Ref. Ares(2024)7764018 - 31/10/2024

D1.1. – Report on urban vulnerability and risk assessment (multi-risk resilience) methodologies and tools

Deliverable summary

Deliverable number	D1.1
Deliverable title	RETIME Deliverable D1.1 - Report on urban vulnerability and risk assessment (multi-risk resilience) methodologies and tools – 30-October-2024-version-1.0-Final
Deliverable related Work Package	WP1
Deliverable type	Report
Dissemination level	Public
Contractual date of delivery	M6 – October 2024
Actual date of delivery	30.October.2024
Deliverable authors	Katarína Hollá (UNIZA), Ľuboš Buzna (UNIZA), Jozef Ristvej (UNIZA), Samuel Kočkár (UNIZA), Steffen Neuner (THK), Christopher Munschauer (THK), Stefania Stellacci (ISCTE), Manuel Ribeiro (ISCTE), José Leandro Barros (ISCTE), Ricardo Pontes Resende (ISCTE), Joy Ommer (KAJO), Milan Kalaš (KAJO), Milica Aleksić (KAJO), Xavier Romão (UPORTO)
Leading partner responsible for the deliverable	UNIZA
Deliverable reviewers	Guilherme Tassari (TUU), Mari Einmann (IBS)
Deliverable version	1.0
Deliverable total number of pages	154
Project grant number	101147113
Project acronym	RETIME
Project title	Urban Adaption and Alert Solutions for a TIMEly (re)Action
Funding scheme	HORIZON Action Grant Budget-Based
Project duration	May 2024 – April 2028 (48 months)
Call	Efficient, sustainable and inclusive energy use HORIZON-CL5-2023-D4-02
Topic	HORIZON-CL5-2023-D4-02-02
Type of action	HORIZON Innovation Action
Start date of the project	1 May 2024
Project Coordinator	ISTAR-ISCTE – University Institute of Lisbon (RETIME@ISCTE-IUL.PT)

Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

Executive summary

The report D1.1 outlines a framework for urban risk assessment, focusing on identification and categorisation of the vulnerabilities of current and future buildings and infrastructure in urban environments exposed to human-induced and climate-change related impacts. It establishes the primary semantic and critical project framework, providing a consistent basis for the RETIME consortium and beyond. Additionally, it includes updated overview of methodologies, e-tools, and data sources currently relevant to RETIME project, ultimately facilitating the preliminary development of exploitable solutions.

Although limitations and caveats are detailed in D1.1, the ultimate goal is to increase awareness of multi-risk approaches available for future operational developments.

The intended audience of this deliverable includes all RETIME Beneficiaries, current and future policy and decision-makers, building users, owners, and managers in RETIME pilot areas. Additionally, D1.1 offers valuable insights for environmental practitioners and members of EU sister projects focused on adaptive mitigation measures for human-induced and climate-related risks. The analysis of data sources and software tools can be also useful for IT developers and private service providers involved in mitigation and anticipatory actions.

History of changes

Title of the document	Version number	Changes	Who	Date
RETIME Deliverable D1.1 - Report on urban vulnerability and risk assessment (multi-risk resilience) methodologies and tools- 27.May.2024 - version-0.1	0.1	Initial version	Ľuboš Buzna (UNIZA), Katarína Hollá (UNIZA)	27.May.2024
RETIME Deliverable D1.1 - Report on urban vulnerability and risk assessment (multi-risk resilience) methodologies and tools- 4.June. 2024 - version-0.2	0.2	Content refinement	Ľuboš Buzna (UNIZA), Katarína Hollá (UNIZA), Steffen Neuner (THK), Christopher Munschauer (THK), Ricardo Resende (ISCTE)	04.June.2024
RETIME Deliverable D1.1 - Report on urban vulnerability and risk assessment (multi-risk resilience) methodologies and tools- 10.July. 2024 - version-0.3	0.3	Added information	Katarína Hollá (UNIZA), Ľuboš Buzna (UNIZA), Jozef Ristvej (UNIZA), Samuel Kočkár (UNIZA), Joy Ommer (KAJO), Stefania Stellacci (ISCTE)	10.July.2024
RETIME Deliverable D1.1 - Report on urban vulnerability and risk assessment (multi-risk resilience) methodologies and tools- 22.July. 2024 - version-0.4	0.4	Added information	Katarína Hollá (UNIZA), Samuel Kočkár (UNIZA), Ľuboš Buzna (UNIZA), Joy Ommer (KAJO), Xavier Romão (UPORTO), Stefania Stellacci (ISCTE)	22.July.2024
RETIME Deliverable D1.1 – Report on urban vulnerability and risk assessment (multi-risk resilience) methodologies	0.5	Formatting text	Ľuboš Buzna (UNIZA), Steffen Neuner (THK), Christopher Munschauer (THK) Samuel Kočkár (UNIZA),	05.August. 2024

and tools-05.August. 2024 - version-0.5			Joy Ommer (KAJO), Milica Aleksić (KAJO), Stefania Stellacci (ISCTE)	
RETIME Deliverable D1.1 - Report on urban vulnerability and risk assessment (multi-risk resilience) methodologies and tools -12. August. 2024- version-0.6	0.6	Improved presentation and added information	Katarína Hollá (UNIZA), Samuel Kočkár (UNIZA), Ľuboš Buzna (UNIZA), Joy Ommer (KAJO), Xavier Romão (UPORTO), Manuel Ribeiro (ISCTE), Leandro Barros (ISCTE), Stefania Stellacci (ISCTE)	12. August. 2024
RETIME Deliverable D1.1 - Report on urban vulnerability and risk assessment (multi-risk resilience) methodologies and tools -27. September. 2024- version-0.7	0.7	Improved presentation and added information	Katarína Hollá (UNIZA) Samuel Kočkár (UNIZA), Joy Ommer (KAJO), Milan Kalaš (KAJO), Stefania Stellacci (ISCTE), Steffen Neuner (THK), Leandro Barros (ISCTE), Leonor Domingos (ISCTE), Xavier Romão (UPORTO)	27. September. 2024
RETIME Deliverable D1.1 - Report on urban vulnerability and risk assessment (multi-risk resilience) methodologies and tools -10. October. 2024- version-0.8	0.8	Improved presentation and added information	Katarína Hollá (UNIZA), Ľuboš Buzna (UNIZA), Samuel Kočkár (UNIZA), Adryana Kachalavová (UNIZA), Joy Ommer (KAJO), Milan Kalaš (KAJO), Stefania Stellacci (ISCTE), Steffen Neuner (THK), Margarida Revés (CML)	10. October. 2024
RETIME Deliverable D1.1 - Report on urban vulnerability and risk assessment (multi-risk resilience) methodologies	1.0	Included feedback received from internal peer review	Katarína Hollá (UNIZA), Ľuboš Buzna (UNIZA), Samuel Kočkár (UNIZA), Adryana Kachalavová (UNIZA), Joy Ommer	30. October. 2024

and tools -30. October. 2024- -version-1.0			(KAJO), Milan Kalaš (KAJO), Stefania Stellacci (ISCTE), Steffen Neuner (THK), Margarida Revés (CML)	

Statement for open documents & Copyrights

This document is property of the RETIME consortium.

Table of Contents

Executive summary 2
History of changes 3
Table of Contents 6
List of Tables 8
List of Figures 10
List of acronyms and abbreviations 11
1. Introduction 14
1.1. Structure of this report and interdependences with RETIME activities 16
2. Core concepts related to multi-risk assessment 17
3. RETIME semantic framework 21
3.1. Purpose of RETIME glossary 21
3.2. Existing Glossaries and RETIME Glossary Development 21
4. Backbone of social vulnerability in urban environments: core studies and methods 26
4.1. Understanding Social Vulnerabilities in Disasters: Importance and Challenges 27
4.2. Overview of social vulnerability assessment approaches and methods 28
4.3. Social vulnerability model for RETIME 29
4.4. Econometric modelling 33
5. Scientific literature review on multi-risk assessment methodologies 35
5.1. Scientific review methodology 35
5.2. A brief analysis of literature review 36
6. Overview of existing datasets and e-tools relevant to RETIME 47
6.1. Available datasets and tools at EU and global scale 47
6.2. Available local datasets and e-tools related to RETIME pilot sites 50
6.2.1. Required information for Hazard Mapping at neighborhood and building scale 50
6.2.2. Data portals and e-tools related to RETIME pilot sites 51
6.3. Building Information Modelling for multi-risk assessment 61
6.4. Virtual Reality scenarios and potential use in multi-risk assessment activities 64

7. Multi-dimensional analysis of vulnerability, risk scenarios, and hazard characteristics in RETIME pilot sites 67
7.1. Geographical analysis of RETIME pilot sites 67
7.1.1. Lisbon pilot area 67
7.1.2. Žilina pilot area 69
7.1.3. Tartu pilot area 70
7.2. Preliminary multi-risk and vulnerability assessment in RETIME pilot sites 72
7.3. Pilot site-specific sources for vulnerability and multi-risk assessment 75
7.3.1. Lisbon pilot area 75
7.3.2. Žilina pilot area 77
7.3.3. Tartu pilot area 78
8. Critical analysis of Vulnerability and Urban Risk and Assessment Methodologies and Recommendations 80
8.1. Critical analysis of vulnerability and multi-risk and assessment methodologies: Literature review perspective 80
8.1.1. Challenges in multi-risk assessments 80
8.1.2. Pathways to address multi-risk assessment challenges 82
8.2. Critical analysis of vulnerability and multi-risk assessment data source and e-tools 83
9. Recommendations for urban risk assessment framework 86
10. Concluding remarks 88
List of References 89
Annex A: RETIME glossary 106
Annex B: Overview of review papers on vulnerability and risks assessment methodologies .. 116
Annex C: Description of potential OA datasets and e-tools suitable for RETIME 138

List of Tables

Table 1. Variables related to 'Criticality assessment' and 'Support capacity assessment'. 31
Table 2. Search terms for scientific review. 35
Table 3. Characterisation of selected scientific reviews (2012-2023). 36
Table 4. Multi-hazard analysis methods identified by (Kappes, Keiler, et al., 2012a). 37
Table 5. Physical vulnerability analysis for multiple hazards (Kappes, Keiler, et al., 2012a). ... 38
Table 6. Multi-hazard risk analysis methods and tools (Kappes, Keiler, et al., 2012a). 38
Table 7. Methods applied for multi-hazard, vulnerability, and multi-hazard risk analyses as identified by (Gallina et al., 2016) 40
Table 8. Multi-hazard risk assessment methods as identified by Wang et al (2020). 41
Table 9. Overview of available data sources and tools applicable for implementing selected RETIME tasks. 47
Table 10. Data portals for Lisbon Metropolitan Area pilot site. 51
Table 11. Data portal for Žilina pilot site. 53
Table 12. E-tools for Žilina pilot site. 56
Table 13. E-tools for the Lisbon pilot site. 57
Table 14. Data Portal for the Tartu pilot site. 58
Table 15. BIM analysis for each building component and relevance for RETIME. 63
Table 16. RETIME glossary. 106
Table 17. Overview of publications on vulnerability and risk assessment methodologies..... 117
Table 18. Copernicus Land Monitoring Service. 138
Table 19. Risk Data Hub. 138
Table 20. ESPON Database. 138
Table 21. River Flood Hazard Maps Europe dataset. 139
Table 22. Extreme precipitation risk dataset. 140
Table 23. Earthquake Hazard dataset. 141
Table 24. European Forest Fire Risk dataset. 141
Table 25. Landslide Susceptibility map dataset. 142
Table 26. Coastal risk dataset. 142
Table 27. Thermal comfort dataset. 143
Table 28. Air quality dataset. 143
Table 29. Land cover, land use, and infrastructure dataset. 144
Table 30. Health sites dataset. 144
Table 31. GISCO dataset. 144
Table 32. European Drought Observatory. 145

Table 33. European Forest Fire Information System. 145
Table 34. European Flood Forecasting System. 146
Table 35. MeteoAlarm – Early Warnings for Europe. 146
Table 36. Global Disaster Alert and Coordination System. 146
Table 37. CLIMA EXTREMO. 147
Table 38. UrbClim (SImulator). 147
Table 39. Risk Data Hub – Data viewer. 148
Table 40. Think Hazard! 149
Table 41. INFORM Index. 149
Table 42. RiskScape – Multi-hazard risk modelling. 150
Table 43. CLIMANDA – Probabilistic Risk Analysis. 151
Table 44. Probabilistic Risk Assessment Platform. 152
Table 45. Open Quake – Seismic risk assessment. 153
Table 46. Heat Action Platform. 153
Table 47. Climate Resilient Cities ToolBox. 154

List of Figures

Figure 1. Structure of this report and interdependences with other RETIME activities. 15
Figure 2. Multi-risk framework, based on EC Joint Research Centre (2017) and Gill et al. (2022). 18
Figure 3. Phases to build the RETIME glossary. 22
Figure 4. Selected RETIME essential terms. 25
Figure 5. Comparison of the components of climate change vulnerability (AR4) and climate risk (AR5) adapted from GIZ and EURAC (2017). 27
Figure 6. Social Vulnerability Assessment method adapted by Tavares et al. (2018). 30
Figure 7. Main research topics in multi-risk identified in a Reinert analysis performed by Curt (2021). 44
Figure 8. Methods applied in the study undertaken by Curt (2021). 45
Figure 9. BIM level of model definition (LOMD). 62
Figure 10. Lisbon Metropolitan Area (NUTS-3 level; source: Risk Data Hub, 2024). 68
Figure 11. City of Lisbon (source: ThinkHazard!, 2024). 68
Figure 12. The district Bairro da Boavista in Lisbon and surrounding districts (source: OpenStreetMap, 2024). 68
Figure 13. Žilina region (NUTS-3 level; source: Risk Data Hub, 2024). 69
Figure 14. Žilina district (source: ThinkHazard!, 2024). 70
Figure 15. Map showing the geographical area and building of the senior house Straník (source: Albert tool, 2024). 70
Figure 16. Tartu - Lõuna-Eesti region (NUTS-3 level; source: Risk Data Hub). 71
Figure 17. The city of Tartu (source: ThinkHazard! platform). 71
Figure 18. The Tartu city centre and surrounding areas (source: OpenStreetMap, 2024). 72
Figure 19. Multi-dimensional risk in Lisbon, Žilina, and Tartu adopted from the ThinkHazard! (Hazard Likelihood) and the Risk Data Hub (Exposure and Vulnerability, 2024). 74

List of acronyms and abbreviations

AEC	Architecture Engineering and Construction
API	Application Programming Interface
AR	Augmented Reality
AR4	IPCC fourth Assessment Report
AR5	IPCC fifth Assessment Report
AR6	IPCC sixth Assessment Report
ATP	Adaption Tipping Point
BIM	Building Information Modelling
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
CA	Consortium Agreement
CAPRA	Central American Probabilistic Risk Assessment
CML	Câmara Municipal de Lisboa (Lisbon Town Council)
CRI	Community resilience index
DRR	Disaster Risk Reduction
EbA	Ecosystem-based Adaptation
EFEHR	European Facilities for Earthquake Hazard and Risk
EFFIS	European Forest Fire Information System
ESDAC	European Soil Data Centre
ESPON	European Grouping on Territorial Cooperation
EC	European Commission
EU	European Union
EURAC	European Academy of Bolzano
ETICS	External Thermal Insulation Composite System
FCT	Foundation for Science and Technology
FUA	Functional Urban Area
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GIS	Geographic Information System
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (German Society for International Cooperation)
GA	Grant Agreement
Hazus	HAZards U.S.
HIP	Hazard Information Profile

HVAC	Heating, ventilation, and air conditioning
INE	Instituto Nacional de Estatística (National Institute of Statistics)
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JRC	(European Commission's) Joint Research Centre
LAU	Local Administrative Unit
LCA	Life Cycle Analysis
LMA	Lisbon Metropolitan Area
LOD	(BIM) Level of Development
LOIN	(BIM) Level of Information Need
LOMD	(BIM) Level of Model Definition
MHVA	Multi-Hazard Assessment of Vulnerability (applied to historic buildings)
NATECH	Natural Hazards Triggering Technological Disasters
NUTS	Nomenclature of Territorial Units for Statistics
OA	Open Access
OSM	OpenStreetMap
PCA	Principal Component Analysis
PTVA	Papathoma Tsunami Vulnerability Assessment
RCP	Representative Concentration Pathways
RIA	Research and Innovation Action
RMS	Risk Management Solutions
SD	Standard Deviation
SFDRR	(UN's) Sendai Framework for Disaster Risk Reduction
SHEEC	The Share European Earthquake Catalogue
SME	Small and Medium Enterprises
SoA	State of the Art
SoVI	Social Vulnerability Index
TC	Technological Change
tCO2	total carbon dioxide
UAE	United Arab Emirates
UN	United Nations
UNDRR	United Nations Office for Disaster Risk Reduction
UNESCO	United Nations Educational, Scientific and Cultural Organization
UN-ISDR	United Nations - International Strategy for Disaster Reduction
VAT	Value Added Tax

VR	Virtual Reality
WHO	World Health Organization
WMO	World Meteorological Organisation

1. Introduction

This report sets the theoretical and methodological background for the RETIME project by providing an overview of key approaches, methodologies, and tools used for multi-risk/multi-hazard resilience assessment in urban environments, including a preliminary risk assessment of the RETIME pilot areas in Portugal, Slovakia, and Estonia. This consortium brings together an interdisciplinary team, so this report introduces key concepts to foster a shared understanding among researchers and members with diverse backgrounds and expertise. To ensure consistency, a unified semantic framework was established.

The establishment of a semantic framework is complex, as discussed in literature (e.g., Murray et al., 2022) and in several European Union (EU)-funded projects (e.g., MYRIAD_EU, BuildERS).

Additionally, this report provides a list of e-tools and data sources that have the potential to be employed or impact the project activities. Further, selected e-tools are applied to assess hazards, vulnerabilities, and risks within the RETIME pilot areas. These analyses are completed by similar kind of information collected from public sources and obtained by employing e-tools that are specific or customised to the pilot sites. This report concludes with a critical analysis of the available methodologies, e-tools, and data sources, along with a reflection on their applicability to project activities.

This report provides an overview of multi-risk assessment methodologies, specifically focused on vulnerable groups and the built environment where they live, work or are attached culturally. The development of multi-risk assessment methodologies is a well-established and very relevant research topic, as proven by almost twenty review publications (2012-2023). For this reason, it was decided to provide an overview of multi-risk methodologies based on the analysis of review papers, rather than conducting another literature review of existing multi-risk assessment studies.

This document is not intended to be exhaustive but is designed to further provide specific and practical guidance for implementing adaptation measures tailored to the physical and socio-economic characteristics of the RETIME pilot sites. The assessment and management of multi-risks are interpreted, discussed, and will be continuously updated across diverse areas that includes legal, academics, and professional practice. Figure 1 illustrates the content structure of this report and the interdependences with other RETIME activities that are detailed in *Section 1.1*.

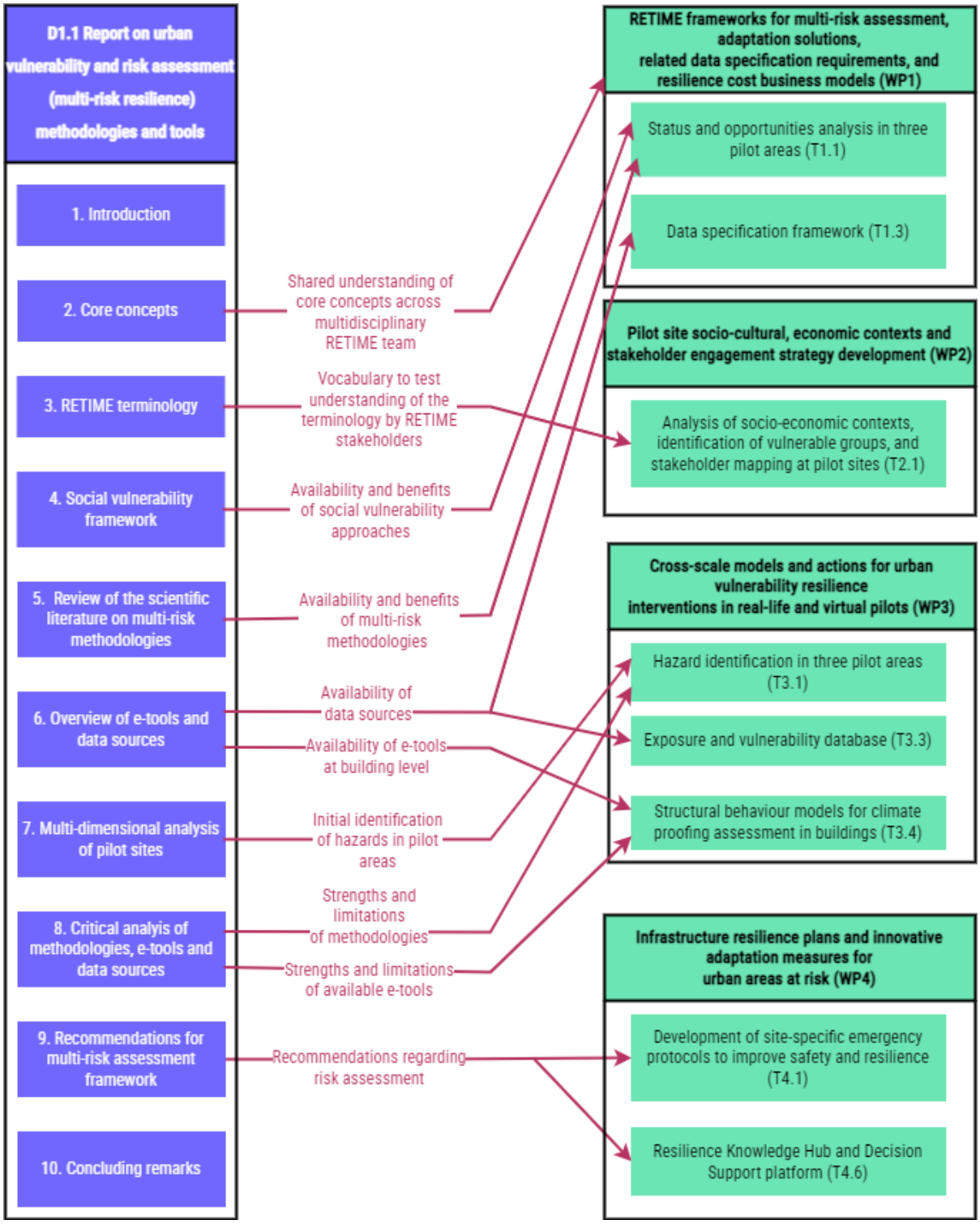


Figure 1. Structure of this report and interdependences with other RETIME activities.

1.1. Structure of this report and interdependences with RETIME activities

As shown in Figure 1, following 'Introduction' section, this report is structured as follows: 2) Core concepts; 3) RETIME terminology; 4) Social vulnerability framework; 5) Review of scientific literature on multi-risk assessment methodologies and discussion of the results; 6) Overview of software e-tools used at EU and national levels and those to be used in RETIME activities; 7) Critical analysis; and 8) Recommendations for a future-oriented analysis of urban risk and vulnerability assessment in the RETIME pilot sites and at EU level.

Connected to the broad academic discourse on multi-risk assessment and vulnerability analysis (4-5), this report highlights the risk evaluation and exposure to hazard at macro-level and summarises outstanding challenges (6). Final critical analysis and recommendations are presented as foundational basis especially for RETIME public authorities, environmental practitioners, research community, and members of EU sister projects focused on adaptive mitigation measures for human-induced and climate-change related risks. The analysis of data sources and software tools can be also useful for IT developers and private service providers involved in mitigation and anticipatory actions.

