Towards a People-Centred Building-Level Multi-Risk Assessment Framework for RETIME Pilot Cities: a Review of Existing Approaches

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Abstract. This paper represents an initial step towards developing a people-centred, building-level multi-risk assessment framework for future application in RETIME pilot cities. The proposed direction draws on European platforms, including the Risk Data Hub and ThinkHazard!, as well as national tools and local studies. An iterative, non-systematic literature review of selected studies published between 2012 and 2023, followed by a critical appraisal of the identified methods, indicates that many existing frameworks remain hazard-centric, operate at coarse spatial scales, and insufficiently address social vulnerability and building-specific needs. Particular attention is given to approaches that map exposure and asset values at building level, account for cascading and compound hazards, and incorporate social vulnerability through demographic characteristics, access to resources, and recovery capacity. The findings reveal persistent methodological gaps, limited data interoperability, and a shortage of high-resolution data, which constrain equitable and building-specific decision-making. Based on these findings, the paper outlines a preliminary conceptual framework connecting interoperable data flows across European, national, and local levels with building-level exposure, physical and social vulnerability, hazard interactions, and accessible visual outputs. The framework is intended to support the prioritisation of interventions, adaptation planning, and the monitoring of impacts over time, and provides a basis for subsequent operationalisation and validation in RETIME pilot cities.

Keywords: Building-level multi-risk assessment, Multi-hazard assessment, Social vulnerability, Cascading and compound hazards, Interoperable data integration, Decision-support framework.

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1 Introduction

Recent research demonstrates strong interrelationships among hazards and highlights the need to consider multi-hazard risk in disaster risk reduction. Nevertheless, many existing approaches remain hazard-focused, operate at coarse spatial scales, and pay limited attention to social vulnerability and building-level needs. The RETIME project focuses on vulnerable buildings and user groups and therefore requires a people-centred approach capable of combining information from European platforms (Risk Data Hub [1] and ThinkHazard! [2]), national tools, and local studies to produce meaningful multi-risk insights for individual buildings. Such an approach should map exposure and asset values at building level, including structural characteristics and each building's functional importance to the community. It should also account for cascading and compound hazards that can affect event likelihood and consequences. Social vulnerability—including demographic characteristics, access to resources, and recovery capacity—must be integrated to support equitable and effective recommendations. Practical implementation further requires interoperable data flows across European, national, and local levels, together with accessible visualisation tools for local authorities and building owners. Finally, a modular decision-support framework is needed to prioritise interventions, support adaptation planning, and monitor impacts over time.

1.1 Scientific literature review on multi-risk assessment methodologies

To strengthen disaster resilience, risk assessments must recognise the multi-hazard nature of disaster risk reduction [3] and the ways in which hazards can modify one another's intensity or probability or trigger additional events [4–7]. Against this background, this paper reviews the state of the art in multi-risk assessment methods and tools and examines their relevance to RETIME's objective of enhancing the resilience of vulnerable buildings and supporting a people-centred built environment. Specifically, the review considers whether existing approaches adequately address building-level exposure, physical and social vulnerability, interactions among hazards, and the integration of data across governance levels. The paper contributes beyond a summary of previous reviews in two ways: first, it evaluates the selected approaches against the specific requirements of RETIME; second, it translates the identified gaps into the components of a preliminary conceptual framework intended for future operationalisation and validation in RETIME pilot cities.

Scientific review methodology

To provide an overview of the state of the art in multi-risk assessment under changing climate conditions, a non-systematic literature search was conducted. An iterative search strategy was applied across Google Scholar™, Scopus™, and Web of Science™. The search terms listed in Table 1 were combined in different ways to identify relevant publications.

Table 1 Search terms used in the literature search.

