response in the built environment (Fig. 15).

For monitoring, the Inventory of Assets indicator emphasizes the importance of maintaining comprehensive, up-to-date records across all selected digital technologies, ensuring effective oversight and decision-making.

Detection capacity is evaluated using indicators such as Probability of Detection, Probability of False Alarm, Accuracy, Success Ratio, and ROC Curve. These metrics provide a robust framework for assessing the reliability and precision of detection technologies in identifying hazards while minimizing false alarms. The ROC Curve graphically represents detection performance, aiding optimization and fine-tuning. For some technologies, their capacity highly depends in the monitoring sensors integrated in the monitoring system which also have their inherit detection capacity. They will also determine the maximum capability of the overall monitoring system. These sensors also have similar metric such as Sensitivity, specificity, accuracy, detection range, resolution, signal-to-noise ratio (SNR),



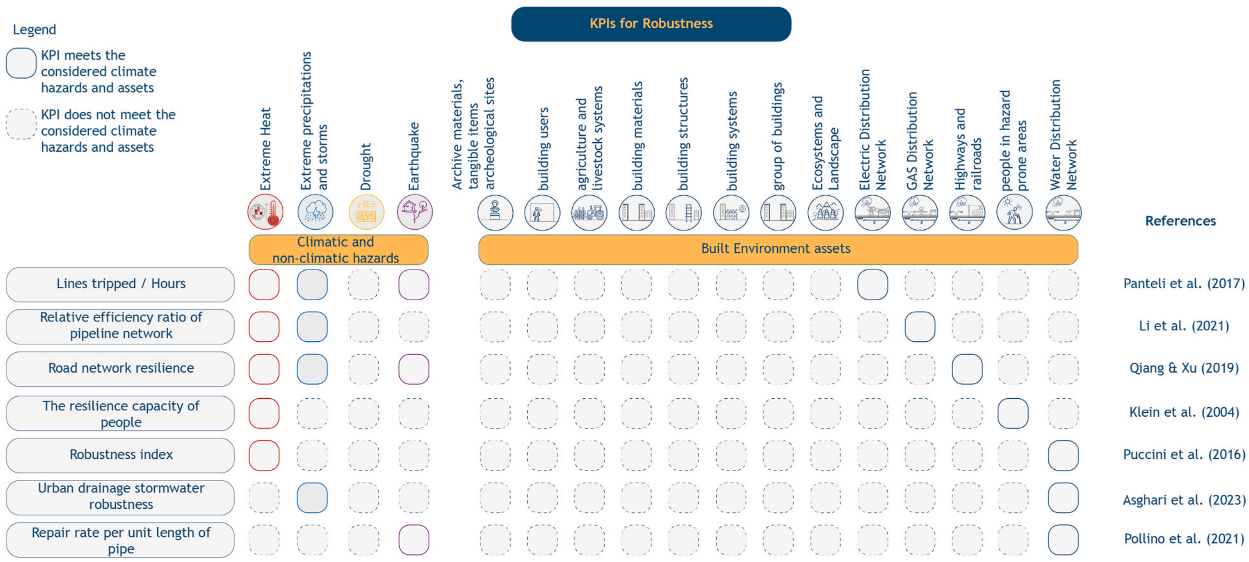


Fig. 9. Final list of KPIs for Robustness (part 1).[125][126][127][128][129][130][131][132][133][134][135][136][137][138]
Fig. 9Final list of KPIs for Robustness (part 2).[139][140][141][142][97][143][144]

false positive rate, and the capability to identify targets across different concentrations or intensities based on the application.

For response capacity, Mean Lead Time measures the average time required to act on detected hazards, reflecting the efficiency of response systems. A comprehensive asset inventory reduces unnoticed risks, while high detection accuracy and swift response times ensure timely interventions, enhancing preparedness and resilience. These indicators collectively provide a strong foundation for