Existing multi-risk resilience assessment strategies and methodologies are identified in this report to facilitate the selection of the most applicable approaches for different urban scenarios, considering variations in features such as climatic futures, current and prospective population density and poverty, urban and environmental features, governance practices, cultures, and energy use patterns.

As shown in Figure 1, the insights provided in this report are essential to undertake other RETIME activities, aimed to: i) identify potential adaptation solutions (T1.2); ii) inform data specification (WP1/T1.3); iii) support a stakeholder engagement that will ensure inclusion of vulnerable groups across RETIME pilot sites (WP2/T2.1); iv) inform RETIME cross-scale modelling activities for urban areas at risk and economically and socially feasible adaptation paths and required data infrastructure (WP3/T3.1, T3.3, and T3.4); and, ultimately, v) advice the development of emergency protocols, knowledge hub, and decision making platform (WP4/T4.1 and T4.6).

Additionally, climate concerns and technology literacy of the key stakeholders in the RETIME pilot sites based on semantic framework and the preliminary hazard analysis will be further mapped during stakeholder activities (WP2/T2.1) and then tested (WP5/T5.2). During on-site social surveys, the familiarity with RETIME terminology will be assessed among local inhabitants and other representatives of relevant organisations or interest groups. The findings will integrate other data related to local stakeholder studies and detailed in the report on stakeholder analysis.

2. Core concepts related to multi-risk assessment

The key concepts essential to multi-risk assessment include *hazard*, *exposure*, *vulnerability* (with a particular emphasis on *social vulnerability* in the context of RETIME), and *coping capacity*. Risk is understood as the interplay between *hazard*, *exposure*, *vulnerability*, and *coping capacity*. A hazard refers to a potentially disastrous event, defined by both its likelihood of occurrence and its potential magnitude (UNDRR, 2017). The *exposure* quantifies the situation of people, housing, infrastructure systems and facilities, production capacities and any other tangible human assets located in hazard-prone areas and in surrounding areas (UNDRR, 2017). Finally, the *vulnerability* captures conditions determined by social, economic, architectural, cultural, and environmental factors or processes that increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards (UNDRR, 2017). To address these challenges, *coping capacity* "is the ability of people, organisations and systems, using available skills and resources, to manage adverse conditions, risk or disasters" (UNDRR, 2017).

The higher degree of *exposure* and often *vulnerability* of both people and infrastructure within urban environments is a driver behind why natural hazards often have greater social and economic impact in urban areas than in rural areas, despite cases with higher rural vulnerability (Cutter et al., 2003a, 2016). Several researchers have pointed out the uneven impact of disasters on marginalised (or disadvantaged) social groups across various dimensions, including income, social status, age, race, gender, and disability (e.g., Cutter et al., 2016). In addition to individual factors, wider socioeconomic issues like poverty, economic inequality, gender inequality, uncontrolled urbanisation, and conflict contribute to increased risk (UNDRR, 2022). Reducing vulnerability requires strengthening *coping capacities* to minimise the degree of loss emerging from a disaster. *Vulnerability* can be influenced by physical attributes (e.g., structural qualities of infrastructure) and socioeconomic attributes (e.g., age, health, and poverty). Vulnerable groups are more affected by disaster events rather than other social groups (Flanagan et al., 2011). The *coping capacity* of households and communities to respond to disasters and climate variability is also unequal, with low-income urban residents and older people having poor access to information and fewer safety nets. The impacts of disasters on buildings and inhabitants can be reduced through preventive measures and robust vulnerability assessments.

Multi-hazard risk assessments pose great challenges, as the impacts of single hazards do not simply sum up, but the hazards interact with each other. They can alter amplitude, probability, and even trigger other hazards (Kappes, Keiler, et al., 2012a; R. Lee et al., 2024; J. Wang et al., 2020; Zscheischler et al., 2020). A simple overlay of single hazards, referred to as 'multi-layer' single hazard approach, does not encompass all facets of multi-hazard risk (Gill et al., 2022).

Understanding the concept of risk in disaster risk science is crucial for comprehending the methods used in multi-risk science. A comprehensive risk assessment must consider all

components of risk, shown in Figure 2, to provide a thorough analysis. Hazards specific to RETIME pilot sites are highlighted in bold.

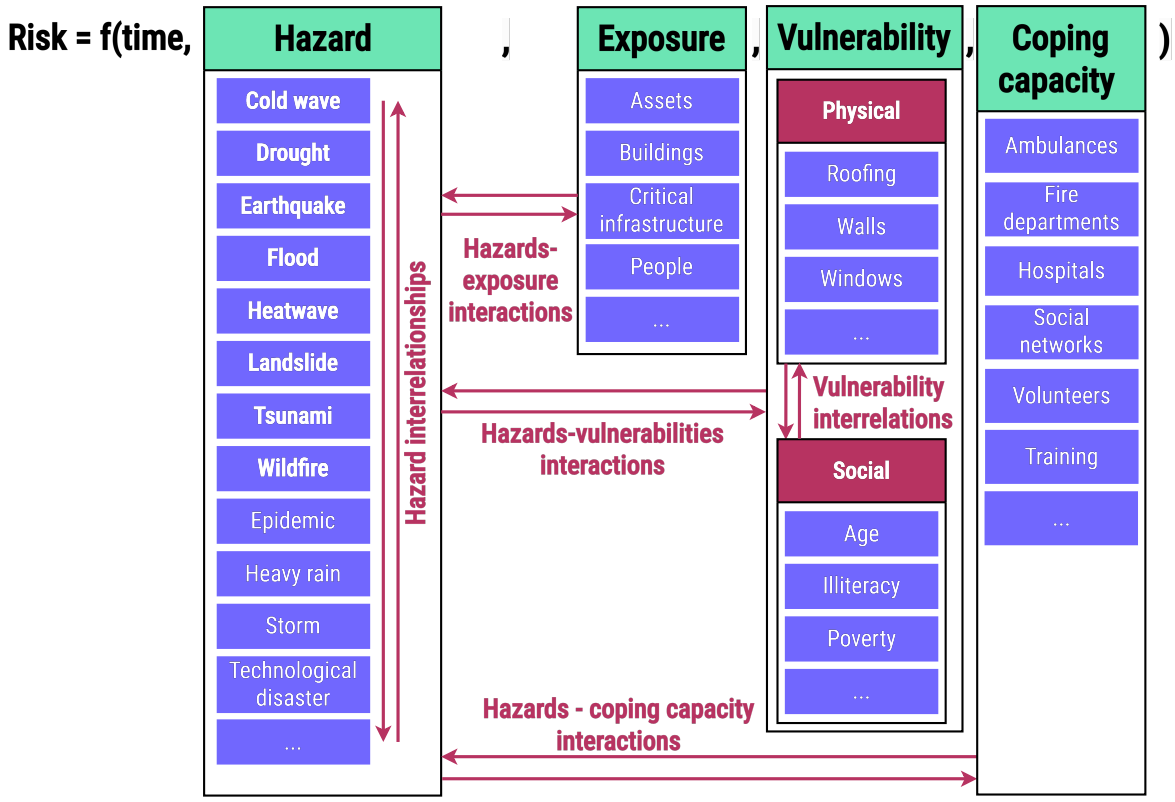


Figure 2. Multi-risk framework, based on EC Joint Research Centre (2017) and Gill et al. (2022).

Risk is expressed in the following equation (1):

$$Risk = f\,(time, Hazard, Exposure, Vulnerability, Coping\ Capacity). \quad (1)$$

To assess risk as a combination of hazard, exposure, vulnerability, and coping capacity is challenging even for single risk assessments. When investigating multi-risks, interactions between the components of risk must be considered, placing further challenges for risk assessment. Two main approaches can be distinguished, as outlined below:

i) *Multi-hazard risk* describes the risk arising from multiple interrelated hazards, and a single vulnerability perspective. Hazards are seen as interrelated, triggering second hazards, amplifying other hazards and compounding with other hazards. However,

vulnerability is not seen as a dynamic concept.[1] The interrelationships of hazards are visualised in Figure 2 by vertical arrows in the hazard box. For example, an earthquake triggers a landslide, but the buildings exposed to both hazards have the same vulnerability throughout the event. This perspective neglects that exposure, vulnerability, and coping capacity differ for different hazards and vulnerability is influenced by each hazard. This 'hazard-silo thinking' approach was contested within UN's Sendai Framework for Disaster Risk Reduction (SFDRR). To sum up, 'multi-hazard risk' only considers risk as 'multi', but 'vulnerability' is considered without any interaction (Gill et al., 2022).

ii) *Multi-risk* closes this relevant gap as it considers both multi-hazard and multi-vulnerability (Gallina et al., 2016; Gill et al., 2022), e.g., an earthquake can trigger a tsunami, increasing the hazard level in the exposed area (multi-hazard). Moreover, the earthquake may compromise the structural integrity of buildings, making them more vulnerable to the subsequent tsunami (multi-vulnerability). This multi-risk approach with influence of hazards to exposure, vulnerability and capacity is shown in Figure 2 by using horizontal arrows connecting the components of risk.

As capacity is in some studies separated from vulnerability (Birkmann & UNU-EHS Expert Working Group on Measuring Vulnerability, 2013; Gill et al., 2022), capacity should also be considered 'multi', as it is time-dependent and influenced by hazards (e.g., a hospital or fire station heavily damaged by an initial earthquake reduces coping capacity for following tsunami). Not only the mentioned problems inherent to the nature of multi-risk are placing difficulties for multi-risk analysis, but science is placing further challenges as two major terminology streams exist in the multi-hazard context (Tilloy et al., 2019). The 'multi-hazard stream' and the 'compound-hazard stream', where the compound-hazard wording is used more often in studies focusing on hydrometeorological hazards (Tilloy et al., 2019). This inconsistency is followed by differences in terminology describing the interaction between hazards, they are described as 'compounding', 'cascading', 'triggering' and many other synonyms (Tilloy et al., 2019; J. Wang et al., 2020). To address this issue, MYRIAD-EU project (2021-2025) aims to enhance a shared understanding of multi-risk, specifically based on a comprehensive review study undertaken by

[1] The main dynamics of the vulnerability are discussed by Ruiter and Van Loon (2022): i) the underlying factors contributing to vulnerability; ii) the evolution of vulnerability during prolonged disasters; and iii) shifts in vulnerability during compounding disasters and societal shocks. Other information is provided in *Section 5*.

Ciurean et al. (2018) and other related studies. These studies cover scientific literature on multi-risk and describe three key types of interrelationships between hazards (Gill et al., 2022):

i) *Triggering Relationship*: "One hazard causes another hazard to occur" (Gill et al., 2022, p. 27),
ii) *Amplification Relationship*: "One hazard can change the likelihood and/or magnitude of additional hazards in the future" (*Ibid*.)
iii) *Compound Relationship*: "Two or more hazards may impact the same region and/or time period with impacts different (greater, lesser) than their sum" (*Ibid*.)

3. RETIME semantic framework

From the start of the RETIME project it was recognised that establishing a shared semantic framework and aligning on the terminology is essential. *Section 3.1* explains the purpose of the RETIME glossary and the main sources employed, and *Section 3.2* clarifies the methodology designed to prepare the RETIME glossary[2] and the outcomes.

3.1. Purpose of RETIME glossary

As stated by Murray et al. (2022), the use of a comprehensive and consistent terminology is essential for designing, implementing, and monitoring disaster risk reduction and for risk-informed investments at every level, including local, regional, national, and global. To ensure a consistent terminology use within the RETIME project, this section outlines the semantic framework and explains the rationale behind its selection. Rather than creating a new glossary, this approach leverages existing knowledge and current lexical frameworks. RETIME glossary is based on terminologies, values, and systems developed within previous EU-funded and international projects and initiatives. RETIME glossary is a living document that has been established based on a 3-steps process (as described in *Section 3.2*).

3.2. Existing Glossaries and RETIME Glossary Development

The process behind the compilation of the RETIME glossary, shown in Figure 3, consists of three phases: i) *analytical phase* to identify a set of existing glossaries related to RETIME; ii) *synthesis phase* to aggregate the terms into a single glossary; and iii) *voting phase* to ensure consensus among RETIME Beneficiaries.

In more detail, relevant documents and different glossaries were analysed to break a concept down and organise it in a coherent manner. Research synthesis phase allows for the integration and compilation of results from the analysis phase, consolidating all terms and definitions in preparation for the two voting stages. The voting phase focuses on selecting terms for the RETIME glossary and assigning them the appropriate definitions.

[2] This glossary will be published on the project website and will be updated throughout the project when necessary.

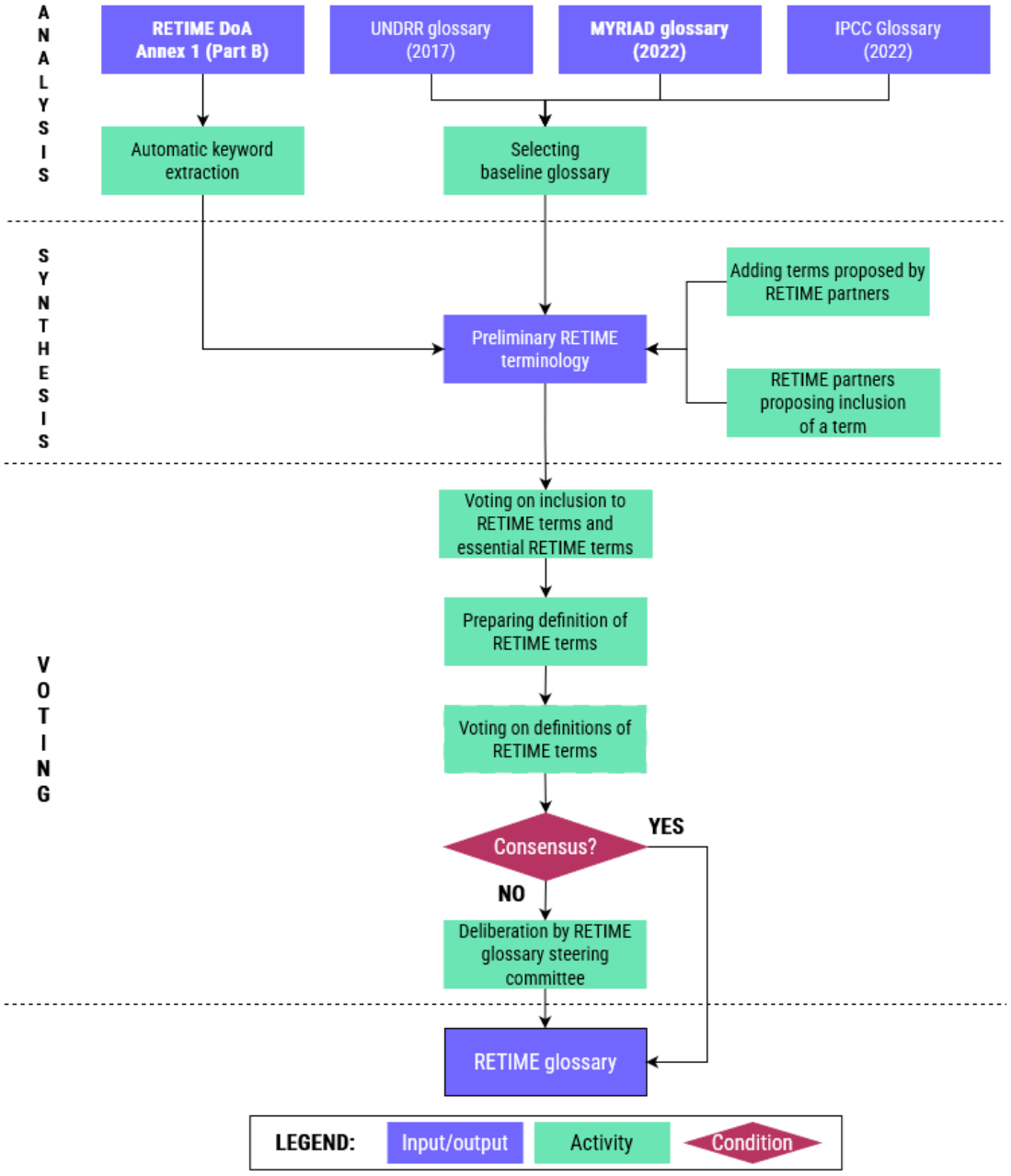


Figure 3. Phases to build the RETIME glossary.

Analytical phase: The most relevant glossaries in the field of Disaster Risk Reduction (DRR) were identified during the first *analysis phase* by the T1.1 members (i.e., academics from three universities, representatives of SMEs and non-profit organisations, and representatives of local core partners responsible for RETIME pilot sites), as follows:

- Intergovernmental Panel on Climate Change (IPCC) glossary (living document, with the last update dated in 2022)(IPCC, 2022)
- Handbook of Multi-Hazard, Multi-Risk Definitions and Concepts established within the MYRIAD-EU project[3](MYRIAD glossary) led by the British Geological Survey (Gill et al., 2022)
- The disaster risk reduction (UNDRR) glossary adopted by the United Nations Office for Disaster Risk Reduction in 2017 (UNDRR, 2017)

The MYRIAD-EU glossary (102 words) was selected as a baseline for the RETIME glossary. The MYRIAD glossary is the most recent and comprehensive glossary (created in 2022), includes a selection of the terminology from Intergovernmental Panel on Climate Change (IPCC) and UNDRR and five other glossaries (WMO,1992; WHO-2020; UNDRR/ISC, 2020; HIPs, 2021; IPCC, 2022). It aligns with internationally recognised standards being based on well-established international glossaries compiled by intergovernmental organisations (e.g., the World Meteorological Organisation – WMO, the UN Office for Disaster Risk Reduction – UNDRR), intergovernmental panels (e.g., Intergovernmental Panel for Climate Change – IPCC). This effort is further supported by national and international initiatives aimed at implementing the Sendai Framework for Disaster Risk Reduction (2015–2030).
The MYRIAD-EU glossary focuses on urban resilience, climate change adaptation, and disaster risk reduction, what is fully in line with the objectives of the RETIME project. It also covers two crucial topics for the RETIME project: population preparedness assessment and disaster risk assessment. In addition, MYRIAD -EU glossary includes terms that may support decision-making and the implementation of practical measures to increase building resilience and reduce disaster risks.
Thus, all terms that are included in the MYRIAD glossary were selected to form an initial set of RETIME candidate terms (*analysis phase*, Figure 3). Further, the extraction of all terms from three terminology glossaries (IPCC, 2022; MYRIAD-EU, n.d.; UNDRR, 2017) were performed and analysed.

[3] The MYRIAD-EU project has received funding from the European Union's Horizon 2020 research and innovation programme call H2020-LC-CLA-2018-2019-2020 under GA: 101003276.

Synthesis phase: It was carried out to prepare preliminary RETIME terminology. The file from analysis part was used for automatic extraction of additional keywords considering the RETIME GA (Part A and B and Annexes), and the RETIME Consortium Agreement (CA) documents, utilising the large language model Chat GPT 4o (19 terms selected). Since MYRIAD glossary is lacking specific words related to building resilience (e.g., automatic building monitoring system, sensitive buildings/infrastructure) plus economic vulnerability, RETIME partners proposed 58 additional terms complementing the initial set to form the preliminary RETIME terminology.

Voting phase: A two-round voting procedure was carried out. In the first round, one representative from each RETIME partner organisation voted for the inclusion of terms in the preliminary RETIME terminology to the RETIME glossary. At the same time, a separate vote was conducted to propose the inclusion of up to 20 terms into the subset of key RETIME terms, called 'RETIME essential terms'. More than 50% of votes was required to approve each term. In the first round of voting, 17 out of 18 partners participated, which represents 94.44% participation. RETIME essential terms are strictly related to key concepts for disaster risk reduction, building resilience, and urban adaptation measures within RETIME. The use of 'RETIME essential terms' should ensure consistent communication and understanding across RETIME Beneficiaries and for key stakeholders. 134 terms were selected for the RETIME glossary and among them 22 were included as 'RETIME essential terms, which are shown in Figure 4.

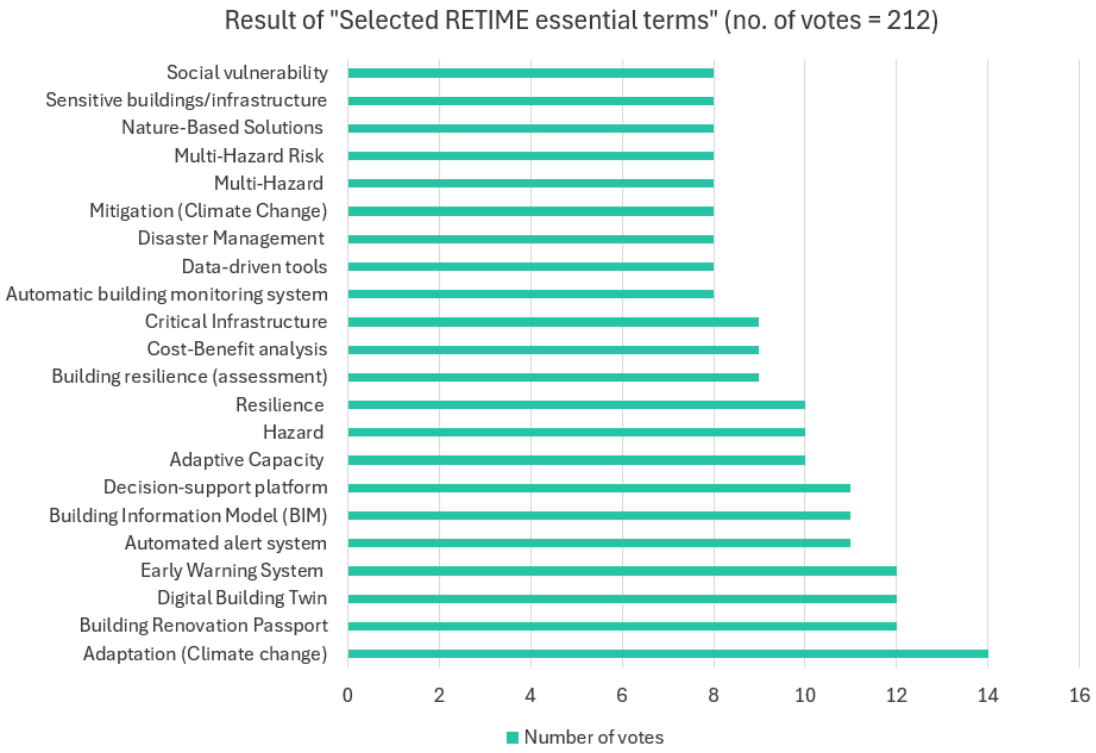


Figure 4. Selected RETIME essential terms.

Then, a definition was formulated for each term selected by five members of RETIME consortium, who are experts in social vulnerability analysis, emergency planning, and building resilience based on existing glossaries, research projects, and scientific publications. The list of terms and their definitions are available as Table 16 in Annex A.

4. Backbone of social vulnerability in urban environments: core studies and methods

Vulnerability is a polysemic term, and the models used to assess it vary wide. The concept of vulnerability has evolved from notions of internal risk factors to a multidimensional understanding that includes physical, social, economic, environmental, and institutional aspects (Birkmann, 2006b). Tobin and Montz (1997), Adger et al. (2004), and Khan (2012) argue that the 'vulnerability' is inherently non-linear. This is due to its intrinsic dynamism of this concept (due to both temporal and spatial variations), and its multidisciplinary and multifaceted nature. Consequently, researchers from various fields of expertise (e.g., structural or systems engineering, geography, ecology, and sociology) concentrate on different aspects of vulnerability (Cutter & Finch, 2008; Y.-J. Lee, 2014; Menoni et al., 2012). Bohle (2001) states that vulnerability consists of internal and external domains (Bohle, 2001). The internal domain refers to resilience and adaptive capacity, while the external domain represents exposure.