Search Items		
architectur*	'critical infrastructure'	'social vulnerability'
assessment	Infrastructure	territorial
build*	Method	tool
'building level'	Modelling	urban*
'building vulnerability'	'multi-risk'	'urban disaster risk'
built	'multi-vulnerability'	'urban vulnerability'
'cascading risk'	Overview	'vulnerability index'
'Compound risk'	Review	-

The iterative searches identified 33 scientific journal articles. In the first screening stage, 11 publications that were not review papers were excluded, leaving 22 review articles. Review papers were retained irrespective of whether they followed a systematic, bibliometric, or narrative approach, because the purpose was to capture aggregated knowledge from different review traditions. In the second stage, the 22 reviews were assessed against two additional eligibility criteria: (i) the principal topic had to be multi-risk or multi-hazard risk assessment; and (ii) the review had to cover both hydrometeorological hazards (e.g. floods) and solid-earth and surface-process hazards (e.g. earthquakes). Six reviews met all three criteria and were therefore included in the detailed analysis. The selected reviews were subsequently appraised in terms of the assessment methodology, geographical scale, spatial resolution, principal findings, identified research gaps, and relevance to the requirements of the RETIME project. The appraisal was qualitative and expert-based.

2 Analysis of the selected literature reviews

Following the selection process, six review articles published between 2012 and 2023 were included in the detailed analysis (Table 2). Based on their review design, four were classified as non-systematic reviews [4, 6, 8, 9], while two used systematic or bibliometric approaches [10, 11]. The studies address multi-hazard risk, multi-risk, or both; however, as noted in [12], the distinction between these concepts is not always explicit. Table 2 also assesses four indicators reflecting their relevance to RETIME's objectives: building vulnerability, social vulnerability, technological hazards, and anthropogenic hazards.

Table 2 Characteristics of the six selected review articles (2012–2023).

Authors (Year)	Title	Systematic review	Building vulnerability	Social vulnerability	Technological hazards	Anthropogenic hazards

Kappes et al. (2012a)	Challenges of analysing multi-hazard risk: a review	NO	**YES**	**YES**	NO	NO
Gallina et al. (2016)	A review of multi-risk methodologies for natural hazards: Consequences and challenges for a climate change impact assessment	NO	**YES**	**YES**	NO	NO
Wang et al. (2020)	A review of the research into the relations between hazards in multi-hazard risk analysis	NO	NO	NO	**YES**	**YES**
Julià and Ferreira (2021)	From single- to multi-hazard vulnerability and risk in Historic Urban Areas: a literature review	NO	**YES**	**YES**	NO	NO
Curt (2021)	Multirisk: What trends in recent works? – A bibliometric analysis	**YES**	**YES**	NO	**YES**	NO
Owolabi and Sajjad (2023)	A global outlook on multi-hazard risk analysis: A systematic and scientometric review	**YES**	NO	NO	NO	NO

To present the current developments clearly, the six reviews are discussed in chronological order, with emphasis on the methods and findings most relevant to RETIME. Because the reviews differ in scope, terminology, and reporting approach, quantitative aggregation of their results was not considered appropriate. The individual summaries are therefore followed by a qualitative synthesis of the principal methodological gaps and their implications for the proposed RETIME framework.

Kappes et al. (2012a)

Kappes et al. (2012a) [4] reviewed the approaches to and challenges associated with multi-risk analysis at a time when the field was still emerging. Their review distinguishes three assessment types: (i) multi-hazard analysis; (ii) physical vulnerability analysis for multiple hazards; and (iii) multi-hazard risk analysis. The authors also examine interactions among hazards, summarise the terminology used in the field, and identify methodological challenges and potential solutions, building on the concepts discussed in [13]. The three assessment types are summarised below.

I) *Multi-hazard analysis methods, classified as qualitative or quantitative, are summarised in Table 3.*

Table 3 Multi-hazard analysis methods (adapted from [4]).

Type	Methodology	Scale	References
Qualitative	(Weighted) hazard interaction matrices	NUTS 3, geomorphic units of a coastal area	[14]
Quantitative	Event trees / fault trees	None given	[15]; [16]

GIS-based methodology	None given	[17]; [18]; [19]
Process modelling	Different scales	[20]; [21]; [22]; [23]; [24]; [25]; [26]; [27]
Probabilistic	None given	[28]

II) Physical vulnerability analysis methods for multiple hazards are summarised in Table 4.

Table 4 Physical vulnerability analysis methods for multiple hazards (adapted from [4]).