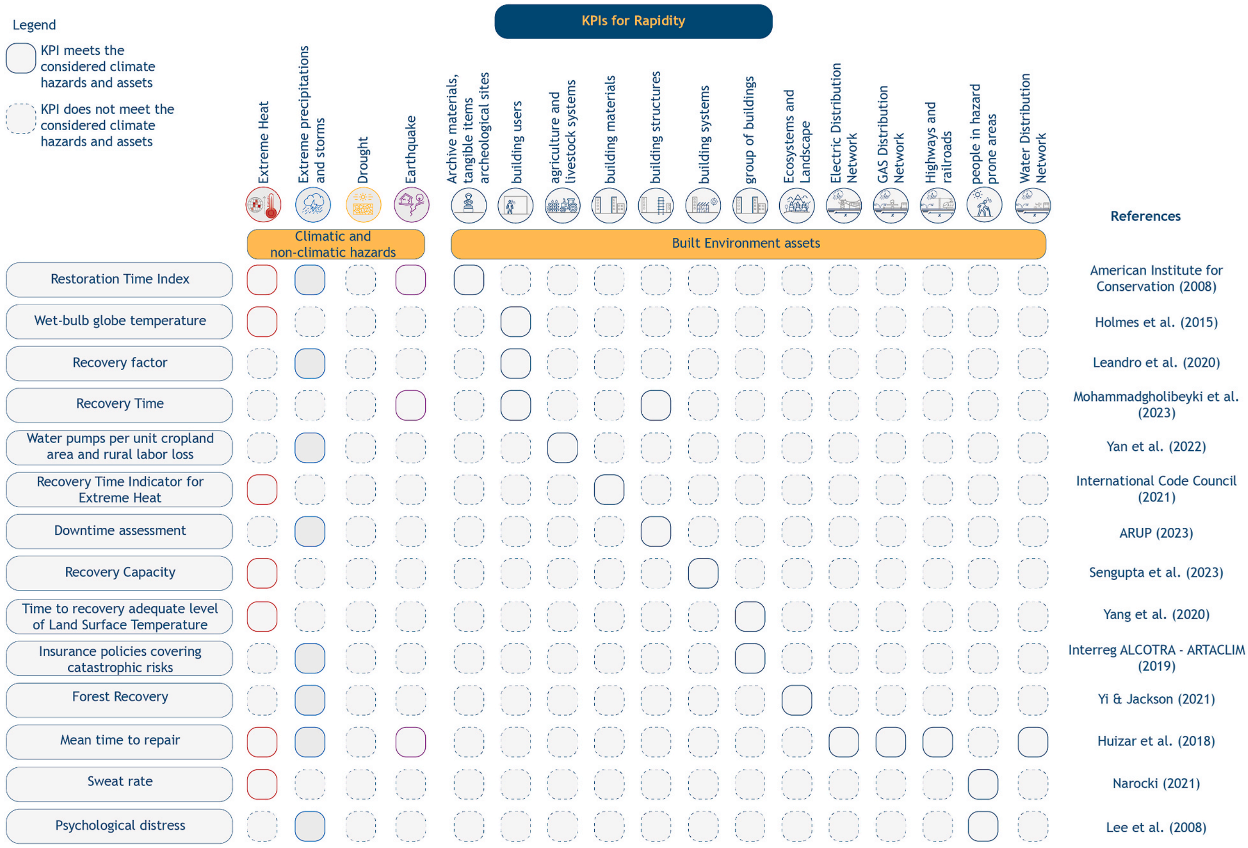


Fig. 10. Final list of KPIs for Rapidity. [145][146][147][148][149][150][151][152][153][154][155][138]