The evolution of the concept of vulnerability is linked to a progressive increase in theoretical and practical complexity, associated to the growing territorial complexity, which is reflected in the wide variety of vulnerabilities and risks. The vulnerability can only be considered through a holistic analysis and assessment at territorial scale, which considers the multidimensionality and spatial and temporal variation of vulnerability at the local scale, as well as the identification and analysis of the different exposed elements (Burton et al., 2018; Y.-J. Lee, 2014; Tapsell et al., 2010). The analysis and assessment of vulnerability have been influenced by multiple conceptual frameworks, with a shift of focus from the physical environment to a social driver and their associated impacts (Burton et al., 2018). One of the most significant cultural shift regards climate change-related vulnerability, where there has been an evolution between the 4th Assessment Report (AR4) (IPCC, 2007) and the 5th Assessment Report (AR5) (IPCC, 2014) from the Intergovernmental Panel on Climate Change (IPCC). This reflects a shift in the concept of vulnerability, integrating climate change adaptation with disaster risk reduction, as shown in Figure 5. The main differences between the conceptual approach in AR4 and AR5 are: a) the combination of hazard, sensitivity, vulnerability, and exposure defines risk and potential consequences in AR5, while in AR4 exposure and potential impact define the vulnerability; b) hazard now encompasses not only climate-related aspects but also physical impacts directly associated with climate; c) the concept of 'exposure' is introduced to emphasise the presence and relevance of exposed elements; and d) probability and uncertainty are explicitly considered (GIZ & EURAC, 2017).

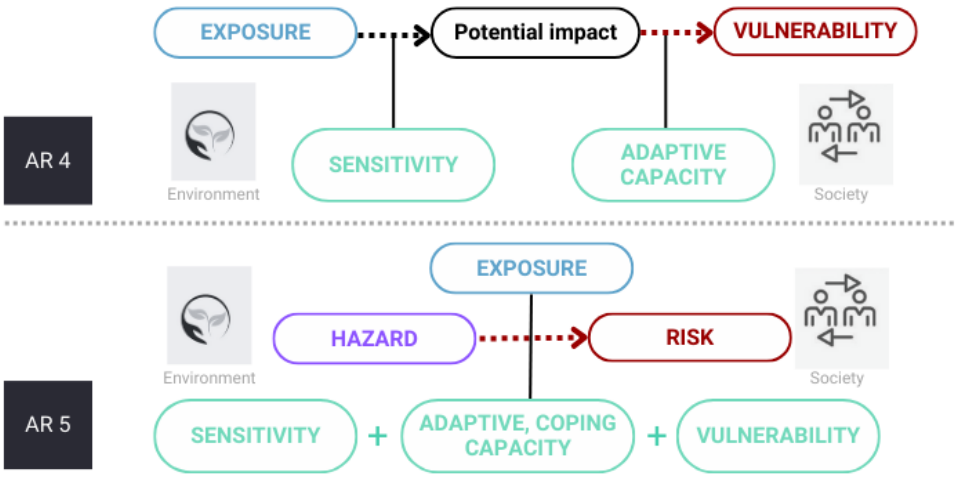


Figure 5. Comparison of the components of climate change vulnerability (AR4) and climate risk (AR5) adapted from GIZ and EURAC (2017).

In recent decades, there has been a growing need to identify and assess social vulnerability related to disasters induced by natural processes and climate change. This is because it is understood that the impacts of these processes are not only dependent on physical forces but are also determined by social and economic factors (Birkmann et al., 2022; Cardona et al., 2012; IPCC, 2022). Vulnerability is a dynamic process characterised by constant interactions between the natural and biophysical systems that influence a given territory, as stated by O'Brien et al. (2005). This dynamism makes it challenging to quantify vulnerability and reduce it to a single, simple metric (Ahrens & Rudolph, 2006). On the other hand, the multidimensionality and complexity of the concept of vulnerability, which encompasses both tangible and intangible characteristics, make it difficult to reduce it to a simple equation or a set of universal indicators for its assessment (Birkmann et al., 2013; Wisner, 2002).

4.1. Understanding Social Vulnerabilities in Disasters: Importance and Challenges

The study of natural and human-made disasters, both seen as socially constructed processes, should focus on the social dimension. Social vulnerability generally indicates the potential for loss. "Since losses vary geographically, over time, and among different social groups, vulnerability also varies over time and space" (Cutter et al., 2003, pg. 242). More importantly, social vulnerability partly arises from social inequalities, factors that affect how different groups are exposed to harm and their capacity to respond. Additionally, it encompasses place-based inequalities.

Social vulnerabilities, linked to the context in which disasters occur, are key to understanding the development of risk conditions that affect the likelihood of such (often multiple) events.
Social vulnerabilities in disasters are crucial indicators for analysing the conditions of social development processes, identifying the dangers and weaknesses of the social system for evaluating the level of investment required for socio-political decisions. With their multidimensional nature, social vulnerabilities analysis aims to understand the level of community exposure and their capacity to respond and recover in the post-disaster period, as stated by Cutter et al. (2003a).
This understanding informs the development of preventive and emergency preparedness actions related to social, political, cultural, and economic planning and intervention process, aiming to minimise and/or mitigate both identified vulnerabilities and associated risks.

4.2. Overview of social vulnerability assessment approaches and methods

Among the various methods based on different conceptual frameworks and indicators are participatory methodologies, simulation-based approaches, and indicator-based methodologies (Hinkel, 2011). These can be grouped into four main streams: i) economic and political approaches; ii) social and ecological approaches; iii) approaches focused on vulnerability and risk assessment through a holistic perspective; and iv) approaches based on climate change adaptation strategies (Birkmann, 2006b).
Regardless of these different approaches, a key similarity among various approaches is the focus on the intrinsic conditions of a society that make it vulnerable to losses and damage. This diversity of conceptual frameworks and assessment methods involves a broad range of factors and dimensions related to vulnerability, which are essential for effective assessment (Birkmann, 2006a; Cutter et al., 2003a; Hagenlocher et al., 2018). The primary factors of vulnerability include susceptibility, exposure, and resilience, each influenced by various dimensions such as economic, social, cultural, structural, environmental, and institutional (Balica & Wright, 2010; Baum et al., 2008; Birkmann, 2006a).
Methods for assessing social vulnerability can be qualitative and quantitative. Qualitative methods are bottom-up based approaches and are generally applied at the local scale (Burton et al., 2018). These methods are based on on-site or off-site social surveys using structured (or semi-structured) interviews and focus groups. Quantitative methods can be deductive, inductive, or hierarchical. Deductive models are based on a top-down approach, where the associated conceptual framework influences the (reduced) selection of indicators that are standardised and aggregated (Tate, 2012). Inductive models, on the other hand, includes a larger number of indicators, which are then reduced to a smaller group using Principal

Component Analysis (PCA) or Factor Analysis (FA). These methods decompose the initial group of variables into several factors, which are then aggregated to construct an index of social vulnerability to environmental hazards. One of the most relevant PCA indexes was developed by a group of researchers from the University of Carolina, coordinated by Cutter, who built the social Vulnerability Index (SoVI) model based on county-level socio-demographic data (Cutter et al., 2003a). At the national level, notable works include those by Mendes et al. (2011) and Tavares et al. (2018), which assessed social vulnerability at the municipal level, considering two dimensions: 'Criticality' and 'Support Capacity'. There are also hierarchical models that typically use a moderate set of indicators (up to 20) aggregated into different analytical pillars to create an index. The selection of different indicators can be carried out using participatory approaches or through the opinions of experts (Barros et al., 2015, 2022; Burton et al., 2018).
The use of this type of index is valuable for shaping new public policies or risk communication strategies (Birkmann et al., 2013; Joint Research Centre & European Commission, 2008). However, Birkmann (2007) emphasises that data availability is a critical factor in choosing which variables to include in the index. Although numerous methodologies exist for creating composite vulnerability indices, most employ deductive or hierarchical approaches that involve a weighted summation of the included variables (Beccari, 2016).

4.3. Social vulnerability model for RETIME

Social vulnerability aids in defining and evaluating the exposure levels of communities, offering valuable insights into their capacity to respond and recover in the aftermath of a disaster (Cutter et al., 2003a). Society is not dimensioned as a homogeneous entity, but rather as a reality influenced from the perspective of the different drivers of vulnerability (e.g., age, gender, education, nationality, access to public facilities, conditions accommodation or the type and degree of disability).
The relevance of the social vulnerability assessment methodology developed by researchers at the Centre for Social Studies (CES), University of Coimbra (Portugal), stems from its focus on two key components of social vulnerability: 'criticality' and 'support capacity'. A high value in the first increases social vulnerability, while a high value in the second attenuates it.
'Criticality' is as the set of characteristics and behaviours of individuals that determine their degree of resistance and resilience in responding to or dealing with disasters and catastrophic scenarios (Mendes et al., 2011). 'Support Capacity' refers to the extent and variety of infrastructure and equipment that bolster community responses (*Ibid.*). This approach was first implemented in Portugal in 2008, covering 278 municipalities in mainland Portugal and 93 parishes within 7 municipalities in the central region. In 2017, a national analysis of social

vulnerability was carried out by Tavares et al. (2018), employing Principal Component Analysis (PCA) based on the studies undertaken by Cutter et al. (2003) and by Schmidtlein et al. (2008) in the United States and by Mendes (2009) in Portugal. Initially, the 2017 assessment of 'support capacity' involved 145 variables, which were later streamlined to 56 through multicollinearity analysis of bivariate correlations. Regarding 'criticality', the initial analysis used 90 variables, which were reduced to 56 via multicollinearity assessment. PCA then selected 22 explanatory variables (Table 1) related to six dimensions of vulnerability, leading to the identification of six analytical components Figure 6. PCA facilitated the identification of 12 key variables (Table 1) across four dimensions of vulnerability. For post-factor analysis, three analytical components were retained, as shown in Figure 6, adapted from Tavares et al. (2018).

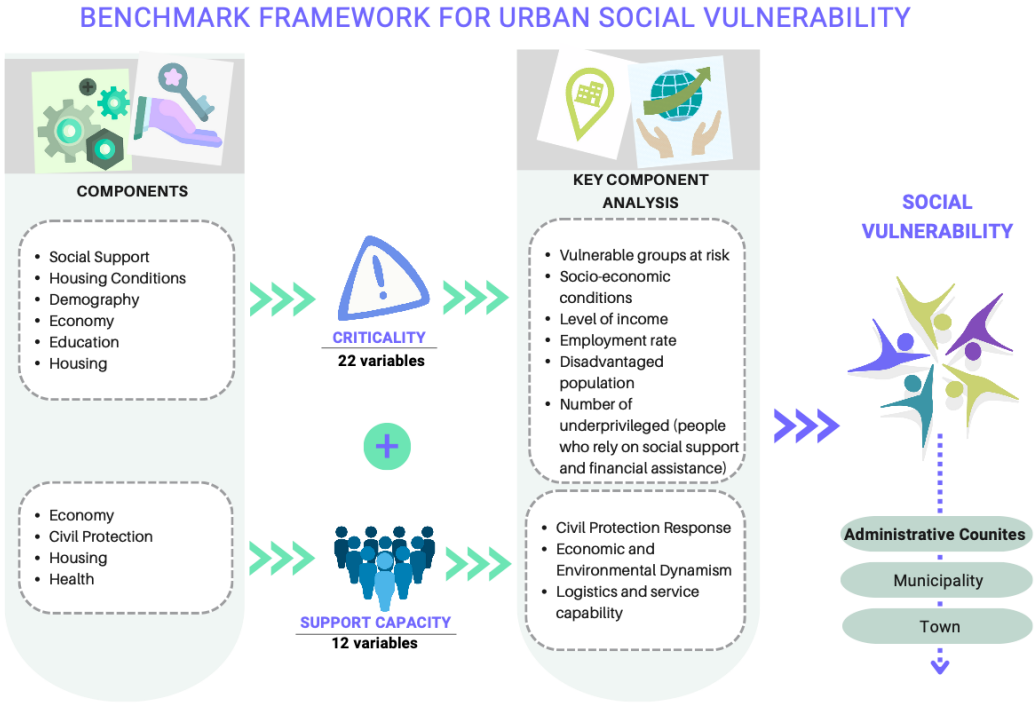


Figure 6. Social Vulnerability Assessment method adapted by Tavares et al. (2018).

This method is effective since it considers the multidimensional nature of vulnerability through the analysis of a broad range of variables. It allows for a comprehensive representation, analysis, and evaluation of vulnerability across its various dimensions at different levels (administrative counties, municipality or town level). In this project, the social vulnerability analysis will focus on selected administrative counties in the three RETIME pilot sites, as outlined in Figure 6 . Additionally, this method supports comparison between regions and municipalities, making it an efficient tool for shaping public policies aimed at reducing vulnerability and managing risks. It also helps in developing programs that promote social cohesion and contribute to building a

more resilient society (Tavares et al., 2018). This method, based on previous studies (Cutter et al., 2003a; Mendes et al., 2011; Schmidtlein et al., 2008; Tavares et al., 2018) will be adapted and used for RETIME social vulnerability assessment (WP2, T2.1) and then to validate status and opportunities analysis in the three pilot sites (WP1, T1.2).

Table 1. Variables related to 'Criticality assessment' and 'Support capacity assessment'.

Criticality assessment	
Variables	**Unit of Measurement**
1) Employed population according to the Census: total and by sector of economic activity - primary sector	%
2) Employed population according to the Census: total and by sector of economic activity - tertiary sector	%
3) Employed population according to the Census: total and by situation in the main occupation - Self-employed as an isolated employer	%
4) Average value of social security pensions by Place of residence	€ / N°
5) Proportion of classic rented or subleased family accommodation	%
6) Resident population under 5 years old	%
7) Proportion of students by secondary education establishment	%
8) Purchasing power	
9) Difficulties of resident population by place of residence, degree of difficulty	%
10) Buildings built before 1919	%
11) Beneficiaries Social Integration Income and Minimum Guaranteed Income	%
12) Employed population according to the Census: total and by sector of economic activity - secondary sector	%
13) Employed population according to the Census: total and by situation in the main occupation – self-employed as an employer	%
14) Employed population according to the Census: total and by situation in the main profession -Worker on behalf of others	%
15) Proportion of students by pre-school education establishment	%
16) Resident population older than 65 years	%
17) Seasonal households	%
18) Deposits from customers in banks, savings banks and mutual agricultural credit	total and by type of customer / hab
19) Social housing - social and supported renting	%
20) Very degraded buildings	%
21) Housing with renting less than 100 euros	%
22) Notarial acts entered into by writ - Properties buying and selling	%
Support capacity assessment	
Variables	**Unit of Measurement**
1) ATM machines	‰
2) Urban waste collected	kg/hab
3) Banks and savings banks	
4) Accommodation capacity in hotel establishments	‰

5) Firefighting corporations	/1000 hab
6) Firefighters	‰
7) Proportion of collective accommodation	/1000 hab
8) Proportion of hospitals	
9) Insurance companies	per 10,000 inhabitants
10) Pharmacies	‰
11) Inhabitants by covered spaces	per 10,000 inhabitants
12) Road network density	

Thus, in the social vulnerability assessment process, procedures associated with the statistical technique of Principal Component Analysis (PCA) are applied, a method previously employed by Cutter et al. (2003a), Mendes et al. (2011), Schmidtlein at al. (2008) and Tavares et al. (2018). Prior to the final running of PCA, redundant variables are eliminated based on the iterative and combined analysis of several indicators, i.e., Pearson correlation matrix; variance rate parameters, which should be greater than 60%; Kaiser-Meyer-Olkin (KMO) sample measurement, which should be greater than 0.6 (Comrey & Lee, 2013). After the definition of the final set of variables, PCA is carried out using normalised values to the z-score, Varimax rotation factor analysis. An analysis of the cardinality or sign interpretation of each principal component is done by identifying in the rotated matrix the variables that have a loading equal to or greater than the module of 0.5 so the factors may be interpreted and, if needed, their respective scores multiplied by −1 (Cutter et al., 2003a; Mendes et al., 2011). This is justified by the fact that PCA cannot interpret the role of variables in increasing or decreasing vulnerability. After calculating 'criticality' and 'support capacity', the social vulnerability composite index is calculated by combining the two components mentioned above. The calculation is made using the following equation (2):

$$Social\ Vulnerability = Criticality \times (1\text{-}Support\ Capacity). \quad (2)$$

High 'criticality' values combined with low 'support capability' values indicate a higher or more severe Social Vulnerability composite index. The results obtained are grouped into different classes that vary from very low to very high in accordance with the standard deviation (SD) and the following categories: 'very low'< 1 SD; 'low' [−1, −0.5 SD]; 'moderate' [−0.5, +0.5 SD]; 'high' [0.5, 1 SD]; 'very high' ≥1 SD (Cutter et al., 2003b).

4.4. Econometric modelling

Econometric modelling aims to quantify the effects of socio-economic variables on disaster impacts. The EU-financed project MEDiate (2022-2025)[4] focuses on approaches available in the literature to measuring the economic impact of floods, based on two approaches: i) the macroeconomic impact on the economy and ii) the impact upon local economy from a loss of a specific piece of infrastructure. Both approaches measure the impact post-disaster and thus such approaches are limited in their ability to forecast the likely effects of a new disaster. Often, macroeconomic approaches are based on an equilibrium model. Another commonly applied mechanism is the use of an input-output model which seeks to assess the vulnerability of interdependent sectors.[5]

After a careful analysis of existing approaches, the MEDiate team proposed the econometric model capturing the local Gross Domestic Product (GPD) impact of a flood in the generic form, as follows in Eq. (3):

$$Disaster\ impact\ on\ GDP = f(social\ vulnerability, community\ resilience). \quad (3)$$

The final econometric model took the following Eq. (4):

$$D_{it} = a + bS_{it-1} + cE_{it-1} + u_{it}, \quad (4)$$

where i is the district, t is time, D_{it} is disaster impact measured as a pure economic impact (log local (GDP) per capita), S_{it-1} is the key social vulnerability index, E_{it-1} is the key community resilience index, u_{it} is the error term.

The model was constructed for Essex County based on 24 flooding events recorded in the Essex County from 2011 until 2023. The social vulnerability index (SVI) incorporated variables, such as population density, ethnic groups, age, household composition, proficiency in English, unemployment, car or van availability, house value, etc. Community resilience index (CRI) factors included economic levels, education levels, household income, among others. This model was developed in two stages. In the first stage, PCA method has been applied to identify key measures for SVI and CRI, respectively. In the second stage, the model parameters were fitted to data. Such a model can be used to compare the expected effects of improving SVI and/or CRI on the flood impact on GDP, while, at the same time, the key variables for each index can be

[4] https://mediate-project.eu [Accessed 3.10.2024]
[5] https://mediate-project.eu/wp-content/uploads/2024/06/D3.2.pdf [Accessed 3.10.2024]

identified. This method facilitates the identification of a target group for investments aimed at strengthening social vulnerability and community resilience.

5. Scientific literature review on multi-risk assessment methodologies

To enhance disaster resilience, it is necessary to thoroughly understand the existing risks faced by living environments, and to acknowledge the multi-hazard nature of disaster risk reduction (UNDRR, 2015). Many important insights have recently been gained in the context of the interrelationship of different hazards. It has been shown that hazards can alter amplitude, probability, and even trigger other hazards (Kappes, Keiler, et al., 2012a; R. Lee et al., 2024; J. Wang et al., 2020; Zscheischler et al., 2020). This section aims to provide an overview of the state of the art (SoA) regarding multi-risk assessment research and explore, if a multi-risk assessment framework exists, which is suitable for the RETIME application, namely, to enhance the resilience of vulnerable building and prioritise a people-centric built environment. This SoA review focuses on methods and tools used by the international scientific community, identify methodological gaps, challenges, and some possible solutions in the field of multi-risk assessment.

5.1. Scientific review methodology

A non-systematic search strategy was employed to provide an overview of the SoA regarding multi-risk assessments in changing climate conditions. An iterative search strategy was utilised to cover a more comprehensive overview of the SoA using different search engines: Google Scholar™, Scopus™, and Web of Science™. The search terms displayed in Table 2 were used in different combinations.

Table 2. Search terms for scientific review.

Search terms				
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		

Using this approach, a database was constructed based on 33 scientific journal articles, of which 22 are reviews, focused on the topics of multi-risk, social vulnerability, and resilience. All publications have been assessed considering the types of risk assessment methodologies, geographical scale and resolution, gaps, major findings, and the relevance for this project (see Annex B). This assessment was based on a subjective basis, although based on expert-

driven assessment work. A set of selection criteria was established to select significant publications. This is relevant in this research and innovation actions (RIA) context since RETIME project covers pilot sites with different citizens' needs, natural and human-induced threats, and distinct architectural and societal context-specific features. Only review papers have been considered, since they aggregate the existing scientific knowledge of this topic and can serve as a good basis for further research. The research scope was not limited to a certain type of studies (e.g., systematic reviews), as other review types can also provide a good overview of certain fields of research. The topic of the review had to be multi-risk assessment or multi-hazard risk assessment, covering natural hazards, both hydrometeorological (e.g., flood) and solid earth and surface process hazards (e.g., earthquakes).

5.2. A brief analysis of literature review

Following the selection process, 6 scientific articles published between 2012 and 2023 are included in this review, as shown in Table 3. These publications can be sorted in two different categories: i) an unsystematic approach as applied by Gallina et al. (2016), Julià and Ferreira (2021), Kappes, Keiler, et al. (2012a), Wang et al. (2020) and ii) a systematic and bibliometric approach conducted by Curt (2021) and Owolabi and Sajjad (2023). The reviews research multi-hazard risk or multi-risk. As described by Gill et al. (2022), a clear distinction between both concepts is not possible for all reviews.
In addition, Table 3 displays the evaluation of five further indicators regarding the relevance in relation to the RETIME project, planned objectives and ambitions. The indicators are: building vulnerability, social vulnerability, technological hazards, or anthropogenic hazards.

Table 3. Characterisation of selected scientific reviews (2012-2023).

Authors (Year)	Title	Systematic review	Building vulnerability	Social vulnerability	Technological hazards	Anthropo-genic 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 highlight current trends and developments, the following reviews are presented in chronological order, summarising the core contents of each study. This is also done, as each review has its own focus and approach of presenting the methods identified. Due to the heterogeneity of the data, a comprehensive aggregation of the results is not feasible. A brief overview of the key challenges in multi-risk research, possible solutions, and the discussion of the results is presented following this review, in *Section 8.1*.

Kappes, Keiler, et al. (2012a)

This review paper was published by Kappes, Keiler, et al. (2012a). Thus, it presents different approaches and challenges in multi-risk analysis when this was an emerging research field at the time. The review covers three assessment types: i) multi-hazard analysis; ii) physical vulnerability analysis for multiple hazards; and iii) multi-hazard risk analysis. Following this overview, challenges and solutions regarding multi-hazard risk analysis are derived. Additionally, relationships between hazards are reviewed and the various terms used are collected and presented, as was addressed by Tiloy et al. (2019). The three assessment types can be summarised as follows:

i) *multi-hazard analysis methods*, categorised as qualitative or quantitative, are shown in Table 4.

Table 4. Multi-hazard analysis methods identified by (Kappes, Keiler, et al., 2012a).