Type	Methodology	Scale	Pros	Cons	References
Qualitative	Indicators/indices	Building level	Many building characteristics can be considered	N/A	[29]; [30]; [31]
Semi-quantitative	Matrices	Building level	Simple; requires less data than vulnerability curves	Limited scope (few building characteristics)	[32]; [29]; [33]
Quantitative	Vulnerability curves (functions)	Building level	Applicable to widespread hazards	High data requirements Limited scope of the analysis (few building characteristics)	[29]; [34]; [33]

III) Identified multi-hazard risk analysis methods and tools are presented in Table 5.

The multi-hazard risk analysis methods and tools identified in [4] are summarised in Table 5.

Table 5 Multi-hazard risk analysis methods and tools (adapted from [4]).

Type	Method / Tool	Reference (or link)
Qualitative	Risk matrix approach: simple overlay of hazard and vulnerability information using land-use maps	[35]
Semi-quantitative	Ranking of areas by hazard and vulnerability levels and presentation in a matrix	[36]; [37];
	Index-based approaches	[38]; [35]; [39]
Quantitative	Hazus (HAZards U.S.)	[40]

RiskScape	[41]
CAPRA	[28]
Probability based approach to identify most dangerous hazard	[42]; [43], [44]; [16]
Damage curves	[34], [45]
Proprietary tools used by insurance companies, generally inaccessible because of trade-secret restrictions and licensing limitations: MRCatPMLService; RiskLink-ALM (Aggregate Loss Module); RiskLink-DLM (Detailed Loss Mode); FloodAUS FireAUS, HailAUS, QuakeAUS, CyclAUS	[46]; [47]; [48]; [49]

Tools developed for insurance applications are often inaccessible, and their source code is generally unavailable because it is proprietary [4]. This lack of transparency limits knowledge exchange and independent evaluation; the tools are therefore not discussed further.

Kappes et al. [4] also discuss approaches to visualising multi-hazard and multi-risk results [43, 50–53]. However, their review is limited to natural hazards and primarily addresses physical vulnerability. It neither incorporates social vulnerability and coping capacity nor proposes a general multi-risk assessment framework. These limitations are particularly relevant to RETIME, which requires a people-centred, building-level approach integrating both physical and social vulnerability.

Gallina et al. (2016)

Gallina et al. (2016) [8] focus on climate change and the associated methodological challenges. Following the structure adapted in [8] from [54], the identified approaches are grouped into three categories: (i) multi-hazard analysis; (ii) exposure and vulnerability analysis; and (iii) multi-hazard risk or multi-risk analysis. The review does not directly address capacity assessment or social vulnerability, which limits its direct applicability to RETIME's people-centred objectives. The methods identified in [8] are summarised in Table 6. Multi-hazard analysis examines interactions among hazards within a defined area; vulnerability analysis assesses the physical vulnerability of exposed elements; and multi-hazard risk analysis combines multi-hazard and vulnerability analyses.

Table 6 Methods used in multi-hazard, vulnerability, and multi-hazard risk analyses (adapted from [8]).

Type of assessment method	Identified methods	References

	i) Multi-hazard analysis	
Quantitative	Probabilistic analysis of historical databases	[55]
	Modelling of climate change	[56]
Semi-quantitative	Cause-effect matrix	[57]; [58]; [59]
Qualitative	None provided	None provided
	ii) Vulnerability analysis	
Quantitative	Fragility or vulnerability curves for physical vulnerability assessment	[60]; [55]; [61]; [45]
Semi-quantitative	Vulnerability indicators derived from geospatial data	[62]
Qualitative	None provided	None provided
	iii) Multi-hazard risk analysis	
Quantitative	Event tree Bayesian networks Monte Carlo simulations	[63]
Semi-quantitative	Assessment with weighted classes	[62]
Qualitative	Questionnaires (exploring hazards and vulnerability)	[35]; [39]; [64]; [65]

Wang et al. (2020)

Wang et al. (2020) [6] emphasise the complexity of interactions among risk components compared with single-hazard risk analysis, extending the observations made in [8] regarding relationships that are omitted from single-hazard approaches. They also reiterate the terminological inconsistencies identified in [66]. A key contribution of their review is the classification of multi-risk research into five categories:

I. NATECH events
II. Human-induced hazards (anthropogenic hazards)
III. Disaster chains (cascading natural hazards)
IV. Domino effects (cascading effects in industrial facilities)
V. Compound hazards

The analysis methods associated with these five categories are summarised in Table 7.