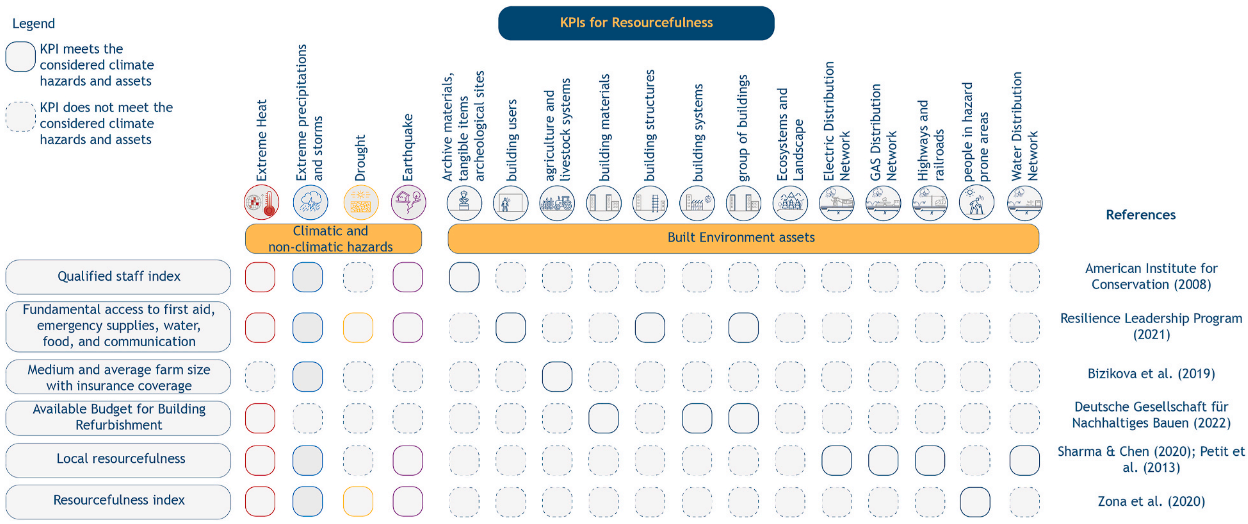


Fig. 11. Final list of KPIs for Resourcefulness.[145][156][157][158][159][160][161]

evaluating the role of digital technologies in hazard management.

3.7. Main findings, strengths, limitations, future perspectives and future developments

The built environment can play a central role in addressing climate-related and non-climatic hazards and impacts through strategic

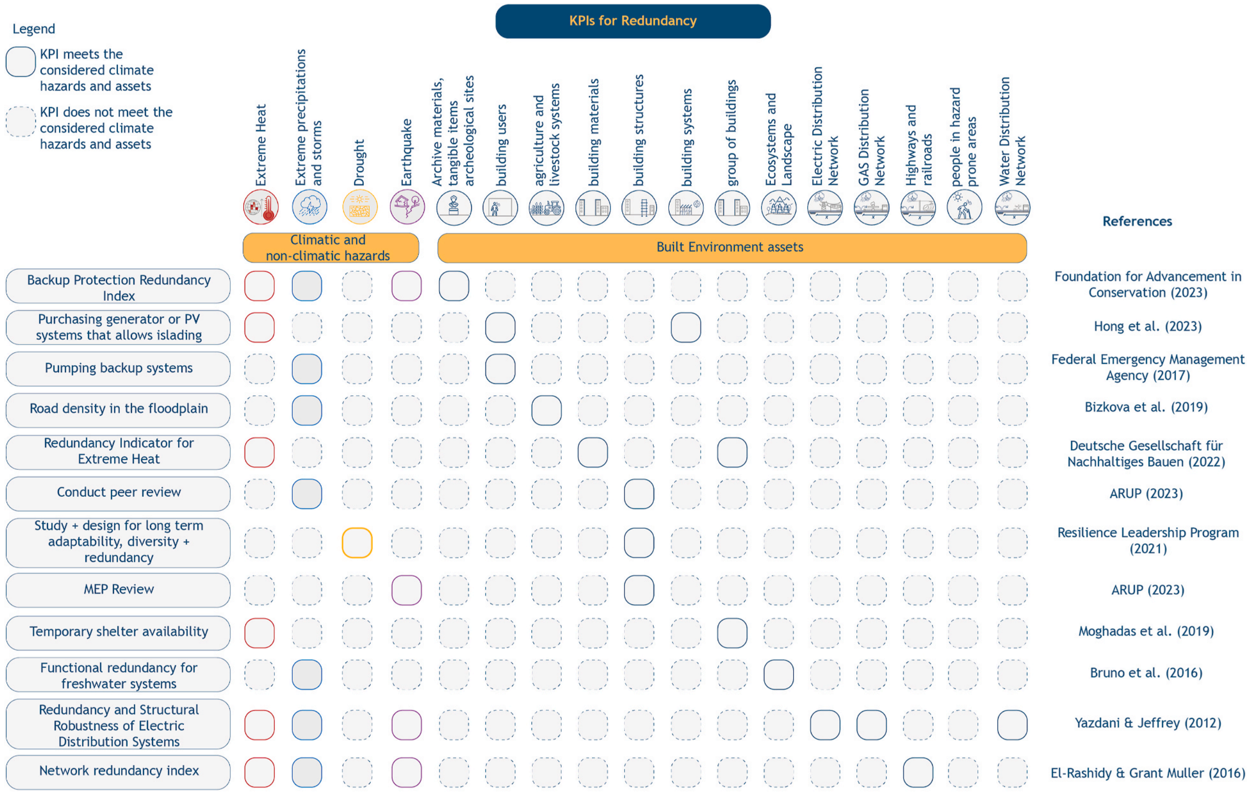


Fig. 12. Final list of KPIs for Redundancy.[156][162][157][163][164][165][166][167][159][168]