Type	Methodology	Scale	References
Qualitative	(Weighted) hazard interactions matrices	NUTS 3, geomorphic units of a coastal area	Tarvainen et. al (2006)
Quantitative	Event trees / fault trees	None given	Egli (1996); Marzocchi et al. (2009)

	GIS-geography based methodology	None given	Carrasco et al. (2003); Huggel et al. (2004); Wichmann & Becht (2003)
	Process modelling	different scales	Cannon & DeGraff (2009); Ewen et al. (2000); Garcin et al. (2008); Harp & Wilson (1995); Bovolo et al. (2009); Keefer (2002); Meyenfeld (2008); Sedan & Mirgon (2003)
	Probabilistic	None given	CAPRA (Central American Probabilistic Risk Assessment)

ii) Physical vulnerability analysis for multiple hazards are presented in Table 5.

Table 5. Physical vulnerability analysis for multiple hazards (Kappes, Keiler, et al., 2012a).

Type	Methodology	Scale	Pros	Cons	References
Qualitative	indicator-/indices	Building level	Many building characteristics considered	*None provided*	Foerster et al. (2009); Puissant et al. (2006); Schneiderbauer, & Ehrlich (2006)
Semi-quantitative	Matrices	Building level	Simple, Requires less data compared to vulnerability curves	Limited scope of the analysis (few building characteristics)	Calvi et al. (2006); Foerster et al. (2009); Menoni (2006)
Quantitative	Vulnerability curves (functions)	Building level	For widespread hazards	High-data requirements Limited scope of the analysis (few building characteristics)	Foerster et al. (2009); Grünthal et al. (2006); Menoni (2006)

iii) Identified multi-hazard risk analysis methods and tools are presented in Table 6.

Table 6. Multi-hazard risk analysis methods and tools (Kappes, Keiler, et al., 2012a).

Type	Method / Tool	Reference (or link)
Qualitative	Risk matrix approach,	Greiving (2006)

	Simple overlay of hazard and vulnerability based on land-use maps	
Semiquantitative	Ranking of areas based on hazard and vulnerability level and display in matrix	Granger et al (1999); Middelman & Granger (2000)
	Index-based approaches	Dilley et al. (2005); Greiving (2006); Greiving et al. (2006)
Quantitative	Hazus (HAZards U.S.)	https://www.fema.gov/flood-maps/products-tools/hazus
	RiskScape	https://riskscape.org.nz/
	CAPRA	https://ecapra.org/
	Probability based approach to identify most dangerous hazard	Bell (2002) ; Bell & Glade (2004), Bründl (2008); Marzocchi et al. (2009)
	Damage curves	Grünthal et al. (2006), Westen et al. (2002)
	Various tools used by insurance companies (mostly inaccessible due to its trade secret status; licenses are difficult to obtain): MRCatPMLService; RiskLink-ALM (Aggregate Loss Module); RiskLink-DLM (Detailed Loss Mode); FloodAUS FireAUS, HailAUS, QuakeAUS, CyclAUS	Munich Re (1998, 2000); Risk Frontiers (2008); RMS (2009)

The tools used by insurance companies are often inaccessible and source code is unavailable, as they are intellectual property of the insurance companies (Kappes, Keiler, et al., 2012a). This lack of transparency is limiting the exchange on these methods and tools, therefore they are not described further (Kappes, Keiler, et al., 2012a).
Further presented are several approaches for the visualisation of multi-hazards and multi-risks (Bell & Glade, 2004; BGR & Desdm, 2009; Garcin et al., 2007; Klein et al., 2006; UN-ISDR, 2009). The review is limited to natural disasters and to physical vulnerability and does not include social vulnerability (Kappes, Keiler, et al., 2012a). The review does not address coping capacities directly, and does not provide a general framework for multi-risk assessment (Kappes, Keiler, et al., 2012a).

Gallina (2016)
Gallina et al. (2016) place emphasis on climate change and associated challenges. The presentation of results in this study is adapted from Kappes et al. (2012), divided for i) multi-

hazard analysis; ii) exposure and vulnerability analysis; and iii) multi-hazard risk or multi-risk analysis. The review provided by Gallina et al. (2016) does not directly address capacity analysis and social vulnerability analysis methods. All methods identified by Gallina et al. (2016) for multi-hazard, vulnerability, and multi-hazard risk assessment are summarised in Table 7, while the missing methods are identified using grey text by the authors of this report. Multi-hazard analysis describes the analysis of the interaction of hazards with each other in a defined area. Vulnerability analysis describes the analysis of the (physical) vulnerability of the exposed elements. Multi-hazard risk analysis is the combination of multi-hazard and vulnerability analysis.

Table 7. Methods applied for multi-hazard, vulnerability, and multi-hazard risk analyses as identified by (Gallina et al., 2016)

Type of assessment method	Identified methods	References
i) Multi-hazard analysis		
Quantitative	Probabilistic analysis of historical databases	Marzocchi et al. (2012)
	Modelling of climate change	Mahendra et al. (2010)
Semi-quantitative	Cause-effects matrix	De Pippo et al. (2008); Garcia-Aristizabal & Marzocchi (2012); Kappes, Gruber, et al. (2012)
Qualitative	*None provided*	-
ii) Vulnerability analysis		
Quantitative	Fragility curves (vulnerability functions) for physical vulnerability	Kappes, Papathoma-Köhle, et al. (2012); Marzocchi et al. (2012); Papathoma-Köhle et al. (2011); Westen et al. (2002)
Semi-quantitative	Vulnerability indicators through geodata	Wipulanusat et al. (2009)
Qualitative	*None provided*	-
iii) Multi-hazard risk analysis		
Quantitative	Event tree Bayesian networks Monte Carlo simulations	Farrokh et al. (2013)
Semi-quantitative	Assessment with weighted classes	Wipulanusat et al. (2009)

Qualitative	Questionnaires (exploring hazards and vulnerability)	Greiving (2006); Greiving et al. (2006); Olfert et al. (2006); Schmidt-Thomé (2006)

Wang et al. (2020)

Wang et al. (2020) draw attention on the complexities inherent to the interaction of risk components in comparison to single-hazard risk analysis, as identified by Gallina et al. (2016), those related to the interplay of risk components which are omitted in single-hazard risk analysis. The terminology inconsistencies identified by Kappes et al. (2012a) are reiterated by Wang et al. (2020). The most relevant aspect of the research undertaken by Wang et al. (2020) is the cataloguing of the multi-risk research divided into five categories, as follows:

i) NATECH events
ii) human-induced hazards (anthropogenic hazards)
iii) disaster chains (cascading natural hazards)
iv) domino effects (cascading hazards in industrial plants)
v) compound hazards

The different analysis methods are shown in Table 8 sorted according to the respective main themes.

Table 8. Multi-hazard risk assessment methods as identified by Wang et al (2020).

Category	Identified analysis methods	References
NATECH events	Probability theory	*Not provided*
	Monte Carlo simulation	Necci et al. (2014)
	Fuzzy evaluation	Cruz et al. (2011); R. Han et al. (2019); Z. Y. Han & Weng (2011)
Anthropogenic hazards (Human-induced hazards)	Historic case study	Bernatchez et al. (2011); Closson & Abou Karaki (2009); Ellsworth (2013); Zhao (2008)
	Physical modeling	*Not provided*
	Overview work	Gill & Malamud (2016)
Cascading hazards (Disaster chains)	Statistical analysis	Jia et al. (2016); Mazzorana et al. (2019); Wan et al. (2017); Wang et al. (2013, 2020)
	Event tree / probality analysis model	Egli (1996); Keefer (2002); Wang et al. (2013)
	Bayesian network	Rahman (2019); Wang et al. (2013)
	Complex network	A. Liu & Wu (2015); Peters et al. (2008); Zheng et al. (2017)

	System simulation	W. Liu & He (2018)
	Cellular automata	Ji et al. (2008); Li et al. (2013); Ohgai et al. (2004); Wolfram (1984)
	Physical modelling	*Not provided*
Domino effects	Statistical analysis	Abdolhamidzadech et al. (2011); Darbra et al. (2010); Kourniotis et al. (2000)
	Modelling / probit model	Bagster (1991); Cozzani et al. (2005); Eisenberg et al. (1975); F. Khan & Abbasi (1998); Mingguang & Juncheng (2008)
	Monte Carlo simulation	Ahmed et al. (2012); He & Weng (2020); Sun et al. (2015)
	Event tree	Bernechea et al. (2013)
	Bayesian network	Khakzad et al. (2013)
	Fuzzy evaluation	*Not provided*
Compound hazards (Concurrent hazards)	Case study-based approach	Cannon et al. (2008, 2010); Eckel (1970); Horsburgh & Horritt (2006); Kelly (2009)

Wang states that no mature methods for multi-risk assessment are developed until 2020, despite of extensive huge research efforts. Being focused on hazards, this review lacks relevant vulnerability dimensions, both physical and social vulnerability.

Julià & Ferreira (2021)

Focusing on historic urban areas, possible approaches from single- to multi-hazard risk analysis are reviewed by Julià & Ferreira (2021). Therefore, risk assessment approaches for three urban hazards (earthquake, flood, and fire) are analysed. For each hazard vulnerability indicators used in different methods (*earthquake*: 4 methods; *flood*: 4 methods; *fire*: 6 methods) are gathered, aggregated, and displayed.

Four semi-quantitative multi-hazard vulnerability assessment methods are presented:

i) *Multi-Hazard Assessment of Vulnerability (MHAV)*, applied to historic buildings (D'Ayala et al., 2006). It assesses the effects of earthquakes, windstorms, flood, and lightning. MHVA is a three-step method based on historical damage data.

ii) *Vulnerability assessment of heritage buildings and contents under catastrophic hazard* (Paupério et al., 2012). Vulnerability index based on the building susceptibility, contents, and the surroundings.

iii) *Enhanced Papathoma Tsunami Vulnerability Assessment* (PTVA) for multi-vulnerability (Kappes, Papathoma-Köhle, et al., 2012). As indicated by Jullià & Ferreira (2021), PTVA is based on three groups of indicators–building-specific information, surroundings and human-related characteristics.

iv) *Framework for the simplified risk analysis of cultural heritage assets* (Romão et al., 2016). Set of flow charts for vulnerability assessment of cultural heritage assets or components.

Curt (2021)

Curt (2021) provides a systematic review and a textual analysis of 178 abstracts of articles published in indexed journals between 2004-2020. Aim is to recognise and analyse topics and trends in the field. The journals publishing most articles in this field are *Journal of Loss Prevention in the Process Industries*, *Reliability Engineering & System Safety*, and *Natural Hazards*. The database was constructed by a systematic search, the removal of duplicates and articles from non-relevant disciplines, leading to 191 references. The textual analysis was conducted on 178 abstracts, excluding 13 reviews, because Curt (2021) focuses on the specific theme analysed in individual articles. The reviews were excluded in this textual analysis since they could skew the results, as these reviews cover multiple research themes and therefore use keywords from various research topics.

The analysis of keywords shows that the terms ‘domino effect(s)’ are used more often in context of industrial plant safety, while ‘cascades’ more often used in context of critical infrastructures, and ‘multirisk’ used for natural hazards. The frequency of themes in the 178 studies identified using Reinert analysis is indicated in Figure 7.

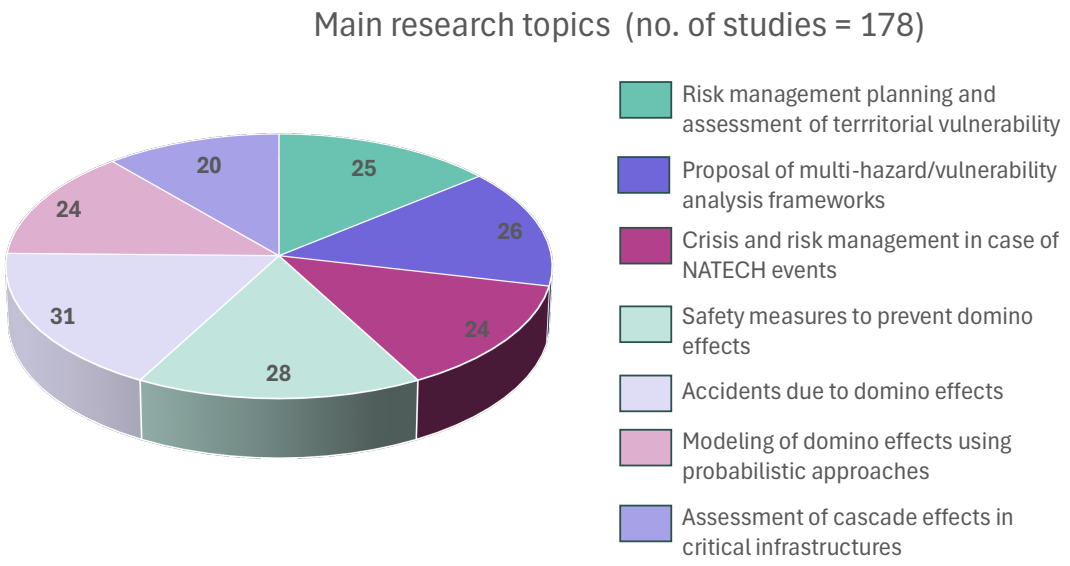


Figure 7. Main research topics in multi-risk identified in a Reinert analysis performed by Curt (2021).

The assessed scientific journal articles focus mainly on risk analysis (no.=75), knowledge production (no.=58), decision support for risk managers and emergency planning (no.=50). Only two publications aim to provide governance analyses, and one is for training purposes, who is trained is not further stated.

The hazards most studied in these articles are fire (no.=23), explosion (no.=21), and flooding combined with other hazards (no.=19). Elements at risk studied are often industrial installations (51.3%) and infrastructures and buildings (21.7%) . Socio-economic issues are addressed in 3 articles only. The methods applied in the articles are provided in summarised form based on the study undertaken by Curt (2021) and shown in Figure 8.

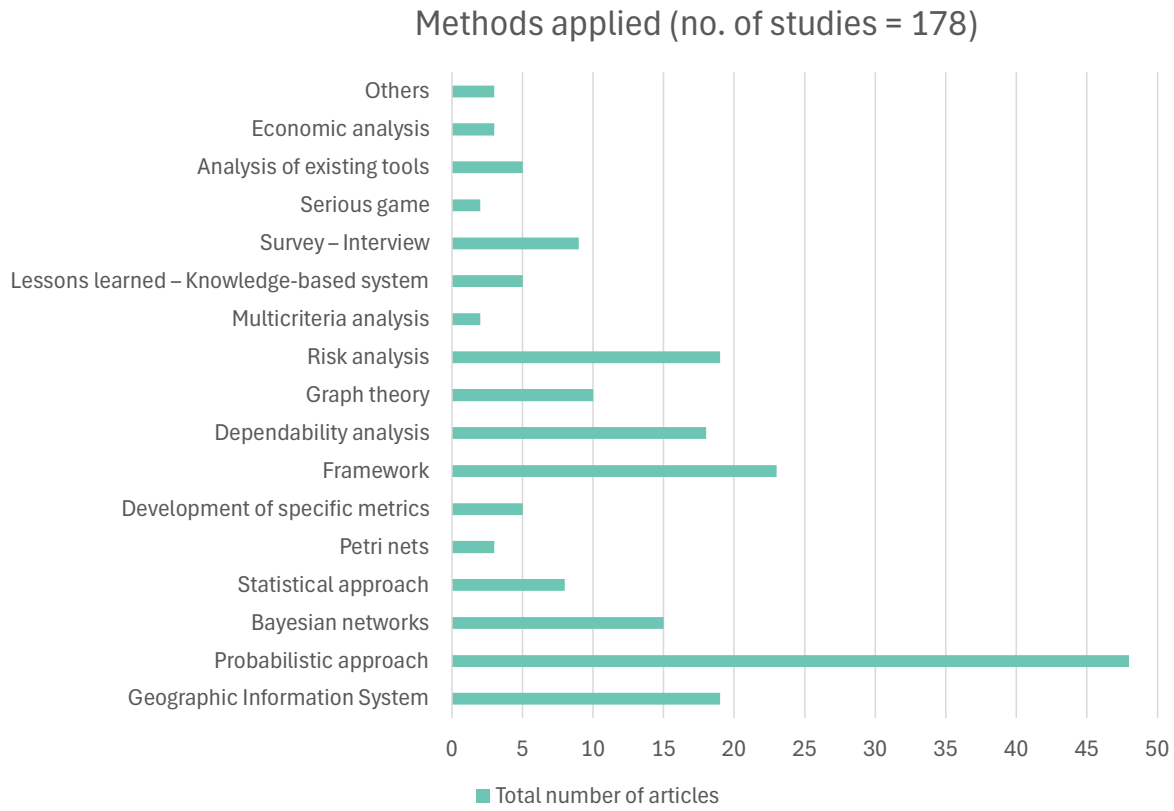


Figure 8. Methods applied in the study undertaken by Curt (2021).

Owolabi and Sajjad (2023)

The systematic and scientometric review from Owolabi mapped 134 publications from 1994 to 2022 with Bibliometrix and VOSviewer.[6] This review is based on a database of abstracts constructed by a systematic search, no further information filtering (or content-based filtering) was applied. Vulnerability and mitigation measures are not covered in the review provided by Owolabi and Sajjad (2023).

It identified the studied topics in multi-hazard risk, contributing authors and countries as well as a temporal overview and trends in research of multi-hazard risk analysis. This is done by

[6] Bibliometrix is a tool for bibliometric analysis: https://www.bibliometrix.org/home/; VOSviewer allows to construct and visualise bibliometric networks: https://www.vosviewer.com/

bibliometric analysis of the abstracts of 134 publications, while no multi-hazard risk analysis methods are presented in the review. The most often used keywords are 'landslide' (104), 'risk assessment' (92), and 'debris flow' (85). One of the most active researchers in this field is Thomas Glade from University of Vienna. The journal *Natural Hazards* has the most publications on this topic (11), followed by *Engineering Geology* and *Natural Hazards and Earth System Sciences* (both 6). An increase in publications can be found starting from the end of 2012, e.g., the review from Kappes, Keiler et al. (2012) was published in the journal *Natural Hazards*.

6. Overview of existing datasets and e-tools relevant to RETIME

This section provides an overview of existing open datasets and e-tools that can support RETIME activities. In particular, datasets and e-tools to be used for hazard, exposure, and vulnerability assessments and hence, multi-risk assessment within RETIME pilot sites are identified at European and global level (*Section 6.1*) and at local level (*Section 6.2*).

6.1. Available datasets and tools at EU and global scale

Several datasets and tools can assist multi-risk assessment and resilience planning. In this context, the datasets were selected based on five criteria:

i) Spatial resolution corresponding to building, neighbourhood, or municipality level
ii) Spatial coverage encompassing RETIME pilot sites
iii) Potential applicability for RETIME tasks
iv) Trustable external source and recognition by EU and international public authorities
v) Open Access (OA)

In addition to the above listed criteria, tools were selected based on their functionalities. Table 9 provides an overview of all datasets and e-tools regarding their applicable RETIME task(s). All selected datasets and tools are described in Annex C.

Table 9. Overview of available data sources and tools applicable for implementing selected RETIME tasks.

Main Purpose (related RETIME tasks)	Potential Data Sources I Authorising organisation(s)
Social indicators and other statistical information on demographics, economy, education, health, environment (T2.1)	INE I Ministry of Finance Pordata I Francisco Manuel dos Santos Foundation (Fundação Francisco Manuel dos Santos) Lisboa Interativa I CML Lisboa Aberta | CML Amadora City Council I LMA Štatistický úrad Slovenskej republiky I Government of the Slovak Republic Statistikaamet I Ministry of Finance of Estonia
Hazard, exposure, vulnerability and risk assessment (T3.1, T3.3)	Risk Data Hub | (European Commission's) Joint Research Centre (JRC) Climate Data Atlas | Copernicus Landing Monitoring Service (CLMS) I EU Census Hub | European Statistical System Database Portal | European Grouping on Territorial Cooperation (ESPON)

	Land Monitoring Service | CLMS I EU
Hazard identification in the three pilot areas (T3.1)	River Flood Hazard Maps | JRC Extreme Precipitation Risk | Copernicus Earthquake Hazard | European Facilities for Earthquake Hazard and Risk (EFEHR) Wildfire Risk Assessment | European Forest Fire Information System (EFFIS) Landslide Susceptibility | European Soil Data Centre (ESDAC) Sea Level Rise | Climate Central Thermofeel (Heat & Cold Wave) | CLMS I EU Air Quality | CLMS I EU
Exposure and vulnerability database (T3.3)	Land cover & use | OpenStreetMap (OSM) Land cover & use | HOT OSM Health Sites | Healthsites.io GISCO | Eurostat
Forecasting and observation for impact-based triggers for and climate proofing assessment of buildings (T3.2, T4.1)	European Drought Observatory | Copernicus Wildfire Observation | Copernicus European Flood Awareness System | Copernicus Early Warnings for Europe | MeteoAlarm GDACS - Global Disaster Alert and Coordination System | UN and EC CLIMA EXTREMO – Risk Warning to Building Occupants During Extreme Weather Events (Portugal) | Foundation for Science and Technology (FCT) UrbClim Local Weather/Air Quality Stations | VITO
Main Purpose (related RETIME tasks)	**Potential E-Tools | Authorising Organisation(s)**
Single-hazard identification in the three pilot areas (T3.1)	Risk Data Hub | JRC Think Hazard | GFDRR
Multi-(hazard) Risk Assessment (T4.6)	INFORM Index | JRC Multi-hazard Risk Modelling | RiskScape CLIMANDA – Probabilistic Risk Analysis (Python) | ETH Zürich Probabilistic Risk Assessment Platform (GIS) | CAPRA OpenQuake – Seismic Risk Assessment | Global EarthQuake Model Foundation
Analysis of climate change projections (T4.3)	Future Weather Generator I CLING | Foundation for Science and Technology (FCT)

Increasing Building Resilience (T4.4, T4.5, T4.6)	The Heat Action Platform | Atlantic Council Climate Resilient Cities Toolbox | Deltares

Although no single database covers all these mentioned aspects, various open databases provide useful and complementary information to carry out different activities, for the hazard identification and assessment within the RETIME pilot sites (WP3/T3.1), if this information is missing. These datasets are of relative fine resolution and can provide information at different scales, at neighbourhood or even building level. For the development of the exposure and vulnerability database (WP3/T3.3), missing data at pilot sites can be supplemented with OpenStreetMap (OSM) or other similar crowdsourced geospatial datasets. However, socio-economic datasets from Eurostat are limited to LAUs (Local Administrative Units) level and are from 2021. Regarding the activities related to the definition of triggers and forecast-based action (WP3/ T3.2 and WP4/ T4.1), multiple EU observation and early warning platforms are listed in Table 9 and detailed in Annex C. These platforms can be used for raising awareness when specific trigger points are reached. In addition, one risk warning platform was indicated which is targeted at building occupants directly (CLIMA EXTREMO).[7]

The review highlighted a few tools that can support the hazard identification, (multi-)risk assessment, and development of roadmaps for increasing the resilience of inhabitants, buildings, and critical infrastructures. Two tools are available indicating the likelihood of different hazards across Europe (Risk Data Hub) and at global level (ThinkHazard!). Both tools indicate these hazard levels at municipality level but not any finer. Therefore, they can support the hazard identification process but may not be suitable for hazard assessment at building level. However, both tools work with a large variety of hazard. In addition to the hazard identification, the Risk Data Hub[8] further provides information on exposure (e.g., related to people and assets) and vulnerability based on different social, economic, physical, and political indicators. A similar tool is available at global level (INFORM Index), based on humanitarian background. Indicators are selected within humanitarian actions, such as aid dependency, deprivation, governance, and only at national level. Yet, the methodology of the tool can be applicable for the risk assessment in RETIME. For a full risk assessment or a multi-risk assessment (WP4/T4.6), different tools are available for implementing RETIME activities. These

[7] http://climaextremo.tecnico.ulisboa.pt/ [Accessed 22.09.2024]
[8] https://drmkc.jrc.ec.europa.eu/risk-data-hub#/ [Accessed 22.09.2024]

tools are based on natural language processing (NLP) or GIS-based mapping tools and provide the risk assessment models, while allowing the integration of external datasets for executing the model.