Table 7 Multi-risk analysis categories and associated methods (adapted from [6]).

Category	Identified analysis methods	References
NATECH events	Probability theory	Not provided
	Monte Carlo simulation	[67]
	Fuzzy evaluation	[68]; [69]; [70];

Anthropogenic hazards (Human-induced hazards)	Historical case-study analysis	[71]; [72]; [73]; [74]
	Physical modelling	Not provided
	Review study	[75]
Cascading hazards (Disaster chains)	Statistical analysis	[76]; [77]; [78]; [79], [6]
	Event-tree/probability-analysis model	[15]; [25]; [79]
	Bayesian network	[80]; [79]
	Complex-network analysis	[81]; [82]; [83]
	System simulation	[84]
	Cellular automata	[85]; [86]; [87]; [88]
Domino effects	Physical modelling	Not provided
	Statistical analysis	[89]; [90]; [91]
	Modelling/probit model	[92]; [93]; [94]; [95]; [96]
	Monte Carlo simulation	[97]; [98]; [99]
	Event tree	[100]
	Bayesian network	[101]
	Fuzzy evaluation	Not provided
Compound hazards	Case study-based approach	[102], [103]; [104]; [105]; [106]

Wang et al. [6] conclude that, despite extensive research efforts, no mature and generally applicable methods for multi-risk assessment had been established by 2020. Their review remains predominantly hazard-focused and gives limited attention to physical and social vulnerability. For RETIME, this reinforces the need for an integrated framework that combines hazard interactions with building-level physical and social vulnerability.

Julià and Ferreira (2021)

Focusing on historic urban areas, Julià and Ferreira (2021) [107] review approaches for the transition from single-hazard to multi-hazard vulnerability and risk assessment. They examine methods addressing three urban hazards—earthquakes, floods, and fires—and compile the vulnerability indicators applied in four earthquake methods, four flood methods, and six fire methods. Their focus on building-level vulnerability in historic urban areas is relevant to RETIME, although the reviewed approaches do not provide a general people-centred multi-risk framework.

The review presents four semi-quantitative methods for multi-hazard vulnerability assessment:

I. *Multi-Hazard Assessment of Vulnerability (MHAV),* applied to historic buildings [108]. This three-step method uses historical damage data to assess the effects of earthquakes, windstorms, floods, and lightning.

II. *Vulnerability assessment of heritage buildings and contents under catastrophic hazard* [109]. Vulnerability index based on the building susceptibility, contents, and the surroundings.
III. *Enhanced Papathoma Tsunami Vulnerability Assessment (PTVA)* for multi-vulnerability [110]. As reported in [107], PTVA uses three groups of indicators: building-specific information, characteristics of the surroundings, and human-related characteristics.
IV. *Framework for the simplified risk analysis of cultural heritage assets* [111]. The framework uses flowcharts to assess the vulnerability of cultural heritage assets or their components.

Curt (2021)

Curt (2021) [10] used a systematic search and bibliometric and textual analyses of abstracts from articles published in indexed journals between 2004 and 2020 to identify the principal topics and trends in multi-risk research. The initial search and the subsequent removal of duplicates and publications from unrelated disciplines produced 191 records. Thirteen review papers were excluded from the textual analysis because their broad thematic coverage could distort the distribution of keywords, leaving 178 abstracts for analysis. The most frequent publication outlets were the Journal of Loss Prevention in the Process Industries, Reliability Engineering & System Safety, and Natural Hazards. Although the study is useful for identifying research trends, its abstract-level analysis provides limited detail on the operational requirements of building-level multi-risk assessment.

The keyword analysis indicates that the term “domino effect(s)” appears primarily in research on industrial plant safety, “cascades” in studies of critical infrastructure, and “multi-risk” in research on natural hazards. The frequency of the themes identified by the Reinert analysis across the 178 abstracts is shown in Figure 1.