actions, solutions and projects that enhance resilience and sustainability. This research provides a significant contribution to risk and resilience assessment frameworks and resilience quantification by developing KPIs that integrate multi-dimensional analyses across various systems and scales. While traditional approaches evaluate resilience by focusing on isolated elements, the proposed KPIs provide a more comprehensive assessment by integrating multiple dimensions of resilience performance of the built environment. These indicators aim to quantify risk and resilience conditions both in the current state (AS IS) and in future possible scenarios (TO BE), enabling stakeholders to make data-driven decisions in planning, design, and management processes.

The identified KPIs (Appendix F) [55] enable built environment practitioners to conduct a holistic assessment of risk and resilience factors. Rather than focusing solely on the building system, as commonly found in literature and practice, these KPIs integrate human health and well-being, quality of life, and environmental rehabilitation with the physical characteristics of the built environment within the resilience assessment process. The study proposes a practical list of quantitative KPIs that can measure the resilience qualities of the built environment previously identified in some researches such as Castaño-Rosa et al. [15], Al-Humaiqani and Al-Ghamdi [16]. In addition, the findings are coherent with the most recent common taxonomy to assess risk and resilience of the built environment for climate and non-climate hazards impacts proposed by Arup [8].

The findings also emphasize the importance of including various systems and assets of the built environment, ensuring that buildings, infrastructure, cultural heritage, and people are all addressed in resilience frameworks. Existing studies, such as Roostaie et al. [193] and Felicioni et al. [25], highlight similar challenges in assessing resilience within urban systems but focus primarily on isolated components, such as structural vulnerabilities. In comparison, this study advances the discourse by adopting a holistic approach that addresses gaps in all the factors entail risk and resilience assessment and integrates cultural heritage considerations, often overlooked in conventional evaluations. Including cultural heritage aligns with recent recommendations by International Council on Monuments and sites [194], which stress the importance of preserving cultural assets to maintain social and historical continuity in disaster-prone areas.

In contrast to existing rating systems such as the City Resilience Index [8] and Building Resilience Index [9], the proposed framework KPIs add value by emphasizing the inclusion of multi-system resilience for addressing different climatic and non-climatic hazards. For example, Mitoulis et al. [26] and Padgett and Tapia [27] advocate for a comprehensive assessment of infrastructure systems, yet fail to fully integrate building, human and environmental dimensions into their evaluations. While traditional tools often focus on structural components, the current approach expands to include human well-being, environmental quality, and socio-economic factors, aligning with findings of the European Climate Risk Assessment [1].

The study also supports insights from Gallego-Schmid et al. [195] and Forzieri et al. [6] regarding the interconnected impacts of climate hazards on urban systems. However, unlike previous works, the proposed KPIs address both climate and non-climate hazards,