Finally, up until now, a tool for the analysis of climate change projections is identified (TWP4/4.3), plus two tools can be used for resilience building (WP4/T4.4, T4.5, and T4.6) in the three RETIME pilot sites, e.g., for heat wave, air pollution peaks (from wildfires, dust storms, and peak Hour Traffic Pollution), and floods. The limitation of these tools is that they are primarily focusing on neighbourhood and not building level, while resilience building activities, among others, aim to provide a centralised building information system at meso- and micro-scale.

6.2. Available local datasets and e-tools related to RETIME pilot sites

This section is divided in two parts. The first part provides an overview of the information required for hazard mapping at neighbourhood and building scale (*Section 6.2.1*). The second part introduces the most relevant OA data portals and e-tools related to RETIME pilot sites (Lisbon, Žilina, and Tartu), which are currently available (*Section 6.2.2*). These existing datasets and tools can be adopted to undertake different tasks in RETIME for initial hazard, vulnerability, and multi-risk analysis at the three RETIME pilot sites.

6.2.1. Required information for Hazard Mapping at neighborhood and building scale

A comprehensive vulnerability database is crucial for enhancing risk response strategies and building resilience in RETIME project (WP3/T3.2, WP4/T4.1, T4.4, and T4.5). However, no single database currently provides a complete overview of vulnerabilities. To create a robust and holistic vulnerability database, the following information must be included. At neighbourhood level:

- Exposure to hazards
- Environmental Factors
- Historic Damage Records
- Response Capabilities and Support Capacity
- Regulatory and Legal Data

At district and building level:

- Date of building construction
- State of building conservation
- Building Structural System (and compliance with legislative requirements)
- Building Function (residential, commercial, industrial, or others)
- Socio-Economic and Demographic Characteristics
- Response Capabilities and Support Capacity

- Regulatory and Legal Data

6.2.2. Data portals and e-tools related to RETIME pilot sites

The available data portals in Lisbon, Žilina, and Tartu are listed in Table 10, Table 11. and Table 13, respectively. E-Tools were only identified for Žilina and are listed in Table 12. These lists are not exhaustive and will be enriched throughout the project.

Table 10. Data portals for Lisbon Metropolitan Area pilot site.

Data Portal: Geodados	
Link to online source	https://geodados-cml.hub.arcgis.com
Access rights	Open Access
Authorising organisation	Lisbon Town Council (CML- Câmara Municipal de Lisboa)
Spatial coverage	Lisbon Municipality
Spatial resolution	Differs for datasets
Potential applicability for RETIME	Analysis of socio-economic contexts, identification of vulnerable groups, and stakeholder mapping at pilot sites (T2.1) Hazard identification in the three pilot areas (T3.1) Exposure and vulnerability database (T3.3) Forecasting and observation for impact-based triggers for and climate proofing assessment of buildings (T3.2, T4.1) Multi-(hazard) Risk Assessment (T4.6) Increasing Building Resilience (T4.4, T4.5, T4.6)
(Exportable) Data format	.CSV, .SHP, GeoJSON, KML, Excel, GeoPackage, Geodatabase SQLite
Application Programming Interface (API) access	https://services.arcgis.com/1dSrzEWVQn5kHHyK/ArcGIS/rest/services
Language	Portuguese
Data Portal: Lisboa Inteligente	
Link to online source	https://lisboaaberta.cm-lisboa.pt/index.php/pt/
Access rights	Open Access
Authorising organisation	Lisbon Town Council (CML- Câmara Municipal de Lisboa)
Spatial coverage	Lisbon
Spatial resolution	Differs for datasets

Potential applicability for RETIME	Analysis of socio-economic contexts, identification of vulnerable groups, and stakeholder mapping at pilot sites (T2.1) Hazard identification in the three pilot areas (T3.1) Exposure and vulnerability database (T3.3) Forecasting and observation for impact-based triggers for and climate proofing assessment of buildings (T3.2, T4.1) Multi-(hazard) Risk Assessment (T4.6) Increasing Building Resilience (T4.4, T4.5, T4.6)
(Exportable) Data format	.XLS, .CSV, .JSON, .GeoJSON, . JSON-LD, .TIFF
API access	Not available
Language	Portuguese
Data Portal: Lisboa interativa	
Link to online source	https://websig.cm-lisboa.pt/MuniSIG/visualizador/index.html?viewer=LxInterativa.LXi
Access rights	Open Access
Authorising organisation	Lisbon Town Council (CML- Câmara Municipal de Lisboa)
Spatial coverage	Lisbon Municipality
Spatial resolution	Differs for datasets
Potential applicability for RETIME	Exposure and vulnerability database (T3.3) Multi-(hazard) Risk Assessment (T4.6) Increasing Building Resilience (T4.4, T4.5, T4.6)
(Exportable) Data format	.PDF, .PNG, .TIF, .geoTIFF, .BMP,.JPEG
API access	Not available
Language	Portuguese, English menu available
Data Portal: Pordata	
Link to online source	https://www.pordata.pt/pt
Access rights	Open Access
Authorising organisation	Fundação Francisco Manuel dos Santos (FFMS)
Spatial coverage	Portugal, at national level and sub-national levels (districts, municipalities).
Spatial resolution	national and regional-level statistics, municipal-level resolution
Potential applicability for RETIME	Analysis of socio-economic contexts, identification of vulnerable groups, and stakeholder mapping at pilot sites (T2.1). Exposure and vulnerability database (T3.3)
(Exportable) Data format	.CSV, .XLS, or .PDF
API access	Not available
Language	Portuguese
Data portal: Statistics Portugal	
Link to online source	https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_main

Access rights	Open Access
Authorising organisation	Statistics Portugal
Spatial coverage	Portugal
Spatial resolution	Differs for datasets
Potential applicability for RETIME	Analysis of socio-economic contexts, identification of vulnerable groups, and stakeholder mapping at pilot sites (T2.1) Hazard identification in the three pilot areas (T3.1) Exposure and vulnerability database (T3.3) Forecasting and observation for impact-based triggers for and climate proofing assessment of buildings (T3.2, T4.1) Multi-(hazard) Risk Assessment (T4.6) Increasing Building Resilience (T4.4, T4.5, T4.6)
(Exportable) Data format	Differs for datasets
API access	Not available
Language	Portuguese, English
Note	Portal users can submit proposals for the dissemination of new datasets.

Table 11. Data portal for Žilina pilot site.

Data Portal: GISPLAN MESTA Žilina	
Link to online source	https://zilina.gisplan.sk/
Access rights	Open Access and log-In for users with credentials
Authorising organisation	T-MAPY Slovensko s.r.o. (private company supplying the tool to the city of Žilina)
Spatial coverage	The geographical area of the city of Žilina given by the administrative division
Spatial resolution	GISPLAN includes several applications (basic application providing information about the administrative division of the city; cadastral map; map of road infrastructure; map of advertisement panels; map of green areas; plan of land-use; map of playgrounds and sport facilities). Spatial resolution is adjusted based on the purpose of each layer
Potential applicability for RETIME	Hazard identification in the three pilot areas (T3.1) Exposure and vulnerability database (T3.3) Forecasting and observation for impact-based triggers for and climate proofing assessment of buildings (T3.2, T4.1) Multi-(hazard) Risk Assessment (T4.6)

(Exportable) Data format	Without logging in, only extraction of maps to PDF files is possible. No information is available about functionalities for users with credentials.
Language	Slovak
API access	Not available
Data portal: Monthly situation report of Ministry of the Interior of the Slovak Republic	
Link to online source	https://slovak.statistics.sk/wps/portal/ext/home
Access rights	Open Access
Authorising organisation	Statistical office of the Slovak Republic
Spatial coverage	Slovakia
Spatial resolution	N/A
Potential applicability for RETIME	Hazard identification in the three pilot areas (T3.1) Multi-(hazard) Risk Assessment (T4.6)
(Exportable) Data format	.docx
API access	https://data.statistics.sk/api/v2/collection?lang=en https://slovak.statistics.sk/wps/portal/ext/Databases/Open_data/
Language	Slovak
Note	The data is available for download in (.docx) format, request of this information in . XLS format possible at the Ministry of the Interior
Data portal: Website of the Statistical Office of the Slovak Republic	
Link to online source	https://slovak.statistics.sk/wps/portal/ext/home
Access rights	Open Access
Authorising organisation	Statistical Office of the Slovak Republic
Spatial coverage	Slovakia
Spatial resolution	Differs for datasets
Potential applicability for RETIME	Analysis of socio-economic contexts, identification of vulnerable groups, and stakeholder mapping at pilot sites (T2.1) Hazard identification in the three pilot areas (T3.1) Exposure and vulnerability database (T3.3) Forecasting and observation for impact-based triggers for and climate proofing assessment of buildings (T3.2, T4.1) Multi-(hazard) Risk Assessment (T4.6) Increasing Building Resilience (T4.4, T4.5, T4.6)
(Exportable) Data format	Differs for datasets
API access	https://data.statistics.sk/api/v2/collection?lang=en https://slovak.statistics.sk/wps/portal/ext/Databases/Open_data/
Language	Slovak, English
Note	Portal users can submit proposals for the dissemination of a new dataset to the Data research Centre (DRC). The DRC is a special

	workplace situated at the headquarters of the Statistical Office of the SR (SO SR) at Lamačská cesta in Bratislava. It is intended to serve the needs of experts, analysts, scientists as well as researchers requesting access to data that have not been published.

Table 12. E-tools for Žilina pilot site.

E-tool: Albert+	
Links to online information	https://www.albert.plus/
Licensing requirements and access rights	Commercial product. A separate payment needs to be done for each report/analysis (the fee is up to 24 Euro VAT)
Authorising organisation	ESPRIT spol. s r.o. (private company) (https://www.esprit-bs.sk/)
Description of relevant functionality	Tool provides for given locality a report (PDF file) that contains analyses of legislative restrictions (e.g., overlaps with national network of protected areas, Natura 2000), natural hazards (risk of flood, seismic activity, etc.), protective zones (e.g., overlaps with road protection zone, airport protective zone), pollution (soil pollution, air pollution), and anthropogenic risks (environmental burdens and landfills, accidents involving industrial buildings or technical infrastructure).
Use	Albert+ serves as a benchmark for hazard, vulnerability, and multi-risk assessment tools developed by RETIME.
Potential applicability for RETIME	Multi-(hazard) Risk Assessment (T4.6)
Language	Slovak, English
Notes	A main business model behind the tool is an information service provided to people interested in buying a real-estate property.
E-tool: Floods-risk map	
Links to online information	https://mpt.svp.sk/svp_vmapportal
Access rights	Open Access
Authorising organisation	Slovak Water management company, state owned enterprise (Slovenský vodohospodársky podnik, š.p.)
Description of relevant functionality	Tool allows visualisation of water maps (e.g., flooding maps, water management map, water level measuring stations, river basins, dams, lakes, flood protection facilities).
Usage	If some of the presented data will be needed, an attempt can be made to get them from the web tool provider.
Potential applicability for RETIME	Hazard identification in the three pilot areas (T3.1) Exposure and vulnerability database (T3.3) Forecasting and observation for impact-based triggers for and climate proofing assessment of buildings (T3.2, T4.1) Multi-(hazard) Risk Assessment (T4.6) Increasing Building Resilience (T4.4, T4.5, T4.6)
Language	Slovak

Notes	There is no direct access to data for user with the public account.

Table 13. E-tools for the Lisbon pilot site.

E-tool: Future Weather Generator	
Links to online information	https://future-weather-generator.adai.pt/
Licensing requirements and access rights	Open-source and cross-platform
Authorising organisation	This software is developed under the CLING Project, which is supported by the Portuguese Foundation for Science and Technology with grant number PTDC/EME-REN/3460/2021.
Description of relevant functionality	The 'Future Weather Generator' is a Java app for researchers and building design professionals. It morphs present-day hourly EPW files used in dynamic simulation to match climate change scenarios and the urban heat island effect.
Use	Dynamic simulation to match climate change scenarios and the urban heat island effect.
Potential applicability for RETIME	Multi-(hazard) Risk Assessment (T4.6) Exposure and vulnerability database (T3.3)
Language	English
Notes	
E-tool: InfoRiscos	
Links to online information	https://www.pnrrc.pt/index.php/geovisualizador/
Access rights	Open Access
Authorising organisation	National Emergency and Civil Protection Authority (ANEPC)
Description of relevant functionality	Tool allows visualisation of risk maps (e.g., floodings, tsunami, heatwaves, etc).
Usage	If some of the presented data will be needed, an attempt can be made to get them from the web tool provider.
Potential applicability for RETIME	Hazard identification in the three pilot areas (T3.1) Exposure and vulnerability database (T3.3) Multi-(hazard) Risk Assessment (T4.6)
Language	Portuguese
Notes	

Table 14. Data Portal for the Tartu pilot site.

Data portal: Estonian open data portal	
Link to online source	https://avaandmed.eesti.ee/
Access rights	Open Access
Authorising organisation	Publishers in the open data portal are all institutions from the public, third and private sectors
Spatial coverage	Estonia and counties
Spatial resolution	Differs for datasets
Potential applicability for RETIME	Analysis of socio-economic contexts, identification of vulnerable groups, and stakeholder mapping at pilot sites (T2.1) Hazard identification in the three pilot areas (T3.1) Exposure and vulnerability database (T3.3) Forecasting and observation for impact-based triggers for and climate proofing assessment of buildings (T3.2, T4.1) Multi-(hazard) Risk Assessment (T4.6) Increasing Building Resilience (T4.4, T4.5, T4.6)
(Exportable) Data format	Differs for datasets
API access	https://avaandmed.eesti.ee/api/datasets/ Estonian API manual
Language	Estonian. The English version is limited to web page menu
Note	This data source was produced within a programme financed by the EU and Investing in your future programme. Portal users can submit proposals for the dissemination of new datasets.
Data portal: Geoportal Republic of Estonia Land Board / Estonian Geoportal	
Link to online source	https://geoportaal.ee/eng/
Access rights	Open Access
Authorising organisation	Estonia Land Board
Spatial coverage	Estonia
Spatial resolution	Differs for datasets

Potential applicability for RETIME	Analysis of socio-economic contexts, identification of vulnerable groups, and stakeholder mapping at pilot sites (T2.1) Hazard identification in the three pilot areas (T3.1) Exposure and vulnerability database (T3.3) Forecasting and observation for impact-based triggers for and climate proofing assessment of buildings (T3.2, T4.1) Multi-(hazard) Risk Assessment (T4.6) Increasing Building Resilience (T4.4, T4.5, T4.6)
(Exportable) Data format	Various (e.g., .SHP, GeoJSON, .GML)
API access	https://metadata.geoportaal.ee/geonetwork/doc/api/index.html
Language	Estonian, English
Data portal: Estonian Research Information System	
Link to online source	https://www.etis.ee/
Access rights	Open Access
Authorising organisation	Estonian Ministry of Education and Research
Spatial coverage	Estonia
Spatial resolution	Differs for datasets
Potential applicability for RETIME	For exploitation activities
(Exportable) Data format	Differs for datasets
API access	Not available
Language	Estonian, English
Note	This data source was produced within a programme financed by the EU and Investing in your future programme. Portal users can submit proposals for the dissemination of new datasets.
Data portal: Website of Statistics in Estonia	
Link to online source	https://www.stat.ee/en
Access rights	Open Access
Authorising organisation	Statistics Estonia
Spatial coverage	Estonia
Spatial resolution	Differs for datasets
Potential applicability for RETIME	Analysis of socio-economic contexts, identification of vulnerable groups, and stakeholder mapping at pilot sites (T2.1) Hazard identification in the three pilot areas (T3.1) Exposure and vulnerability database (T3.3) Forecasting and observation for impact-based triggers for and climate proofing assessment of buildings (T3.2, T4.1)

	Multi-(hazard) Risk Assessment (T4.6) Increasing Building Resilience (T4.4, T4.5, T4.6)
(Exportable) Data format	Differs for datasets
API access	https://andmed.stat.ee/api/v1/en https://andmed.stat.ee/help/api-manual.pdf
Language	Estonian, English
Note	This data source was produced within a programme financed by the EU and Investing in your future programme. Portal users can submit proposals for the dissemination of new datasets.
Data portal: Tartu City geoHUB	
Link to online source	https://geohub.tartulv.ee/
Access rights	Open Access
Authorising organisation	Tartu City
Spatial coverage	Tartu
Spatial resolution	Differs for datasets
Potential applicability for RETIME	Analysis of socio-economic contexts, identification of vulnerable groups, and stakeholder mapping at pilot sites (T2.1) Hazard identification in the three pilot areas (T3.1) Exposure and vulnerability database (T3.3) Forecasting and observation for impact-based triggers for and climate proofing assessment of buildings (T3.2, T4.1) Multi-(hazard) Risk Assessment (T4.6) Increasing Building Resilience (T4.4, T4.5, T4.6)
(Exportable) Data format	Various (e.g., .SHP, . GeoJSON, .GML)
API access	https://gis.tartulv.ee/arcgis/rest/services
Language	Estonian, English menu available
Data Portal: Tartu City geoportal	
Link to online source	https://tartu.maps.arcgis.com/apps/mapviewer/index.html
Access rights	Open Access
Authorising organisation	Tartu City
Spatial coverage	Tartu
Spatial resolution	Differs for datasets
Potential applicability for RETIME	Analysis of socio-economic contexts, identification of vulnerable groups, and stakeholder mapping at pilot sites (T2.1) Hazard identification in the three pilot areas (T3.1) Exposure and vulnerability database (T3.3) Forecasting and observation for impact-based triggers for and climate proofing assessment of buildings (T3.2, T4.1)

	Multi-(hazard) Risk Assessment (T4.6) Increasing Building Resilience (T4.4, T4.5, T4.6)
(Exportable) Data format	Various (e.g., .SHP, .GEOJSON, .GML)
API access	https://tartu.maps.arcgis.com/sharing/rest
Language	Estonian, English menu available

6.3. Building Information Modelling for multi-risk assessment

Building Information Modelling (BIM) is one of the most relevant design and management tool for managing digital representations of physical and functional characteristics of buildings and their environments. It enables the remote monitoring and iterative improvement of the entire construction project through a comprehensive and extensible database of intelligent objects. BIM facilitates multi-risk assessment and supports the decision-making process by visualising simulated environments and monitoring external or internal changes and their impact on the living conditions of inhabitants. Finally, it can facilitate the identification of potential changes across various project design scenarios, which may vary based on occupancy types and environmental stressors.

Its effectiveness has been proven in literature for over a decade in various contexts, especially when associated with other tools. For example, GIS data sources and machine learning (ML) algorithms have been used for pre-disaster planning of dynamic evacuation routes that change depending on event conditions (Shiau et al., 2023), considering the crowding effect (Cheng et al., 2017) or human behaviour (Ma & Wu, 2020). Additionally, real-time monitoring can be enhanced by integrating BIM and Internet of things (IoT) data (Huang et al., 2023), with wireless sensor network for indoor safety management. BIM models can easily be used with VR/AR technology to better communicate with population and with non-technical users, overcoming geographical and language barriers. BIM has been applied specially to address risks related to fire, earthquake, and flood scenarios, while other natural or human-induced hazards have been neglected so far. Additionally, there is a need for more quantitative approaches in this field (Khanmohammadi et al., 2020). BIM models can simulate and analyse building responses to natural hazards identifying both weak points and structural and occupational vulnerabilities. They allow for detailed scenario-based planning and risk assessment, improving design resilience and safety measures. Integration of real-time data and historical records will enhance predictive capabilities and emergency preparedness (for seismic damage prediction (Mousavi et al., 2022; Welch et al., 2014).

To ensure that the data that is gathered and included in the models is sufficient and necessary throughout the project phases, it is necessary employ the Level of Information Need (LOIN)[9] (*Building Information Modelling — Level of Information Need — Part 1: Concepts and Principles*, 2024). This framework enables effective decision-making, coordination, and project execution, depending on the *Level of Model Definition* (LOMD), that is the sum of the Level of Detail (LOD) plus the Level of Information (LOI), as shown in Figure 9.[10]

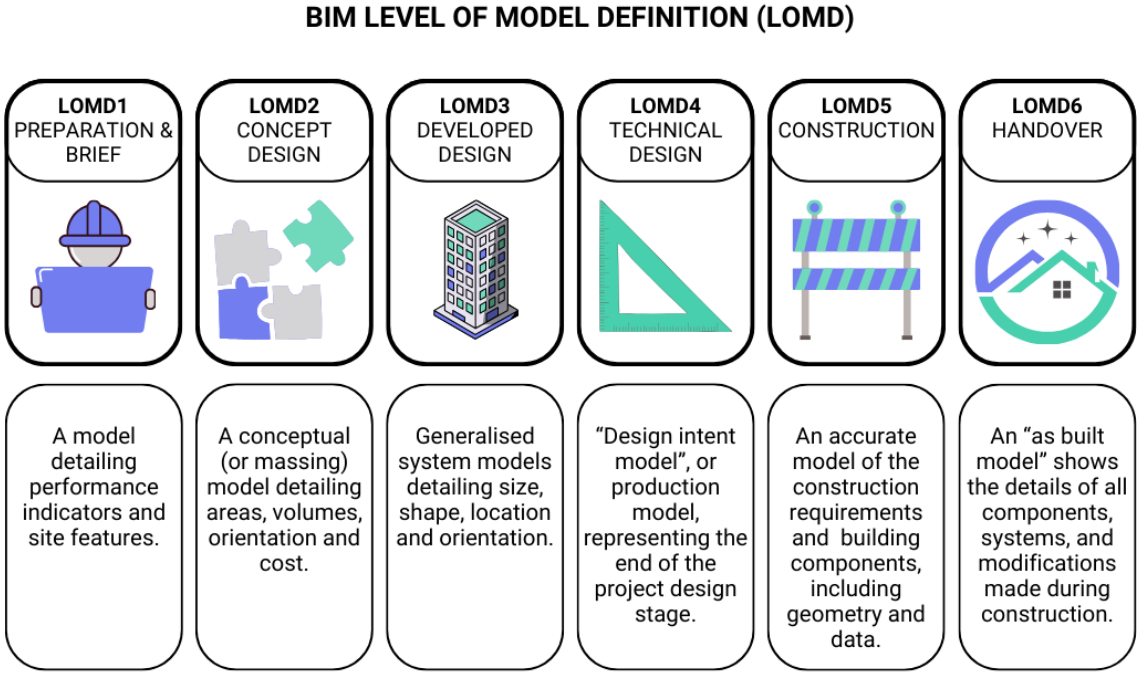


Figure 9. BIM level of model definition (LOMD).

LOD identifies the completeness and reliability of the information at different stages throughout the project lifecycle. Each LOD level outlines what is included in the model, ranging from simple geometric shapes at lower levels to fully functional elements or building components at higher levels.

[9] The LOIN describes the granularity of the exchanged information in terms of geometric data, alphanumeric data, and documentation.

[10] *Figure 9* is adapted by the authors from the illustration published in: https://evolve-consultancy.com/lod-lod-loi/ [Accessed 23 July 2024]

Table 15 shows the main building characteristics (considering load-bearing and non-load-bearing components) at building and district levels, and their relevance for RETIME activities, ranging from evaluating environmental performance to estimating hazard vulnerability or assessing the impact of thermal differences due to climate change.

Table 15. BIM analysis for each building component and relevance for RETIME.