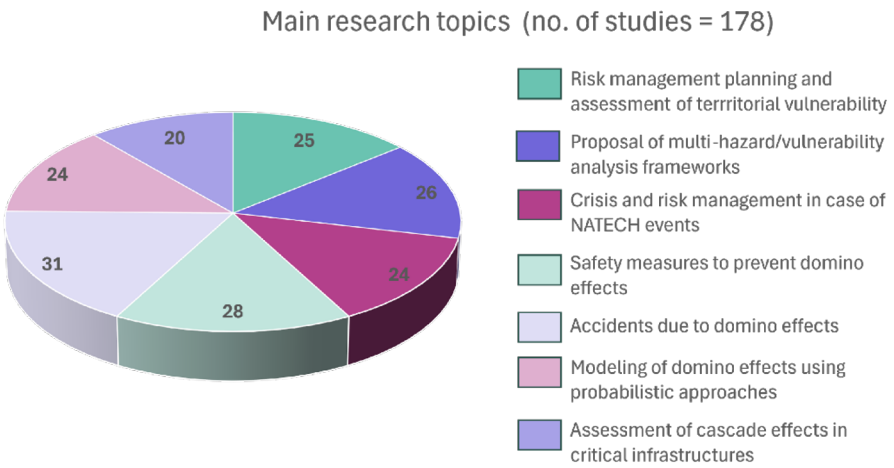


Figure 1 Main topics in multi-risk research identified using Reinert analysis (based on data reported in [10]).

Among the 178 articles analysed in [10], the most frequent research orientations were risk analysis (n = 75), knowledge production (n = 58), and decision support for risk managers and emergency planning (n = 50). Only two publications examined governance, while one addressed training; however, the target group of the training was not specified.

The most frequently studied hazards were fire (n = 23), explosions (n = 21), and flooding in combination with other hazards (n = 19). Industrial installations constituted 51.3% of the elements at risk examined, while infrastructure and buildings accounted for 21.7% [10]. Only three articles addressed socio-economic issues. The methods identified across the reviewed articles are summarised in Figure 2, based on [10].

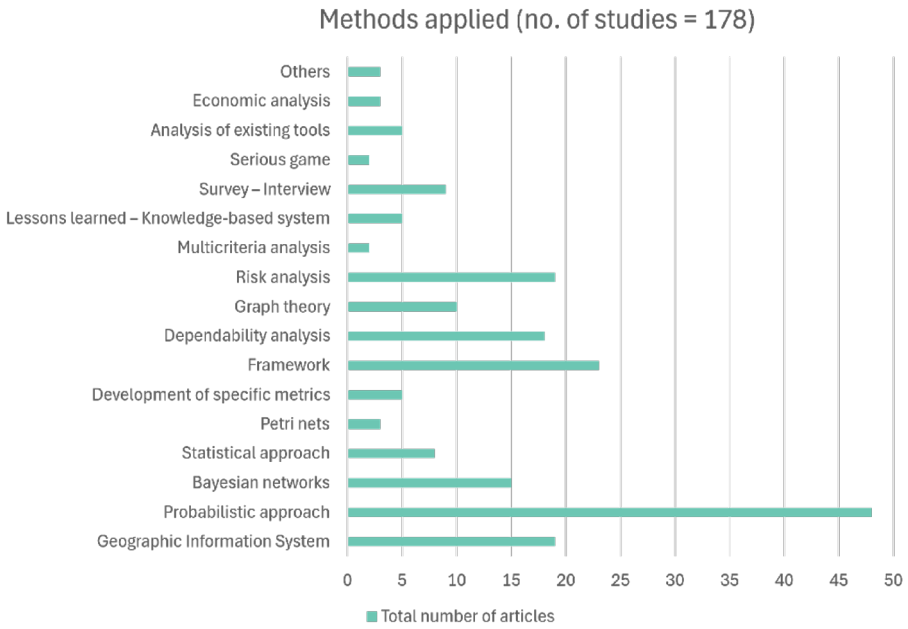


Figure 2 Methods reported in the 178 articles analysed by Curt (based on data reported in [10]).