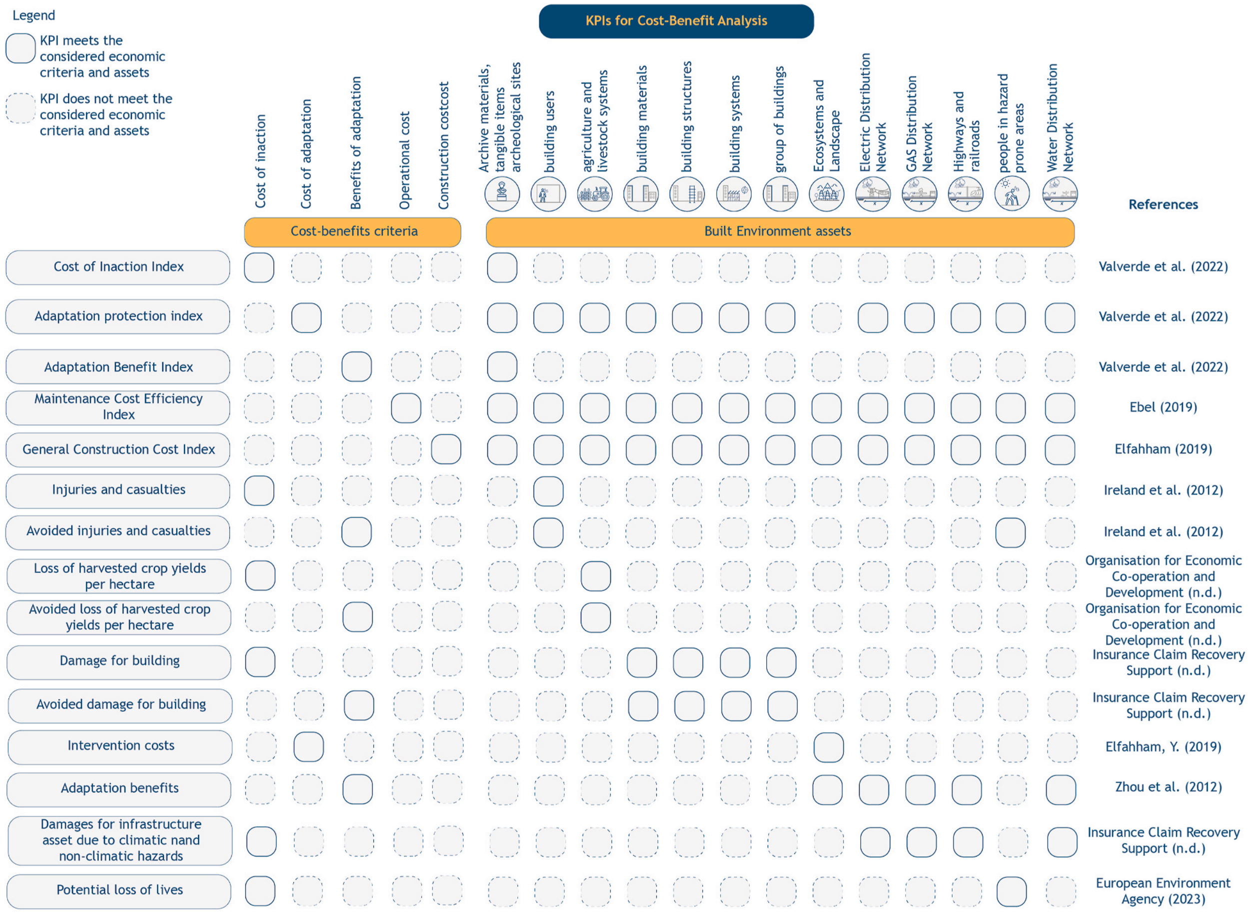


Fig. 13. Final list of KPIs for cost-benefit analysis.[169][170][171][172][173][174][175][176][177]

such as earthquakes, within a unified framework. This integration ensures that stakeholders can address the increasing frequency and intensity of hazards in a rapidly changing climate while accounting for location-specific hazards context.

When compared with works such as Crowley et al. [2] and Zebisch et al. [30], which focus on risk assessment metrics in seismic and climate contexts, the proposed KPIs advance the field by identifying additional KPIs for resilience qualities of the built environment, including robustness, redundancy, resourcefulness and rapidity. These dimensions are essential for evaluating the ability of built environment systems to recover post-event, yet remaining underrepresented in existing frameworks. Incorporating these qualities ensures that the resilience of built environment systems is assessed comprehensively, addressing the dynamic interdependencies across multiple sectors.

The strengths of the research lie in its practicality, adaptability, and ability to address real-world challenges. The quantitative KPIs can support simulation capabilities that allow stakeholders to evaluate the impacts of various policies, strategies, actions and solutions on risk and resilience scores. This feature supports decision-making processes at multiple levels, from individual buildings to urban districts and territories. By aligning with established standards for adaptation to climate change such as ISO 14091:2021[41], the KPIs offer a valuable tool for policymakers, urban planners, real estate owners, designers and infrastructure managers to prioritize policies, strategies, actions and solutions, optimize resource allocation, and enhance preparedness against climatic and non-climatic hazards.

Furthermore, the research reflects findings from Halder and Bandyopadhyay [196] regarding the importance of quantitative tools for improving climate and non-climate adaptation strategies. The inclusion of KPIs to evaluate the AS IS and TO BE conditions of built environment systems aligns with international efforts to promote adaptive and proactive resilience planning. This ensures that decision-makers have access to robust metrics for identifying vulnerabilities and monitoring the effectiveness of resilience measures over time.