Characteristic	Building level	District Level	Relevance for RETIME
Building envelope geometry	Building/block footprint, deployment area, number of floors, total height (height of the underground and above-ground building).	External envelope geometry, including balconies, overhangs, neighbour buildings, trees, and any other volumes that can shade or affect the building	Assessment of thermal comfort, environmental impact, and cost estimation
Structural system	Foundation and load-bearing structure	'Building block' effect, structural reliability	Estimation of vulnerability to storms and earthquakes or other geohazards
Windows	Window area in each facade and roof	Window characteristics: orientation, depth in the facade, external and internal shading system, and glass characteristics (e.g., solar gain and thermal resistance)	Calculation of solar gains according to facade orientation, calculate building and the thermal performance of the house
(External) Walls	Construction type (e.g., ETICS -External Thermal Insulation Composite System), concrete, masonry, or brick), total thickness, and quality construction material	Layers' thickness, materials features, hygro-thermal and acoustic characteristics and conservation state, and presence of thermal bridges	Calculation of heat gains and losses through walls, calculation of buildings and house thermal performance
Roof	*Same as Walls*	*Same as Walls*	*Same as Walls*
Heating, ventilation, and air conditioning (HVAC),	Existing systems and their capacity	System Characteristics: *Availability:* Not currently in place or in place. *Type:* Individual (for each house) or collective systems. *Efficiency:*	Calculation of system capacity and its resilience to extreme phenomena such as heat waves or heavy rain

renewable energy, power and water supply and drainage, and other systems		Varies by system type. *Utilities:* Bills for Electricity, gas, water, and heating	

A high-level analysis of available data can be performed to explore its potential for methodologies and tools developed within RETIME project. In RETIME, as 'a built model' will be used to assess the performance of individual building components in selected building blocks, as well as the overall performance of the building and how it integrates with its surroundings.
RETIME also aims to employ BIM to carry out a comprehensive Life-Cycle Analysis (LCA) of buildings in selected pilot sites (WP4/T4.2).

6.4. Virtual Reality scenarios and potential use in multi-risk assessment activities

Augmented Reality (AR) and Virtual Reality (VR)-based tools have traditionally been applied in sectors such as gaming, entertainment, healthcare, education, architecture, and real estate. However, within RETIME project, it was found that fully integrated VR solutions linked to Building Information Modelling (BIM) were not readily available to meet the specific needs and priorieties defined in this project. Instead, VR has proven to be particularly valuable in scenarios designed to develop skills in crisis situations, where its interactive capabilities allow for a better understanding and prediction of various crisis scenarios. The following text provides a brief literature review, focusing on the applications of VR across various sectors, with particular emphasis on its use in planning, risk management, and enhancing resilience to crises. These applications serve as an inspiration for the potential use of VR within the RETIME project. While VR is being adopted in other sectors such as architecture, construction, and healthcare, its full potential in these areas remains yet to be fully explored.
Among others, Wang et al. (2018) demonstrated that the integration of VR with BIM can significantly enhance the accuracy of architectural design visualisation and decision-making processes in the Architecture, Engineering, and Construction (AEC) sector. Their study was conducted in the context of improving education and practice in quantity surveying (QS), utilising software such as Autodesk Revit 2016, Autodesk 3ds Max Design 2015, and Unity. The study included structured interviews with 200 construction professionals, including quantity surveyors, BIM specialists, and architects, who tested the VR-BIM system and provided feedback on its effectiveness. These participants were specific end-users with relevant expertise in the AEC sector, and their insights helped assess the practical applications of the system. VR proved

to be an effective tool for closer-to-real visualisation of future projects, allowing participants to better understand the different phases of construction and the potential risks that could arise during the project lifecycle.

León et al. (2024) focused on the use of VR for simulating risks associated with vertical evacuation of buildings in tsunami-prone areas. VR was utilised to create realistic evacuation simulations, allowing participants to 'experience' these crisis situations and test different evacuation strategies. This approach led to a better understanding of how these strategies could be implemented in practice and which factors influence decision-making processes during evacuation. The participants, a sample of 151 individuals, were primarily local residents from Viña del Mar, Chile, along with some visitors. Furthermore, VR was integrated with agent-based models that simulate real-time decision-making processes of individuals, enabling the identification of weaknesses in evacuation plans and ultimately improving the effectiveness of vertical evacuations. Such simulations not only serve as an effective training tool for local authorities but also as a means to optimise policies aimed at increasing safety in tsunami-prone areas.

Boton et al. (2018) applied VR in a 4D BIM environment to analyse construction schedules, enabling real-time simulation of individual construction phases and early identification of potential issues, such as spatial-temporal conflicts, equipment access limitations, and material handling inefficiencies. The study demonstrated how VR can provide a platform for detailed project planning and analysis, improving problem predictability and reducing risks associated with construction delays. VR could also be used for scenario-based solutions focused on long-term strategic decision-making. Experts and decision-makers could better understand the impacts of their decisions and assess which policies best contribute to urban resilience.

Lin et al. (2018) used VR to enhance interaction between designers and stakeholders in healthcare projects. VR was used in a semi-immersive environment, particularly in the design of a cancer hospital, allowing medical staff (doctors, nurses) and stakeholders to experience 3D models of healthcare spaces, such as patient rooms and outpatient areas. This helped communicate complex design solutions more effectively, improving mutual understanding and decision-making. Through the use of VR, stakeholders could review room layouts, lighting, and space allocation, and provide real-time feedback, which led to significant design improvements. This approach demonstrated that VR is an effective tool for enhancing communication and collaboration among different teams. Similarly, through VR scenarios, local communities and experts could be engaged in planning climate change adaptations, enabling residents to 'visit' future versions of their city and understand how proposed solutions would mitigate risks, potentially increasing their support for the project.

Afzal & Shafiq (2021) focused on the use of VR in safety training within multicultural workplaces, particularly in the construction industry in the UAE. The study demonstrated that VR could overcome language barriers in a multilingual environment by simulating real workplace scenarios, such as fall hazard prevention. The participants included construction managers, safety inspectors, and workers from diverse linguistic backgrounds, including English, Arabic, Urdu, and Pashto speakers. VR was used to enhance the understanding of safety protocols by providing real-time immersive experiences. This enabled participants to better prepare for potential risks, such as falls from height, and improved their ability to respond to emergency situations effectively. The study concluded that 4D BIM-enabled VR improved safety knowledge, hazard identification, and communication among multilingual teams.

Samarakkody et al. (2023) focused on the use of VR combined with other technological innovations to enhance urban resilience to disasters. VR was applied to simulations of urban scenarios, particularly in the context of smart cities, enabling users to explore different urban layouts and disaster response strategies. For instance, simulations of flooding in densely populated areas allowed city planners to identify infrastructure vulnerabilities and assess the effectiveness of proposed disaster mitigation measures. This application of VR enabled participants, such as urban planners and disaster response teams, to better understand risks associated with natural disasters like floods or earthquakes, and to evaluate potential solutions. Furthermore, VR can be integrated with sensor systems to monitor real-world environments in real time. Data from air quality or flood risk sensors can be visualised in these simulations, aiding in the prediction of crisis situations

In RETIME, VR and AR applications can play a key role in assessing the impacts of various crisis scenarios, such as those based on RCP2.6, RCP4.5, and RCP8.5 scenarios defined by the IPCC. Augmented Reality (AR) will be utilised to enrich BIM models with data related to building pathologies and the state of conservation of construction elements through voice commands, supporting smart inspections during the planning phase of renovation works. AR will be integrated with VR hardware, robots, and drones, enhancing real-time data collection and visualisation. In this way, local communities and professionals will be able to observe how different risks affect specific areas and infrastructures, leading to improved preparedness and decision-making processes. VR models will also be used to materialise the emergency management plans developed under task T4.1, for the purpose of testing and training crisis scenarios. Realistic simulations will enable local authorities, firefighters, paramedics, and other professionals to practice their responses to crisis situations in a safe, simulated environment without real-world threats, thereby increasing their preparedness for potential hazards.

7. Multi-dimensional analysis of vulnerability, risk scenarios, and hazard characteristics in RETIME pilot sites

This section is divided into three parts. *Section 7.1* provides a brief overview of geographical areas related to three RETIME pilot sites. Existing Europe-wide sources and e-tools (Risk Data Hub and ThinkHazard!) are used to conduct comparable preliminary hazard, vulnerability and multi-risk analyses in *Section* 7.2. *Section 7.3* present analysis based on pilot-site specific sources and e-tools.

7.1. Geographical analysis of RETIME pilot sites

This Section introduces the main spatial and demographics characteristics of geographical areas, which will be further analysed in *Section 7.2*. The analyses are conducted at two resolution levels, supported by the 'Risk Data Hub'[11] and ThinkHazard! [12] e-tools, respectively.

7.1.1. Lisbon pilot area

RETIME considers the Lisbon Metropolitan area, which is centred on Lisbon, the capital of Portugal. Lisbon is one of the oldest European cities. Situated along the western coast of the Iberian Peninsula, facing the Atlantic Ocean, it features iconic landmarks, historic buildings, and cultural sites that overlook the Tagus River. RETIME focuses on district *Bairro da Boavista* (meaning *District with a Good view*) which is a municipal affordable neighbourhood with approximately 20 thousand inhabitants, in the northwest of Lisbon, close to Monsanto Forests Park (1 000 ha). In Risk Data Hub and ThinkHazard! were selected areas that include or intersect with the pilot area. Figure 10 shows the Lisbon Metropolitan Area (Area: 3015 km^2; Population: 3 million), as shown in the Risk Data Hub tool, while Figure 11 displays the city of Lisbon as shown in ThinkHazard! tool (Area: 100 km^2; Population: 0.567 million). The map of the district *Bairro da Boavista and* surrounding areas that will be the subject of further analysis in the RETIME project is depicted in Figure 12.

[11] https://drmkc.jrc.ec.europa.eu/risk-data-hub#/ [Accessed on 26 August 2024]
[12] https://thinkhazard.org/en/ [Accessed on 26 August 2024]

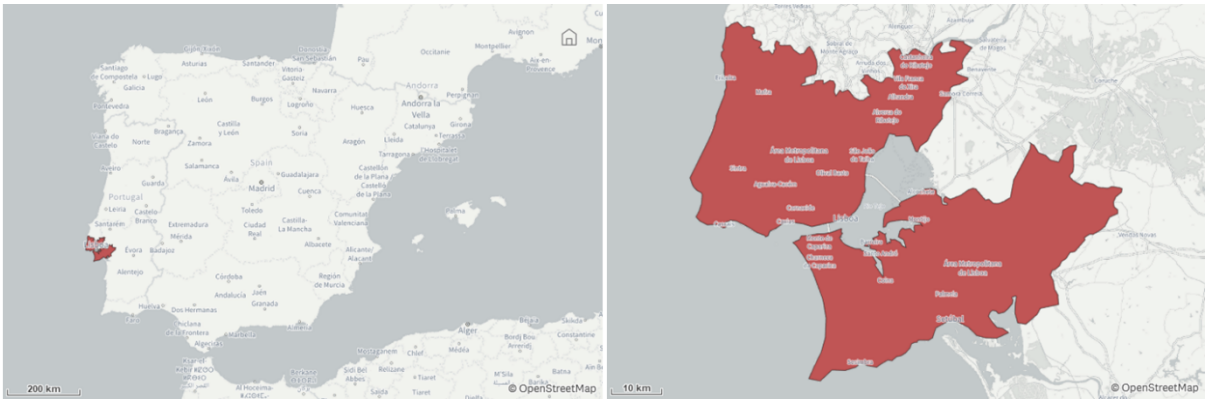


Figure 10. Lisbon Metropolitan Area (NUTS-3 level; source: Risk Data Hub, 2024).



Figure 11. City of Lisbon (source: ThinkHazard!, 2024).

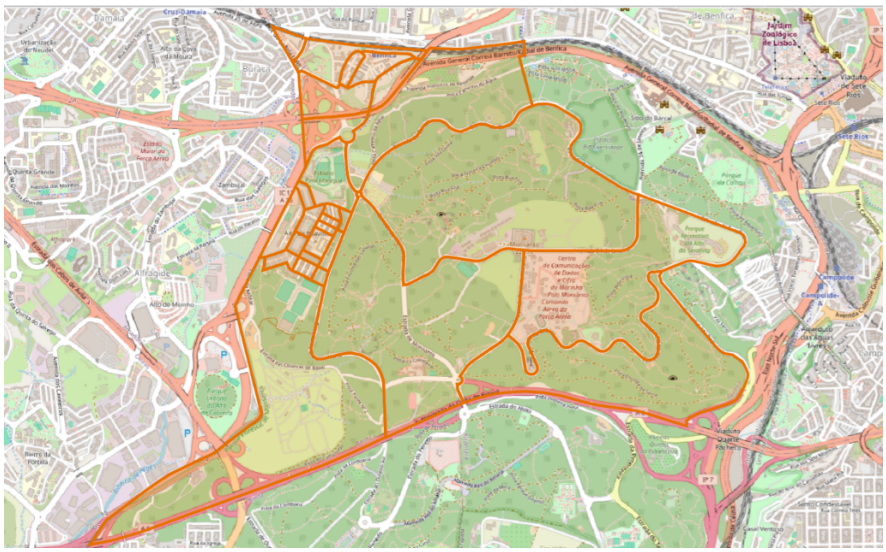


Figure 12. The district Bairro da Boavista in Lisbon and surrounding districts (source: OpenStreetMap, 2024).

7.1.2. Žilina pilot area

Žilina Region (Area: 6 809 km^2; Population: 689k) is the third largest region in Slovakia and accounts for 13.8% of the territory. It is bordered by the Czech Republic in the north-west, Poland in the north, the Prešov Region in the east, the Banská Bystrica Region in the south and the Trenčín Region in the south-west. On a medium scale, RETIME considers the city of Žilina (Area: 80.02 km^2, Population: 80k), the fourth largest city of Slovakia, and capital town of the Žilina Region and a namesake district (*okres*). It is located in the north central part of the country, at the confluence of Váh, Kysuca and Rajčianka rivers. Žilina city and the district (Area: 815 km^2, Population: 160k) belong to the Trans-European Transport Network (Baltic Adriatic Corridor).

The Žilina pilot targets vulnerable hotspots, e.g., the senior house Straník), that with high exposure to multiple hazards, increasing trend in their magnitude and frequency due to climate change, along with social and structural vulnerability of infrastructure, such as those affecting people with special needs and buildings of particular significance for use or cultural value. The geographical area available in the Risk Data Hub (Figure 13) represents the Žilina region. The ThinkHazard! e-tool allows to analyse the area of the Žilina district (Figure 14). The location of the senior house Straník is visualised ain Figure 15.

.

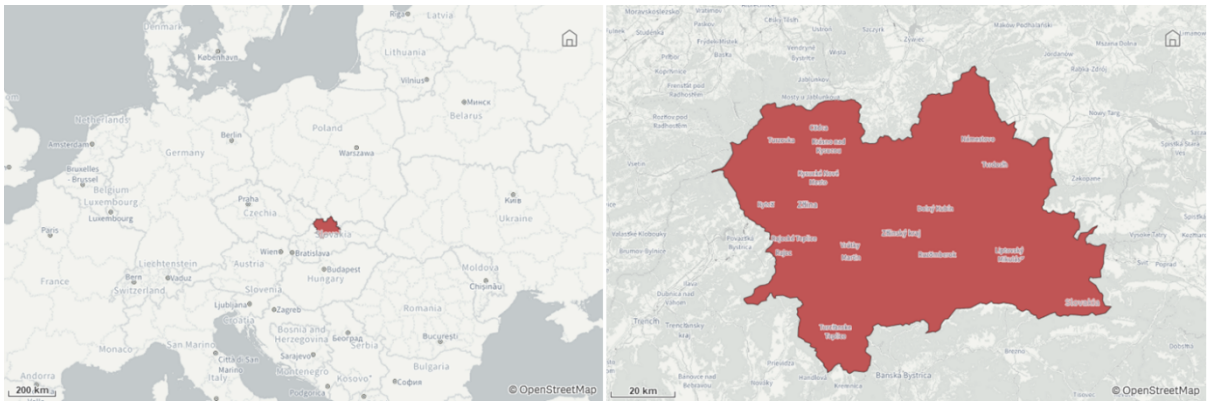


Figure 13. Žilina region (NUTS-3 level; source: Risk Data Hub, 2024).

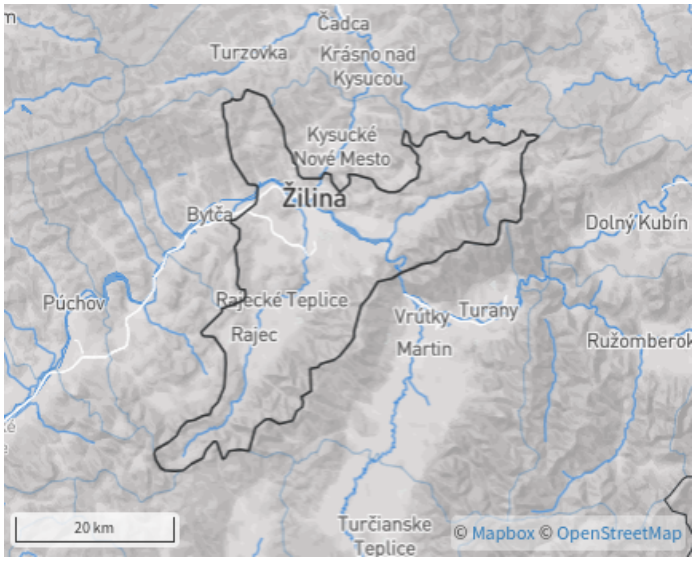


Figure 14. Žilina district (source: ThinkHazard!, 2024).

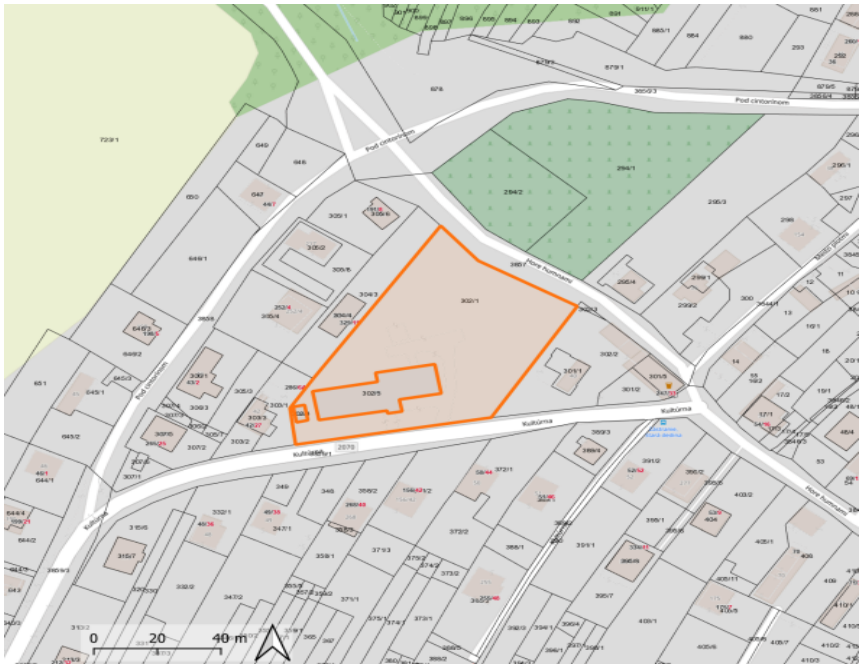


Figure 15. Map showing the geographical area and building of the senior house Straník (source: Albert tool, 2024).

7.1.3. Tartu pilot area

Tartu (Area: 39 km^2; Population: 100k) is the second largest city in Estonia, situated in Southern part of the country. It is 186 kilometres southeast of Tallinn and 245 kilometres northeast of Riga, Latvia. Tartu lies on the Emajõgi river, which connects the two largest lakes in Estonia, Lake Võrtsjärv and Lake Peipus. The river Emajõgi divides Tartu into two parts being one of the potential sources for natural disasters. The city encompasses a combination of government,

commercial, and residential areas. It showcases innovative smart city initiatives aimed at reducing environmental impact and enhancing resilience. The integration of green spaces, efficient transportation systems, and renewable energy solutions in the city centre, where this project will be focused, highlights the commitment to face adverse climate change impacts. The historic centre exemplifies how a forward-thinking approach to urban planning can create a model for eco-friendly living and serve as an inspiration for other communities. Figure 16 shows the location of city of Tartu as mapped in 'Risk Data Hub' and the Tartu Lõuna-Eesti Region (Area: 15 799 km^2; Population: 322k), while Figure 17 shows the maps from 'ThinkHazard!'. The Tartu city centre and surrounding areas are visualised in Figure 18.

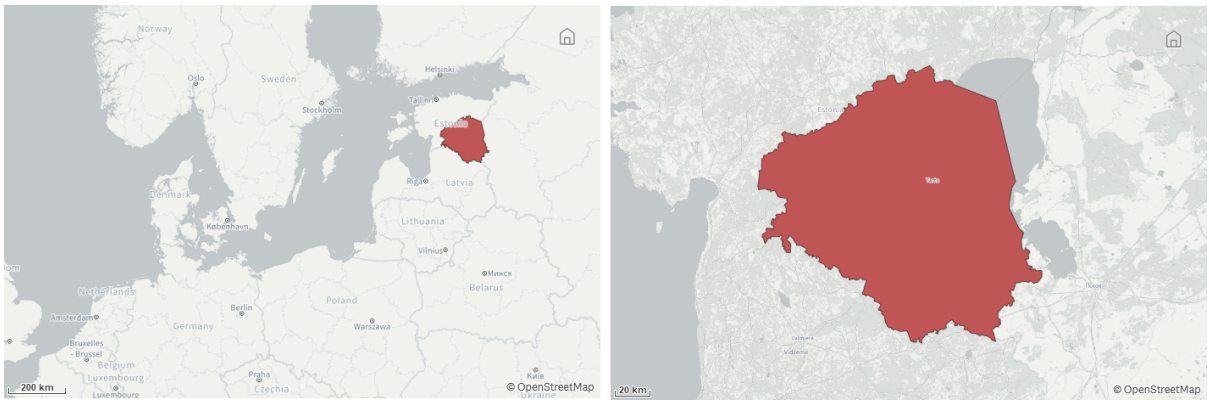


Figure 16. Tartu - Lõuna-Eesti region (NUTS-3 level; source: Risk Data Hub).

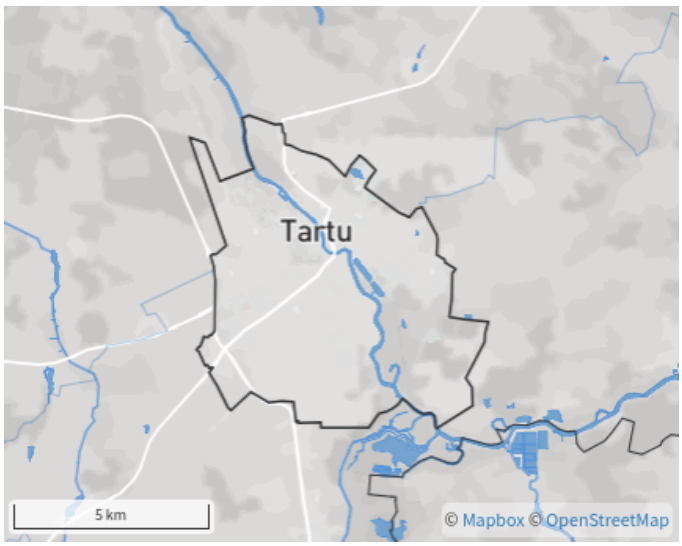


Figure 17. The city of Tartu (source: ThinkHazard! platform).