Owolabi and Sajjad (2023)

Owolabi and Sajjad (2023) [11] conducted a systematic and scientometric review of 134 publications from 1994 to 2022 using Bibliometrix [112] and VOSviewer [113]. Their database consisted of abstracts identified through a systematic search, with no additional content-based screening. The review maps research topics, contributing authors and countries, publication trends, and frequently used keywords, but does not examine vulnerability or mitigation measures.

The most frequent keywords identified were “landslide” (104 occurrences), “risk assessment” (92), and “debris flow” (85). Thomas Glade of the University of Vienna was identified as one of the most active authors in the field. Natural Hazards published the largest number of articles on this topic (11), followed by Engineering Geology and Natural Hazards and Earth System Sciences, with six articles each. An increase in the number of publications was observed from the end of 2012 onwards. Nevertheless, because the analysis is bibliometric and based primarily on abstracts, it does not present or evaluate specific multi-hazard risk assessment methods. Consequently, it provides limited direct guidance for operationalising a building-level, people-centred framework for RETIME.

3 Synthesis of findings and preliminary RETIME framework

The six selected reviews provide complementary insights, but none offers a complete solution that meets all RETIME requirements. Kappes et al. [4], Gallina et al. [8], and Wang et al. [6] examine hazard interactions and multi-hazard risk, while Julià and Ferreira [107] provide detailed approaches to physical vulnerability at building level. Curt [10] and Owolabi and Sajjad [11] identify broader research trends but provide limited methodological detail for operational assessment. Across the six reviews, social vulnerability, coping and recovery capacity, high-resolution building data, and interoperable data exchange are either absent or only partially addressed. These combined gaps indicate that no single existing method can be directly adopted for RETIME.

To address these gaps, a preliminary modular framework is proposed for future application in RETIME pilot cities. The first module collects and harmonises hazard, exposure, and vulnerability data from European platforms, including the Risk Data Hub [1] and ThinkHazard! [2], national tools, and local datasets. The second module identifies relevant single, cascading, compound, and technological hazards and their interactions. The third module characterises building-level exposure and physical vulnerability, including structural characteristics, occupancy, asset values, and the building's functional importance to the community. The fourth module integrates social vulnerability and capacity through demographic characteristics, access to resources, coping capacity, and recovery capacity. The fifth module combines these components into transparent building-level multi-risk profiles and decision-support outputs, including maps, intervention priorities, adaptation options, and indicators for monitoring changes over time.

The framework is explicitly people-centred: results should be interpreted together with local authorities, building owners, and affected population groups and communicated through accessible visualisations. Immersive or scenario-based simulations may subsequently be developed as optional communication and training outputs once the underlying risk assessment has been operationalised. At this stage, the framework remains conceptual and requires implementation, testing, and validation in the RETIME pilot cities.

4 Conclusion

This paper used an iterative, non-systematic literature review and qualitative expert appraisal to examine the suitability of existing multi-risk approaches for RETIME. Of the 33 scientific journal articles identified, 22 were review papers and six met all eligibility criteria for detailed analysis. The selected studies provide useful components for examining hazard interactions, physical vulnerability, research trends, and risk communication. However, none combines building-level resolution, physical and social

vulnerability, cascading and compound hazards, interoperable data, and end-user-oriented decision support within a single operational approach.

The principal contribution of this paper is the translation of the identified methodological gaps into a preliminary modular framework linking data harmonisation, hazard interactions, building-level exposure and physical vulnerability, social vulnerability and capacity, and decision-support outputs. The findings support prioritising interoperable data exchange, transparent treatment of uncertainty, stakeholder-specific visualisation, and participatory interpretation of results. Multi-risk maps, indices, and scenario-based tools may support risk communication, provided that their assumptions and limitations remain transparent to decision-makers.

Immersive simulations are proposed only as a potential communication and training extension of the framework, rather than as an assessment method validated by this review. Once the underlying data and models have been operationalised, such simulations could allow stakeholders to explore cascading-hazard scenarios and the distributional consequences of different adaptation options. Future work will operationalise and validate the framework in RETIME pilot cities, assess data availability and spatial resolution, and evaluate its usefulness with local authorities, building owners, and vulnerable population groups. Because the present review was non-systematic and the appraisal was qualitative and expert-based, the findings should be regarded as a structured foundation for further development rather than a definitive comparison of all existing methods.

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