Despite its contributions, the study acknowledges several limitations. First, the depth of the analysis, particularly for less-defined resilience qualities such as robustness, redundancy, rapidity, and resourcefulness. These qualities are critical for understanding the capacity of built environment systems to recover from hazards. However, the lack of specific indicators in existing scientific literature remains a challenge. Future research must prioritize developing metrics for these dimensions to ensure a more comprehensive evaluation.

Additionally, the geographical scope of the study was limited to the EU built environment context and related to the main hazards

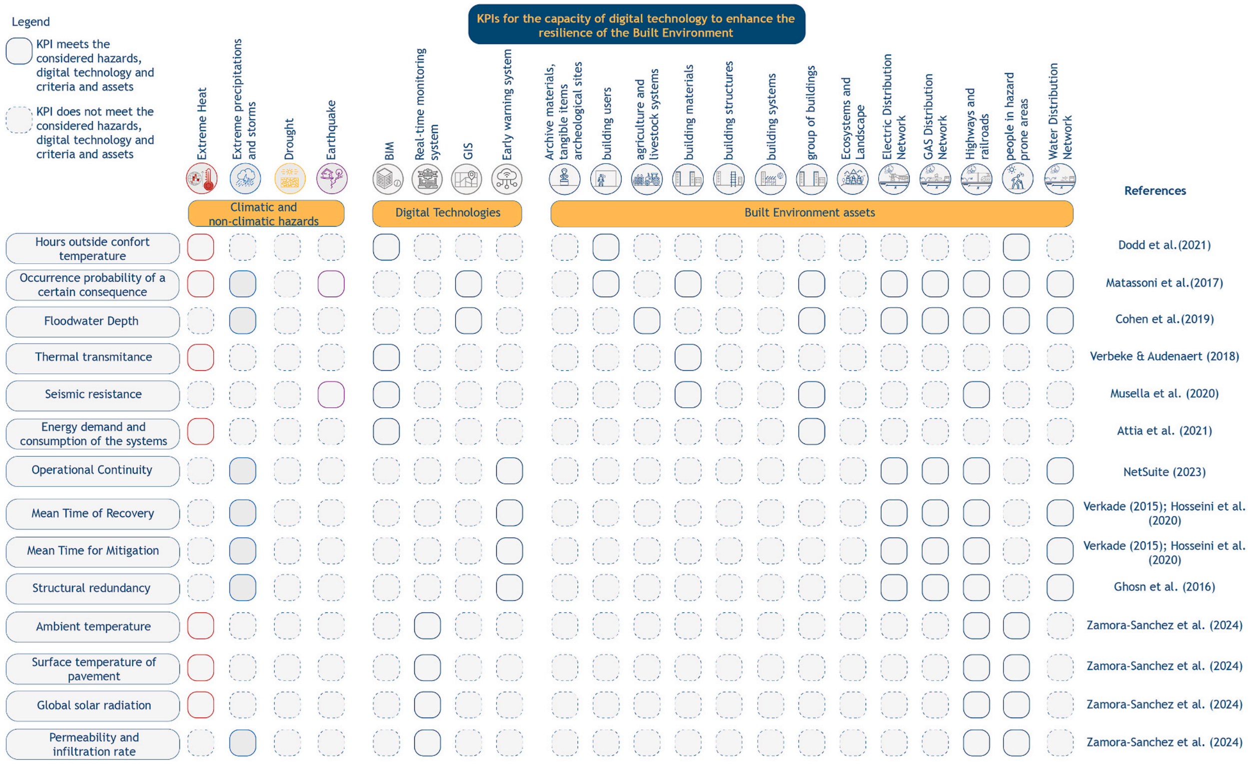


Fig. 14. Final list of KPIs for capacity of digital technologies to enhance the resilience of the Built Environment.[178][179][101][180][181][182][183][184][185][186][187]

of this region. While the KPIs provide valuable insights for stakeholders in Europe, their applicability to other regions with distinct environmental, social, and economic conditions may require further adaptation. This limitation aligns with findings from Sharifi & Khavarian-Garmsir [197], who stress the importance of location-specific resilience assessments to address diverse climate vulnerabilities. Furthermore, the study did not fully consider cascading and compounding impacts, which are increasingly relevant in resilience planning [24,198,199]. Future studies must expand the scope to include these complex interactions.