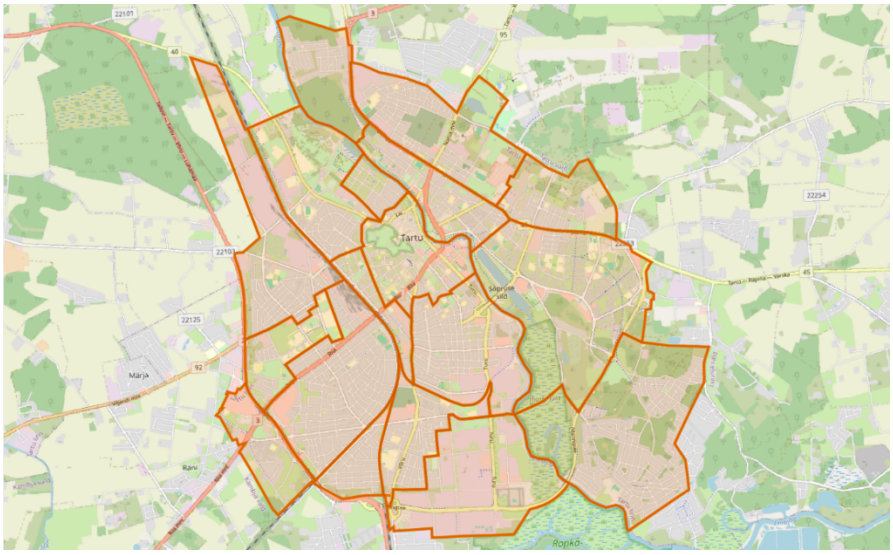


Figure 18. The Tartu city centre and surrounding areas (source: OpenStreetMap, 2024).

7.2. Preliminary multi-risk and vulnerability assessment in RETIME pilot sites

This preliminary analysis is based on e-tools and platforms detailed in *Section 6.1* and Annex C. As outlined in *Section 6*, the 'Risk Data Hub' and 'ThinkHazard!' are the most suitable open access platforms/tools for multi-risk assessments. Both provide an overview and preliminary assessment of hazard, exposure, and vulnerability at European and global level, including the RETIME pilot areas. More specifically, the 'ThinkHazard!' platform provides an overview on hazard likelihoods in a municipality (or any coarser scale). The hazard likelihood is indicated using four qualitative categories (very low, low, medium, and high).

The Risk Data Hub provides an overview on exposures and vulnerabilities in the pilot areas. The exposure data is available for municipality level (LAU - Local Administrative Units), while the vulnerabilities are only indexed down to NUTS 3 level.

The vulnerability index adopted in the Risk Data Hub includes the following interrelated dimensions:

- *Social:* indicators area related to health, dependencies, social participation, education, demographics, and population structures
- *Economic:* indicators are related to economic well-being of the country and the population, inequalities, and employment situations
- *Political:* indicators related to governmental efficiency and political stability, adaptation strategies, regional quality of governments

- *Environment:* indicators related to protected areas, environmental well-being, and biodiversity
- *Physical:* indicators related to infrastructure, heritage, and others

Unfortunately, the 'Risk Data Hub' currently does not provide exposure information for all hazards identified in the 'ThinkHazard!'.

The multi-dimensional risk analysis of RETIME pilot sites, based on the information from the 'ThinkHazard! Platform' (hazard likelihood) and the Risk Data Hub (exposure and vulnerability), is shown in Figure 19. The vulnerability index is independent from hazards and provides information on vulnerability in form of scores ranging from 0 to 10, whereas 10 indicates a high vulnerability. The exposure is expressed for the population, buildings, critical infrastructure, and agriculture. Critical infrastructure covers various sectors listed in the EU Taxonomy,[13] such as water supply, sewerage, waste management and remediation, energy, and transport. The vulnerability is categorised into social, economic, political, environmental, and physical dimensions.

[13] https://ec.europa.eu/sustainable-finance-taxonomy/taxonomy-compass [Accessed on 25 September 2024]



Figure 19. Multi-dimensional risk in Lisbon, Žilina, and Tartu adopted from the ThinkHazard! (Hazard Likelihood) and the Risk Data Hub (Exposure and Vulnerability, 2024).

As shown in the first row of Figure 19, the hazard likelihood varies across the RETIME pilot sites. While some hazards are present in Lisbon, Žilina, and Tartu (i.e., earthquake, landslide, river flood, urban flood, water scarcity and wildfire), their likelihood is different for each pilot site. For

example, the hazard with the highest probability for Lisbon is wildfire, for Žilina it is landslide and for Tartu it is river flooding. In addition, the hazard of extreme heat is only present in Žilina and Lisbon. The tsunami hazard is expectable only in Lisbon.
The second row of the figure presents exposures of people and assets. In the Risk Data Hub, exposure data are only available for some hazards (i.e., river floods and landslides) and vary between pilot sites and exposed objects. The most exposed to landslides are the population and buildings in Lisbon while in Tartu, exposure to river floods is primarily linked to population and agriculture. Exposure data of landslide hazards in Tartu is missing in the Risk Data Hub. In Žilina, river flood exposure was assessed high for buildings, critical infrastructure, and the population. Whereas landslide exposure is highest for the population in Žilina.
The overall vulnerability index of the Risk Data Hub ranges from 0 to 10 while 10 refers to extreme high vulnerability. According to the Risk Data Hub, overall, all pilot sites have rather moderate vulnerabilities (Lisbon: 4.7, Tartu: 5.29, and Žilina: 4.05). Across the pilot sites, the highest social vulnerability is found in Tartu with 6.08 compared to 4.30 (Lisbon) and 3.87 (Žilina). Physical vulnerability differs only slightly between Lisbon and Žilina, ranging from 7.82 to 7.29, while it is significantly lower in Tartu (2.15).
The summary depicted in Figure 19 provides a first overview on the hazards and risks of the pilot sites. However, the fact that this figure is based on assessments performed at European and global scale and hence, can be used as a pre-assessment. However, risk assessments using local data and knowledge are non-neglectable. At the same time used for validating this (more superficial) pre-assessment.

7.3. Pilot site-specific sources for vulnerability and multi-risk assessment

7.3.1. Lisbon pilot area

Several scientific studies apply multi-risk methodologies to the Lisbon Metropolitan area (LMA). Mascheri et al. (2024) conducted comprehensive multi-risk assessment in LMA, focusing on the evaluation of vulnerability and risks associated with both earthquake and flood. The study assessed the vulnerability of historic unreinforced masonry structures (URM) located in the *Baixa Pombalina* district (downtown centre)[14] in Lisbon. This multi-risk analysis involves a

[14] The literature on architectural and structural features related to this district and the re-construction phases after the 1755 earthquake is very extensive, e.g., Penn, Wild, and Mascarenhas (1996).

comprehensive analysis of hazard, vulnerability, and exposure components. The analysis revealed significant disparities in estimated losses, with earthquake damages substantially outweighing those from flooding. Importantly, the findings indicate that structural vulnerability to earthquakes is greater than to floods, influencing risk assessment outcomes. This research lays the groundwork for future studies that could incorporate combined hazard assessments and probabilistic analyses. The exposure model utilised data collected through remote sensing and GIS, which provided information about the value and location of the buildings.

In the study by Xofi et al. (2022) , the methodology for seismic vulnerability assessment provides a structured approach to identifying vulnerable areas within the LMA. One of its strengths is the ability to correlate building parameters with vulnerability index results, which enhances the understanding of spatial distributions of risk. However, the classification of 'non-evaluated' buildings as Class D could lead to a conservative bias, potentially overestimating overall vulnerability. This highlights a critical limitation in the methodology, as relying on assumptions about structural irregularities without thorough evaluation may skew results. The recommendation for additional fieldwork to refine building characteristics is a vital step toward improving the robustness of the database.

Xofi et al. (2022) presented the vulnerability analysis of buildings in the LMA shows that reinforced concrete (RC) structures are more vulnerable compared to unreinforced masonry (URM) buildings (average index of 50.7 for RC *vs*. 37.2 for URM). Despite URM buildings typically being older and more susceptible to damage, many RC buildings lack adequate seismic provisions, particularly those built before 1983. This highlights the urgent need for effective risk mitigation strategies, especially in the light of potential severe earthquake scenarios. The study proposes a simplified seismic vulnerability assessment methodology that can quickly identify the most at-risk areas and building types, emphasising the importance of improved data collection to refine vulnerability assessments.

The results indicate that RC buildings generally show higher vulnerability due to the prevalence of older structures built before modern seismic codes were introduced. While URM buildings are typically more vulnerable by nature, they show a lower average vulnerability index compared to RC buildings in this study. In Portugal, municipalities like Oeiras and Lisbon exhibit higher vulnerability levels, especially for RC structures. The study also highlights a correlation between higher population density and increased risk levels, making urban areas like Lisbon and its surroundings more susceptible to significant impacts during seismic events.

Regarding the *Baixa Pombalina* district in Lisbon, key risks and vulnerabilities were identified through a multi-hazard assessment:

Seismic Risk: *Baixa Pombalina* faces a significant seismic hazard, influenced by historical events like the 1755 earthquake. The Peak Ground Acceleration (PGA) value of approximately 0.3 g indicates a high level of risk. Combined with the Maximum Likely Seismic Intensity (MLSI), this value offers a clear picture of the potential severity and frequency of seismic events.

Building Vulnerability: Building vulnerability is assessed using the Vulnerability Index (I*v), a numerical measure ranging from 0 – 100, with higher values indicating greater susceptibility to seismic damage. Many historic buildings, including 'Pombalino' structures, have I*v values around 70, suggesting high vulnerability. Buildings with an I*v above 50 are considered at particular risk of significant damage during earthquakes.

Exposure of Population and Infrastructure: A large portion of Baixa Pombalina's residents live in older unreinforced masonry (URM) buildings, making up about 60% of the area's building stock. The combination of dense population and historic structures increases exposure, with up to 20-30% of buildings potentially affected during a major earthquake.

Risk Assessment: The combination of a high I*v (>50) and a PGA value of 0.3 g places *Baixa Pombalina* in the "very high" to "extreme" risk category. This helps identify priority areas for resilience measures and preventive action against future seismic events.

7.3.2. Žilina pilot area

To the best of the current knowledge, no scientific publication currently applies a multi-risk assessment methodology specifically to evaluate the vulnerability of the Žilina Region (Žilinský kraj) focusing solely on the Žilina district. Currently, a specific risk assessment can be addressed through the Albert tool (analysed in *Section 6.2.2*, Table 12) for the pilot area. This tool defines the possible occurrence of the hazard, its exact description, providing a clear interpretation and the probability of occurrence of the hazard in selected areas in Žilina Region. For the analysis, the area where is located the senior house Straník, shown in Figure 15, was selected. The following hazards related to the pilot area have been identified: *natural* risk from radon activity, flood risk, risk from seismic activity, risk from slope deformation. Unfortunately, regarding *anthropogenic-hazards,* no data are provided.

It is important to mention the limitations of this tool. The Albert tool may not identify some risks simply because there is lack of data. Therefore, it is essential to integrate this tool with other resources and studies addressed at local level. Potential risks can be simulated from input data with varying positional accuracy. Based on this analysis, the risks in Žilina region and its administrative counties, vary as defined using Albert tool, as indicated below:

Radon Risk: Radon is a radioactive gas that can infiltrate buildings and accumulate indoors, posing a serious health risk to residents, especially in older, non-insulated buildings. The pilot area is classified as having a medium radon risk. There is a probability of increased volumetric activity of radon in the underlying soils. In urban planning, attention should be paid to the risk of radon infiltration, and preventive measures should be implemented accordingly.

Flood Risk: A medium flood risk was also identified for the pilot area, mainly associated with major floods, which can occur as a result of prolonged rainfall and the overflowing of riverbanks. The Albert tool estimates occurrence of such events in the pilot area less than once in 10 years. This represents a significant risk for the people and the infrastructure. Given the historical flood-related events in the region, measures should be taken to mitigate this risk.

Seismic Risk: A low level of seismic risk is determined for senior house Straník. The area of Slovakia is not a highly seismically active. There is a reference maximum ground acceleration of 0.63 m/s^2 in this area. Although the likelihood of earthquakes is low, the impact, particularly for historic buildings and infrastructure, could be significant. Therefore, it is important to consider this factor in the rehabilitation and recovery plans.

Slope Deformations: Low risk is also recorded regarding slope deformations, which can cause landslides in some locations. Given the slope and geological composition of the soil around senior house Stranik, this risk should be monitored, and adequate measures should be taken in case of any instability in the slopes, since the impact upon buildings, mobility infrastructure and other facilities can be high.

7.3.3. Tartu pilot area

As the most suitable source of information for specific analysis of the Tartu pilot area were identified the Tartu Energy 2030 plan, which serves as the source for the following information, is a key tool guiding the city adaptation efforts to climate change and increasing urban resilience. The plan focuses on multi-hazards, particularly those related to urban planning, energy management, and public infrastructure:

Heat Waves: Tartu has identified several key climate-related risks, based on current statistics and projections, as outlined in the Tartu Energy 2030 document. One of the main risks is heat waves, which have intensified significantly in recent years. These prolonged periods of extreme temperatures have serious impacts on public health, particularly affecting vulnerable groups such as the elderly and children. Increased demand for cooling systems further stresses the

energy infrastructure. The urban environment is also subject to the urban heat island effect, which leads to higher temperatures in densely populated areas, increasing cooling costs and the health risks for residents. The city is implementing green infrastructure projects, such as expanding parks and green roofs, to mitigate this effect and reduce urban temperatures.

Cold Waves: Although less frequent, cold waves lead to increased energy consumption for heating, which places a strain on vulnerable groups. As outlined in Tartu Energy 2030, the city is focusing on modernising heating systems to improve energy efficiency and mitigate the negative effects of extreme low temperatures.

Flooding: Another significant risk is flooding, mainly due to the proximity to the Emajõgi River. Increased rainfall and spring snowmelt raise the risk of both river and urban flooding, especially in low-lying areas. Floods can have devastating consequences for infrastructure, such as transportation networks, bridges, and residential areas located in flood zones. As reported in the Tartu Energy 2030 plan, the city is implementing flood protection measures, including levees and improved drainage systems, to better manage stormwater. Public awareness campaigns and flood warning systems have also been put in place to inform residents of impending floods.

Storms and Strong Winds: Tartu also faces risks from other extreme weather events, such as storms and strong winds. These natural phenomena can damage buildings and disrupt public services, such as electricity and transportation. To minimise these risks, the city is strengthening public infrastructure, including energy grids and transportation systems, to withstand the disruptions caused by storms and high winds.

The Tartu Energy 2030 plan sets out specific targets and metrics to monitor the effectiveness of adaptation measures. One of the key goals is to reduce carbon emissions by 40% by 2030, with the long-term objective of achieving carbon neutrality by 2050. A major focus is also placed on improving the energy efficiency of buildings and infrastructure, particularly in the residential and public sectors. For example, emissions from the residential sector are set to decrease from 184,000 tCO2 to 77,000 tCO2 by 2030. In terms of flood protection, the city is investing in infrastructure solutions to reduce the risk of flooding, although detailed financial estimates were not provided in the document.

8. Critical analysis of Vulnerability and Urban Risk and Assessment Methodologies and Recommendations

This section summarises the gaps and outstanding challenges related to vulnerability and multi-risk assessment, specifically focusing on RETIME pilot sites. The section is organised into two parts: *Section 8.1* discusses methodologies available in the scientific literature, while *Section 8.2* shows e-tools and data sources available in the pilot sites.

8.1. Critical analysis of vulnerability and multi-risk and assessment methodologies: Literature review perspective

Urban risk and vulnerability assessment methodologies are crucial for understanding and mitigating risks associated with disasters in urban environments. Existing frameworks often emphasise the multi-hazard nature of risks, integrating various methodologies to assess vulnerability and resilience. However, several gaps and challenges persist in their application, particularly in relation to the RETIME framework's objectives of enhancing resilience in buildings and infrastructure.

8.1.1. Challenges in multi-risk assessments

Many presented review papers identify challenges in multi-risk assessments, the aforementioned terminology issues are reiterated in the articles Kappes et al. (2012), Tilloy et al. (2019) and Wang et al. (2020). Further on, the direct comparison of hazards is challenging, as hazard process characteristics and measurement units differ (Kappes, Keiler, et al., 2012a). For example, an earthquake is measured in Richter scale and is a sudden onset disaster, whereas a riverine flooding is usually measured in meters of water level or in cubic meters waterflow and usually a slow onset disaster. This could be solved by standardisation, semi-quantitative or qualitative approaches (Kappes, Keiler, et al., 2012a). Another solution is the analysis of risk, e.g., measured in annual probability of loss of life. Analysing multi-risk is a data-demanding and complex process (Julià & Ferreira, 2021; Kappes, Keiler, et al., 2012a).
A great challenge poses the silos and different separated disciplines working on multi-risk. Two main streams of hazards are present: ‘natural hazards’ and ‘man-made hazards’. Based on these two categories, five main silos in multi-risk research can be identified: i) hydrometeorological hazards (e.g., storms; influenced by climate change), ii) solid earth and surface process hazards (e.g., earthquakes); iii) technological hazards triggered by anthropic activities (e.g., incidents in industrial plants), iv) technological hazards triggered by natural events (NATECH event); v) and critical infrastructure cascade effects (e.g., water outages due to blackouts), as detailed by (J. Wang et al., 2020). They are often clearly segregated making analysis more difficult (Curt, 2021; Gallina et al., 2016; J. Wang et al., 2020). Curt (2021) identified the main themes in multi-risk

research: natural hazards (both hydrometeorological (e.g., flood) and solid earth and surface process hazards (e.g., earthquakes) are analysed in 28.7% of the studies. NATECH events are studied in 13.5% (Curt, 2021). Pure technological multi-hazards, so called 'domino effects' in industrial plants are studied by 46.6%, while cascading effects in critical infrastructure systems are addressed in 11.2% of total studies (Curt, 2021).

Regarding the combination of the four silos, some methods combine hydrometeorological and solid earth and surface process hazards. It is important to note that human induced hazards are often overlooked due to uncertainties in the estimation of human influence and the long time between human intervention and disasters (Gallina et al., 2016; J. Wang et al., 2020). To mention an example, deforestation may initially reduce wildfire risks, but heavy rain occurring many years later can lead to landslides.[15] Regarding technological hazards, studies on the combination of natural and technological hazards, the NATECH events are only a small part (13.5%) compared to pure domino effect studies in industrial plants (46.6%) (Curt, 2021). The interaction of natural hazards and cascade effects of critical infrastructures is often overlooked. But critical infrastructure systems can provide the intermediate link for disasters to spread over wide areas (J. Wang et al., 2020).

Often multi-risk analysis is focused on physical vulnerability. Social vulnerability is lacking in most assessments (Curt, 2021; Julià & Ferreira, 2021; J. Wang et al., 2020). Gallina et al. (2016) and Kappes (2012a) even do not further investigate social vulnerability in their reviews. Further on, the dynamic of exposure (J. Wang et al., 2020) and vulnerability, both physical and social, is often not considered (Curt, 2021; Gallina et al., 2016; Kappes, Keiler, et al., 2012a; J. Wang et al., 2020). Dynamical aspects of multi-risk are paramount and need to be considered in multi-risk assessments, because hazards are influenced by climate change and human interventions over time, as well as vulnerability and exposure is changed by hazards (Curt, 2021; Gallina et al., 2016; Julià & Ferreira, 2021; Kappes, Keiler, et al., 2012a; J. Wang et al., 2020). A primary disaster will force people to leave exposed areas but also enhances vulnerability of buildings and inhabitants. These interactions are creating a complex disaster-pregnant environment, leading to difficulties in modelling the complex risk networks and spatiotemporal aspects of multi-risk (Gallina et al., 2016; Kappes, Keiler, et al., 2012a; J. Wang et al., 2020). This leads to often

[15] To mention an example, landslide risk influenced by population and forest-cover changes in the Kivu Rift (Depicker et al., 2021) or increase in landslides due to land use changes in New Zealand by European settlers (Glade, 2003), or landslides triggered by earthquakes (Keefer, 2002).

abstract models used in multi-risk assessments, and the refinement is insufficient. The physical interactions between hazards need to be identified accurately, as stated by J.Wang et al.(2020). Many hazards are underrepresented in current scientific research, as the most studied hazards assess “earthquake debris flow, coastal typhoons and inland floods” (J. Wang et al., 2020, p. 2014), flooding and earthquake (Curt, 2021) and flood, landslide, and debris flow (Owolabi & Sajjad, 2023).

Recalling the inefficacy of the models noted by Wang et al. (2020), several existing multi-risk assessments fail to account for climate change on hazards and future climate conditions (Gallina et al., 2016). Specifically, cross-sectoral impact models are missing (Gallina et al., 2016). Often multi-risk assessments rely on present or historical data, not considering future changes in hazard scenarios (Gallina et al., 2016; J. Wang et al., 2020). Data availability and interoperability also pose significant challenges (Curt, 2021). Poorly studied topics are multi risk governance and training (Curt, 2021). As stated by Curt (2021), a limitation of the current scientific literature is the lack of focus on adaptation of decision support tools to meet stakeholder requirements and the need for developing validation studies of existing multi-risk assessment methods.

Currently, there is no mature method for multi-risk analysis integrating the interrelationship between hazards and vulnerability comprehensively and effectively (Gallina et al., 2016; Julià & Ferreira, 2021; Kappes, Keiler, et al., 2012a; J. Wang et al., 2020).

8.1.2. Pathways to address multi-risk assessment challenges

To address the challenges associated with multi-risk assessment, the following pathways should be pursued at the methodological, technological and communication levels, as outlined below:

- Methods for multi-hazard, vulnerability, and multi(-hazard) risk assessment need to be developed through an interdisciplinary approach (Curt, 2021; Gallina et al., 2016; Julià & Ferreira, 2021; J. Wang et al., 2020).
- A generalised methodology for specific categories of multi-hazards could enhance comparability between results (J. Wang et al., 2020).
- Detailed scenario development on multi-hazards in socio-economic and human influenced geosystems, as researchers indicate this need is still unmet (Gallina et al., 2016; Kappes, Keiler, et al., 2012a).
- Multi-vulnerability could be analysed using three-dimensional vulnerability surfaces expanding two-dimensional vulnerability curves (Kappes, Keiler, et al., 2012a).

- Sectorial modelling tools should ensure data exchange across sectors for the modelling of future climate scenarios and resulting impacts on natural, socio-economic and hazard systems (Gallina et al., 2016).
- Integrated assessment models should be developed to couple climate change with socio-economic assumptions to better reflect changing vulnerability (Gallina et al., 2016).
- A synthetic multi-risk index (Gallina et al., 2016) and multi-risk maps can enhance the communication of results (Curt, 2021; Gallina et al., 2016).
- The communication of risk analysis results to non-professionals and the public should be enhanced (Curt, 2021; Gallina et al., 2016; J. Wang et al., 2020), by actively involving stakeholders throughout all risk assessment processes using participatory approaches, such as workshops and serious games (Curt, 2021; Gallina et al., 2016).
- Fault trees, cause trees, and bowtie diagrams can be helpful in risk communication (Curt, 2021).
- Uncertainties inherent to risk and risk analysis should be shared in an appropriate way (Gallina et al., 2016), e.g., especially using a easy understandable language and broader channels in order to educate and inform the public.
- There is no one-size-fits-all solution. Different stakeholders will need different communication and visualisation approaches (Kappes, Keiler, et al., 2012a).

8.2. Critical analysis of vulnerability and multi-risk assessment data source and e-tools

Many existing assessments rely primarily on a set of quantitative data, overlooking qualitative indicators especially related to social vulnerability and community resilience. This is mainly caused by the fact that quantitative data is more abundant due to the fact that data can be collected easier whereas qualitative-based methods are also limited by being time-consuming and relying on smaller sample sizes (Tavares et al., 2018). Furthermore, methods that incorporate stakeholder engagement and local knowledge tend to produce more context and evidence-based results, and hence, are less commonly applied (J. Wang et al., 2020).
In this context, the review of available European datasets for multi-risk assessments reflects this phenomenon of lacking qualitative data: hazard maps can be found at relatively fine scale for each of the hazards discussed in the RETIME pilot sites.