Looking ahead, further developments are essential to ensure the relevance, usability, and impact of the proposed KPIs. Integrating these indicators into practical case studies will enhance their applicability in diverse settings, enabling stakeholders to test and refine their use in real-world projects. For instance, works by Ellena et al. [4] and D'Amico et al. [34] demonstrate the value of case studies for validating risk and resilience indicators and identifying context-specific priorities. Additionally, incorporating the KPIs into existing risk and resilience assessment tools and digital platforms will optimize their usability, ensuring widespread adoption across sectors.

From a policy perspective, the adoption of the proposed KPIs has significant implications for the built environment lifecycle. By promoting actions that reduce exposure and vulnerability while enhancing resilience, the KPIs align with EU directives and sustainability goals. Policymakers can leverage these indicators to develop targeted strategies that address climate and non-climate hazards, ensuring that risk and resilience are embedded into planning, design, and construction processes. This aligns with the DNSH principle and findings from Ricciardi et al. [40] and IPCC [200], which emphasize the need for sustainable and climate-proof development.

4. Conclusions

In conclusion, this study advances the field of risk and resilience assessment by developing a novel set of quantitative KPIs that address critical gaps in existing frameworks. The main contribution of this research lies in the identification and structuring of measurable indicators that capture key risk determinants and resilience qualities across a range of climatic and non-climatic hazards, built environment systems and assets, spatial scales, and user groups. By doing so, it directly responds to the core objectives of the study: to support comprehensive, comparative, and scalable assessments of level of risk and resilience in AS IS built environment systems and assets conditions and future TO BE built environment systems and assets conditions with the integration of measures.

The findings emphasize the importance of a holistic approach that integrates human well-being, environmental sustainability, and cultural heritage — both tangible and intangible — into resilience planning.

While the framework proposed in this study offers a comprehensive and integrative structure for assessing risk and resilience across the built environment, several limitations must be acknowledged.

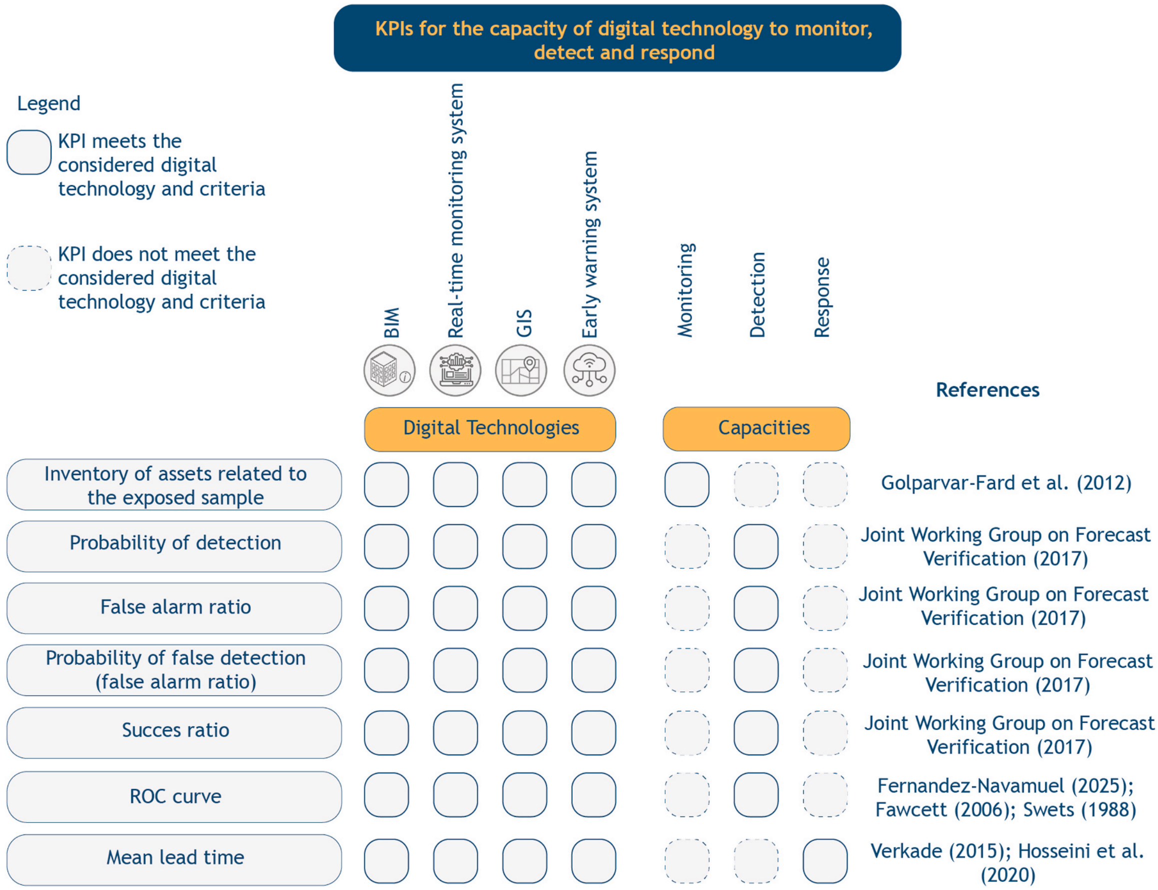


Fig. 15. Final List of KPIs for capacity of digital technologies to monitoring, detection and response.[188][189][190][191][192][186]

First, the implementation of the full set of KPIs, along with their associated resilience qualities and dimensions, may present practical challenges in small-to medium-scale planning contexts. These contexts often face resource constraints—limited technical expertise, budgetary restrictions, or insufficient data availability—which may hinder the full deployment of the framework, particularly its more advanced or data-intensive components. Additionally, the need to tailor KPIs to local conditions may require a level of contextualization that is not easily replicable without dedicated support or capacity-building.

Second, the framework relies on the availability of robust, spatially-explicit, and thematically diverse datasets, which may not be uniformly accessible across different territories. This can affect the comparability and consistency of assessments, especially when applied in regions with fragmented data infrastructures.

Third, while the current methodology has been designed to be flexible and adaptable, its fully validation has so far been conducted on selected case studies. Broader application and iterative refinement across varied geographic, socio-economic, and governance contexts will be essential to improve its transferability and scalability.

To address these limitations, future research should focus on.

- Developing simplified or modular versions of the framework for contexts with constrained capacities;
- Testing the operationalization of the indicators in real-world planning and design processes at different spatial scales, selecting only the most adequate indicator for the built environment asset corresponding to a specific case study;
- Exploring the integration of the framework into existing regulatory and policy instruments to support its institutional uptake;
- Expanding the framework with dynamic indicators (e.g., real-time monitoring, adaptive thresholds) to improve its responsiveness to changing climate and development conditions.

These directions will support the transition from a conceptual and methodological contribution to a tool that is operationally embedded in climate-resilient and regenerative planning and design practices.

Moving forward, future research should focus on addressing the limitations identified, refining the proposed metrics, and expanding their geographical application to ensure wide relevance and transferability. Ultimately, the KPIs developed in this research offer a valuable tool for stakeholders, enabling more informed decision-making to mitigate risks, strengthen adaptive capacity, and build resilient and sustainable communities.

CRediT authorship contribution statement

Guglielmo Ricciardi: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Mattia Scalas:** Writing – review & editing, Formal analysis. **Carmela Apreda:** Writing – review & editing, Formal analysis. **Alfredo Reder:** Writing – review & editing, Validation, Supervision, Methodology. **Paola Mercogliano:** Writing – review & editing, Supervision, Funding acquisition. **Hélder S. Sousa:** Writing – review & editing, Formal analysis. **Monica Santamaria-Ariza:** Writing – review & editing. **José C. Matos:** Writing – review & editing, Validation, Methodology, Conceptualization. **Antonio Di Pietro:** Writing – review & editing, Formal analysis. **Chiara Ormando:** Writing – review & editing, Formal analysis. **Erika Palmieri:** Writing – review & editing, Formal analysis. **Cristina Attanasio:** Writing – review & editing, Formal analysis. **Florencia V. De Maio:** Writing – review & editing, Formal analysis. **Saimir Osmani:** Writing – review & editing, Formal analysis. **Maria Gavrouzou:** Writing – review & editing, Formal analysis. **Diamanado Vlachogiannis:** Writing – review & editing, Formal analysis. **Athanasios Sfetsos:** Writing – review & editing, Formal analysis. **Rania Christoforou:** Writing – review & editing, Methodology, Formal analysis. **Mina Moayyedi:** Writing – review & editing, Methodology, Formal analysis. **Marcel Schweiker:** Writing – review & editing, Formal analysis. **Juan Aguilar Lopez:** Writing – review & editing, Formal analysis.

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Declaration of competing interest

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

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Appendix F. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2025.105720.

Data availability

I have shared the data link to Zenodo platform

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