Spatial resolution: With the ambition of RETIME to work at building level, it is of high importance that datasets are of fine resolution. As indicated above, some European datasets, especially, for vulnerability assessment may not be of satisfying resolution but also other datasets may be

limited to a spatial resolution of 1 km or more. For instance, census data is an important source, but this data is not available at e.g., neighbourhood or building level. Moreover, census data can be outdated as they are updated only every 10 years and partly these updates are based on small sample groups.
Looking at the European hazard datasets, the resolution can vary from 90m (flood hazard) to about 50 km (earthquake). Despite this big difference between layers and the coarse resolution of some datasets, it does not directly mean that these datasets are not applicable in Retime tasks. In fact, most of the hazard maps identified as potentially applicable have a resolution around 1 km; thus, they can be deemed suitable for the identification of hazards and exposure of specific buildings if no local dataset is available. These datasets could then be complemented during the project with e.g., air quality observation data or local (multi-)hazard assessments.
Overall, the review on datasets, but also data portals and e-tools further highlighted the need for fine resolutions data and tools which can be used for analysis at building levels. In terms of tools, several e-tools were identified for multi-risk assessment that are either python or GIS-based and can be used at any scale or for any spatial resolutions. However, the assessment highly depends on the input data which need to be available and have an adequate resolution.

Differences in local data and e-tool availability across the three pilot sites: In addition to the overview of datasets and e-tools at European scale, this analysis also focused on open access datasets available at each pilot site and potential tools being used in RETIME.
As identified in *Section 7.3,* different approaches to vulnerability and multi-risk assessment are applied in the pilot sites of Lisbon, Žilina, and Tartu. Lisbon studies focused on comprehensive multi-risk methodologies, while Žilina relies on limited data and e-tools (like Albert). More specifically, in Lisbon, advanced methods such as remote sensing and GIS are used for detailed vulnerability assessments of historic buildings against earthquakes and floods, revealing that reinforced concrete buildings are more vulnerable than non-reinforced masonry structures. In contrast, the Žilina pilot lacks scientific studies, and its vulnerability assessment is limited to a few identified risks, such as radon and flooding, without considering anthropogenic hazards.
Tartu, on the other hand, showcases a proactive approach to risk assessment in relation to climate change, with the city planning for emission reductions and adaptation to multiple hazards, including extreme temperatures and floods. Tartu also strives to integrate risk assessment into urban planning, a strategy that is missing in Žilina, where data and analyses are limited.
While the need for comprehensive and systematic approaches to risk assessment is more relevant in Lisbon and Tartu, Žilina illustrates the consequences of lack of data and methodological tools, which may lead to incomplete risk evaluations. Overall, advanced models

of vulnerability assessment are employed in Lisbon and Tartu, while Žilina indicates a need for further research and improved data availability.

Adaptation and Resilience Strategies: While comprehensive frameworks like the IPCC and UNDRR provide guidelines for adapting to climate change, they often fail to integrate specific local strategies for urban environments, which consider the specificities of each area, especially local inhabitants and vulnerable (or marginalised) groups. As recently discussed by Lee et al. (2024), this oversight can result in inadequate planning and responses to local vulnerabilities. To avoid this pitfall, adaptation and resilience strategies at pilot cites and findings will be further analysed.

9. Recommendations for urban risk assessment framework

To enhance the resilience of vulnerable groups and buildings while prioritising a people-centric approach to the built environment, it is essential to consider multiple factors and their interdependencies. Based on an extensive review of DRR research, methods, (input) datasets and e-tools, the following recommendations are proposed:

- ***Integrate Risk Assessments with Local Context:*** RETIME should leverage knowledge, results, insights from existing risk assessment studies, considering cultural and territorial features and adapt to each local context of the pilot sites. This involves considering natural, anthropogenic, and technological hazards while integrating interdisciplinary approaches on vulnerability and resilience. In addition, the experiences of local residents should always play a role to link the more theoretical approaches with the local context.
- ***Develop a Hybrid Assessment Model:*** Combining quantitative metrics with qualitative assessments provides a more comprehensive understanding of urban vulnerabilities. This makes it possible to offer a low-threshold approach that can also engage non-experts.
- ***Supplement Existing European Datasets with Local Data:*** Where high-resolution data is not available, existing datasets can be complemented with local observations or specialised assessments. For example, adding local air quality data or site-specific hazard assessments can help improve the accuracy and applicability of multi-risk assessments.
- ***Prioritise the Use of Flexible Hazard, Vulnerability and Risk Assessment Tools:*** The review indicates that several flexible e-tools (e.g., Python or GIS-based) are available for hazard, vulnerability and risk assessments. These tools should be leveraged more effectively, provided that adequate resolution data is available.
- ***Facilitate the Use of Proper Terminology:*** As outlined in the RETIME semantic framework, clear definitions and essential terminology are critical for effective communication among stakeholders. RETIME should therefore contribute to the standardisation of definitions in the European environment.
- ***Focus on Future-Proofing Infrastructure:*** The framework should prioritise strategies that enhance the resilience of existing and future buildings, including critical facilities and mobility infrastructure, against multiple emerging and future risks, including climate change impacts. Social trends and expected climatic changes therefore need to be taken into account.
- ***Implement Continuous Learning and Feedback Mechanisms:*** Establishing a feedback loop for ongoing multi-dimensional assessments will help refine methodologies over time.

- ***Enhance stakeholder engagement and communication:*** A participatory approach to involve the stakeholders in the RETIME assessment process is crucial.

This approach would allow urban planners, building owners, managers, city officials, AEC professionals, and residents to easily identify and prioritise context-based solutions to enhance resilience at the district and building levels.

10. Concluding remarks

Comprehensive multi-risk resilience strategies for urban areas represent a crucial component for urban adaptation and alert Solutions for a timely (re)Action. Throughout this report key methodologies, tools, and data sources essential to assessing urban vulnerability and risk in response to climate-related hazards are presented together with their critical analysis and some preliminary analysis related to the three RETIME pilot sites. The multi-hazard and multi-risk approaches highlight the complexity of urban resilience in a world increasingly affected by dynamic and interconnected risks, as well as by unpredictable adverse climate-change impacts. The impact of hazards affects in a different way inhabitants and the built environments, marked by specific social, economic, and structural vulnerabilities. This analysis shows that successful risk mitigation strategies require a nuanced understanding of the local context. Each RETIME pilot site faces unique challenges due to geographic, climatic, cultural, and social conditions, and is differently positioned due to geo-political and technological settings. The combination of updated and real-time datasets, combined ML data gathering approaches, advanced modelling and tools, such as BIM and AV/VR applications offer promising pathways for improving urban preparedness and resilience.

One of the major challenges identified is the integration of data from diverse sources and scales. The interoperability of tools and the ability to synthesise data across platforms and geographies is crucial for creating a cohesive urban risk assessment framework. The report also highlights the necessity of including social vulnerability as a core element of risk assessment, ensuring that current populations and future generations are not overlooked in the planning and implementation of resilience measures.

Moving forward, the development of user-centric platforms that involve active collaboration among stakeholders, local authorities and other special interest groups, and vulnerable communities will be vital. The refinement of decision-making tools will continue to play a pivotal role in achieving a more resilient urban future. In conclusion, this report has laid a well-grounded foundation for understanding the state-of-the art on urban vulnerabilities and multi-risk assessment. The next phases will involve translating these insights into practical and scalable RETIME solutions. Collaboration across public, private (or semi-private), as well as academic sectors remains essential to achieve a sustainable and resilient urban future.

List of References

Abdolhamidzadeh, B., Abbasi, T., Rashtchian, D., & Abbasi, S. A. (2011). Domino effect in process-industry accidents – An inventory of past events and identification of some patterns. *Journal of Loss Prevention in the Process Industries*, *24*(5), 575–593. https://doi.org/10.1016/j.jlp.2010.06.013

Adger, A., Brooks, N., Bentham, G., Agnew, M., & Eriksen, S. (2004). *New indicators of vulnerability and adaptive capacity*.

Afzal, M., & Shafiq, M. T. (2021). *Evaluating 4D-BIM and VR for Effective Safety Communication and Training: A Case Study of Multilingual Construction Job-Site Crew*. *11*(8), 24. https://doi.org/10.3390/buildings11080319

Ahmed, M., Jerez, S., Matasic, I., Prodhomme, G., & Reimeringer, M. (2012). Explosions and Structural Fragments as Industrial Hazard: Domino Effect and Risks. *Procedia Engineering*, *45*, 159–166. https://doi.org/10.1016/j.proeng.2012.08.137

Ahrens, J., & Rudolph, P. M. (2006). The importance of governance in risk reduction and disaster management. *Journal of Contingencies and Crisis Management*, *14*(4), 207–220. https://doi.org/10.1111/j.1468-5973.2006.00420.x

Bagster, F. (1991). Estimation of Domino Incident Frequencies-An Approach. *Process Safety and Environmental Protection*, *69*, 195–199.

Balica, S., & Wright, N. G. (2010). Reducing the complexity of the flood vulnerability index. *Environmental Hazards*, *9*(4), 321–339. https://doi.org/10.3763/ehaz.2010.0043

Barros, J. L., Tavares, A. O., Santos, A., & Fonte, A. (2015). Territorial vulnerability assessment supporting risk managing coastal areas due to tsunami impact. *Water*, *7*(9), 4971–4998. https://doi.org/10.3390/w7094971

Barros, J. L., Tavares, A. O., Santos, P. P., & Freire, P. (2022). Enhancing a Coastal Territorial Vulnerability Index: Anticipating the impacts of coastal flooding with a local scale approach. *Coastal Management*.

Baum, S., Horton, S., & Choy, D. L. (2008). Local urban communities and extreme weather events: Mapping social vulnerability to flood. *The Australasian Journal of Regional Studies*, *14*(3), 251–273.

Beccari, B. (2016). A comparative analysis of disaster risk, vulnerability and resilience composite indicators. *PLoS Currents*, *8*. https://doi.org/10.1371/currents.dis.453df025e34b682e9737f95070f9b970

Bell, R. (2002). *Landslide and snow avalanche risk analysis—Methodology and its application in Bíldur*. Rheinische Friedrich-Wilhelms-Universität Bonn, NW-Iceland.

Bell, R., & Glade, T. (2004). Multi-hazard analysis in natural risk assessment. *Risk Analysis*, *4*, 197–206.

Bernatchez, P., Fraser, C., Lefaivre, D., & Dugas, S. (2011). Integrating anthropogenic factors, geomorphological indicators and local knowledge in the analysis of coastal flooding and erosion hazards. *Ocean & Coastal Management*, *54*(8), 621–632. https://doi.org/10.1016/j.ocecoaman.2011.06.001

Bernechea, E. J., Vílchez, J. A., & Arnaldos, J. (2013). A model for estimating the impact of the domino effect on accident frequencies in quantitative risk assessments of storage facilities. *Process Safety and Environmental Protection*, *91*(6), 423–437. https://doi.org/10.1016/j.psep.2012.09.004

BGR & Desdm. (2009). *Guidebook for assessing the risks to natural hazards—Case study: Province of Central Java. Tech. Rep.* Bundesanstalt für Geowissenschaften und Rohstoffe and the Geological Agency of Indonesia.

Birkmann, J. (2006a). Indicators and criteria for measuring vulnerability: Theoretical bases and requirements. In *Measuring vulnerability to natural hazards: Towards disaster resilient societies* (1st ed., pp. 55–77). United Nations University Press.

Birkmann, J. (2006b). Measuring vulnerability to promote disaster-resilient societies: Conceptual frameworks and definitions. In *Measuring vulnerability to natural hazards: Towards disaster resilient societies* (1st ed., pp. 9–54). United Nations University Press.

Birkmann, J. (2007). Risk and vulnerability indicators at different scales: Applicability, usefulness and policy implications. *Environmental Hazards*, *7*(1), 20–31. https://doi.org/10.1016/j.envhaz.2007.04.002

Birkmann, J., Cardona, O. D., Carreño, M. L., Barbat, A. H., Pelling, M., Schneiderbauer, S., & Welle, T. (2013). Framing vulnerability, risk and societal responses: The MOVE framework. *Natural Hazards*, *67*(2), 193–211. https://doi.org/10.1007/s11069-013-0558-5

Birkmann, J., Jamshed, A., McMillan, J. M., Feldmeyer, D., Totin, E., Solecki, W., & Alegría, A. (2022). Understanding human vulnerability to climate change: A global perspective on index validation for adaptation planning. *Science of The Total Environment*, *803*(150065). https://doi.org/10.1016/j.scitotenv.2021.150065

Birkmann, J. & UNU-EHS Expert Working Group on Measuring Vulnerability (Eds.). (2013). *Measuring vulnerability to natural hazards: Towards disaster resilient societies* (Second edition). United Nations University Press.

Bohle, H.-G. (2001). Vulnerability and Criticality: Perspectives from Social Geography. *Newsletter of the International Human Dimensions Programme on Global Environmental Change*, *2*, 1–7.

Boton, C. (2018). Supporting constructability analysis meetings with Immersive Virtual Reality-based collaborative BIM 4D simulation. *Automation in Construction*, *96*, 1–15. https://doi.org/10.1016/j.autcon.2018.08.020

Bovolo, C. I., Abele, S. J., Bathurst, J. C., Caballero, D., Ciglan, M., Eftichidis, G., & Simo, B. (2009). A distributed framework for multi-risk assessment of natural hazards used to model the effects of forest fire on hydrology and sediment yield. *Computers & Geosciences*, *35*(5), 924–945. https://doi.org/10.1016/j.cageo.2007.10.010

Bründl, M. (2008). *Risikokonzept für Naturgefahren—Leitfaden. Tech. Rep*. Nationale Plattform für Naturgefahren PLANAT.

Building information modelling—Level of information need—Part 1: Concepts and principles (ISO Nos. 7817-1:2024). (2024).

Burton, C., Rufat, S., & Tate, E. (2018). Social vulnerability. In *Vulnerability and resilience to natural hazards* (pp. 53–81).

Calvi, G. M., Pinho, R., Magenes, G., Bommer, J. J., Restrepo-Vélez, L. F., & Crowley, H. (2006). Development of seismic vulnerability assessment methodologies over the past 30 years. *ISET Journal of Earthquake Technology*, *43*(3), 75–104.

Cannon, S. H., & DeGraff, J. (2009). The Increasing Wildfire and Post-Fire Debris-Flow Threat in Western USA, and Implications for Consequences of Climate Change. In K. Sassa & P. Canuti (Eds.), *Landslides – Disaster Risk Reduction* (pp. 177–190). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-69970-5_9

Cannon, S. H., Gartner, J. E., Rupert, M. G., Michael, J. A., Rea, A. H., & Parrett, C. (2010). Predicting the probability and volume of postwildfire debris flows in the intermountain western United States. *Geological Society of America Bulletin*, *122*(1–2), 127–144. https://doi.org/10.1130/B26459.1

Cannon, S. H., Gartner, J. E., Wilson, R. C., Bowers, J. C., & Laber, J. L. (2008). Storm rainfall conditions for floods and debris flows from recently burned areas in southwestern

Colorado and southern California. *Geomorphology*, *96*(3–4), 250–269. https://doi.org/10.1016/j.geomorph.2007.03.019

Cardona, O. D., Van Aalst, M. K., Birkmann, J., Fordham, M., McGregor, G., Rosa, P., & Thomalla, F. (2012). Determinants of risk: Exposure and vulnerability. In *Managing the risks of extreme events and disasters to advance climate change adaptation: Special report of the intergovernmental panel on climate change* (pp. 65–108). Cambridge University Press.

Carrasco, R. M., Pedraza, J., Martin-Duque, J. F., Mattera, M., Sanz, M. A., & Bodoque, J. M. (2003). Hazard Zoning for Landslides Connected to Torrential Floods in the Jerte Valley (Spain) by using GIS Techniques. *Natural Hazards*, *30*(3), 361–381. https://doi.org/10.1023/B:NHAZ.0000007171.13298.01

Cheng, M.-Y., Chiu, K.-C., Hsieh, Y.-M., Yang, I.-T., Chou, J.-S., & Wu, Y.-W. (2017). BIM integrated smart monitoring technique for building fire prevention and disaster relief. *Automation in Construction*, *84*, 14–30. https://doi.org/10.1016/j.autcon.2017.08.027

Ciurean, R., Gill, J., Reeves, H. J., O'Grady, S., & Aldridge, T. (2018). *Review of multi-hazards research and risk assessments*. British Geological Survey. http://nora.nerc.ac.uk/id/eprint/524399/

Closson, D., & Abou Karaki, N. (2009). Human-induced geological hazards along the Dead Sea coast. *Environmental Geology*, *58*(2), 371–380. https://doi.org/10.1007/s00254-008-1400-3

Comrey, A. L., & Lee, H. B. (2013). *A First Course in Factor Analysis*. Taylor & Francis. https://books.google.sk/books?id=RSsVAgAAQBAJ

Cozzani, V., Gubinelli, G., Antonioni, G., Spadoni, G., & Zanelli, S. (2005). The assessment of risk caused by domino effect in quantitative area risk analysis. *Journal of Hazardous Materials*, *127*(1–3), 14–30. https://doi.org/10.1016/j.jhazmat.2005.07.003

Cruz, A. M., Krausmann, E., & Franchello, G. (2011). Analysis of tsunami impact scenarios at an oil refinery. *Natural Hazards*, *58*(1), 141–162. https://doi.org/10.1007/s11069-010-9655-x

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

Cutter, S. L., Ash, K. D., & Emrich, C. T. (2016). Urban–Rural Differences in Disaster Resilience. *Annals of the American Association of Geographers*, *106*(6), 1236–1252. https://doi.org/10.1080/24694452.2016.1194740

Cutter, S. L., Boruff, B. J., & Shirley, W. L. (2003a). Social Vulnerability to Environmental Hazards. *Social Science Quarterly*, *84*(1), 242–261. https://doi.org/10.1111/1540-6237.8402002

Cutter, S. L., Boruff, B. J., & Shirley, W. L. (2003b). Social Vulnerability to Environmental Hazards. *Social Science Quarterly*, *84*(2), 242–261. https://doi.org/10.1111/1540-6237.8402002

Cutter, S. L., & Finch, C. (2008). Temporal and spatial changes in social vulnerability to natural hazards. *Proceedings of the National Academy of Sciences (PNAS)*, *105*(7), 2301–2306. https://doi.org/10.1073/pnas.0710375105

Darbra, R. M., Palacios, A., & Casal, J. (2010). Domino effect in chemical accidents: Main features and accident sequences. *Journal of Hazardous Materials*, *183*(1–3), 565–573. https://doi.org/10.1016/j.jhazmat.2010.07.061

D'Ayala, D., Copping, A., & Wang, H. (2006). *A conceptual model for Multihazard assessment of the vulnerability of historic buildings*.

De Pippo, T., Donadio, C., Pennetta, M., Petrosino, C., Francesco, T., & Valente, A. (2008). Coastal hazard assessment and mapping in Northern Campania, Italy. *Geomorphology*, *97*, 451–466. https://doi.org/10.1016/j.geomorph.2007.08.015

De Ruiter, M. C., & Van Loon, A. F. (2022). The challenges of dynamic vulnerability and how to assess it. *iScience*, *25*(8), 104720. https://doi.org/10.1016/j.isci.2022.104720

Depicker, A., Jacobs, L., Mboga, N., Smets, B., Van Rompaey, A., Lennert, M., Wolff, E., Kervyn, F., Michellier, C., Dewitte, O., & Govers, G. (2021). Historical dynamics of landslide risk from population and forest-cover changes in the Kivu Rift. *Nature Sustainability*, *4*(11), 965–974. https://doi.org/10.1038/s41893-021-00757-9

Dilley, M., Chen, R. S., Deichmann, U., Lerner-Lam, A., Arnold, M., Agwe, J., Buys, P., Kjekstad, O., Lyon, B., & Yetman, G. (2005). Natural disaster hotspots: A global risk analysis. *World Bank Disaster Risk Management Series*, *5*, 1–132. https://doi.org/10.1007/978-3-322-82113-3_1

EC. Joint Research Centre. (2017). *Index for risk management - INFORM: Concept and methodology, version 2017*. Publications Office. https://data.europa.eu/doi/10.2760/094023

Eckel, E. B. (1970). *The Alaska earthquake, March 27, 1964: Lessons and conclusions* (Vol. 546). US Government Printing Office.

Egli, T. (1996). *Hochwasserschutz und Raumplanung: Schutz vor Naturgefahren mit Instrumenten der Raumplanung - dargestellt am Beispiel von Hochwasser und Murgängen*. vdf, Hochsch.-Verl. an der ETH.

Eisenberg, N. A., Lynch, C. J., & Breeding, R. J. (1975). *Vulnerability model. A simulation system for assessing damage resulting from marine spills. Final report*. Enviro Control, Inc., Rockville, Md.(USA).

Ellsworth, W. L. (2013). Injection-Induced Earthquakes. *Science*, *341*(6142), 1225942. https://doi.org/10.1126/science.1225942

Ewen, J., Parkin, G., & O'Connell, P. E. (2000). SHETRAN: Distributed River Basin Flow and Transport Modeling System. *Journal of Hydrologic Engineering*, *5*(3), 250–258. https://doi.org/10.1061/(ASCE)1084-0699(2000)5:3(250)

Farrokh, N., Zhongqiang, L., Gordon, W., & Jochen, Z. (2013). Framework for multi-risk assessment, Deliverable D5. 2. *MATRIX Proj*.

Flanagan, B. E., Gregory, E. W., Hallisey, E. J., Heitgerd, J. L., & Lewis, B. (2011). A Social Vulnerability Index for Disaster Management. *Journal of Homeland Security and Emergency Management*, *8*(1), 000010220215477355179 2. https://doi.org/doi:10.2202/1547-7355.1792

Foerster, E., Krien, Y., Dandoulaki, M., Priest, S., Tapsell, S., Delmonaco, G., Margottini, C., & Bonadonna, C. (2009). *Methodologies to assess vulnerability of structural systems*.

Gallina, V., Torresan, S., Critto, A., Sperotto, A., Glade, T., & Marcomini, A. (2016). A review of multi-risk methodologies for natural hazards: Consequences and challenges for a climate change impact assessment. *Journal of Environmental Management*, *168*, 123–132. https://doi.org/10.1016/j.jenvman.2015.11.011

Garcia-Aristizabal, A., & Marzocchi, W. (2012). *Framework for Multi-risk Assessment. Deliverable 5.2. MATRIX project (Contract n 265138)*.

Garcin, M., Desprats, J. F., Fontaine, M., Pedreros, R., Attanayake, N., Fernando, S., Siriwardana, C. H. E. R., De Silva, U., & Poisson, B. (2008). Integrated approach for coastal hazards and risks in Sri Lanka. *Natural Hazards and Earth System Sciences*, *8*(3), 577–586. https://doi.org/10.5194/nhess-8-577-2008

Garcin, M., Prame, B., Attanayake, N., De Silva, U., Desprats, J. F., Fernando, S., Fontaine, M., Idier, D., Lenotre, N., Pedreros, R., & Siriwardana, C. H. E. R. (2007). *A geographic information system for coastal hazards—Application to a pilot site in Sri Lanka. Final report BRGM/RP-55553-FR, Bureau de recherches géologiques et minières (BRGM)*.

Gill, J. C., Duncan, M., Ciurean, R., Smale, L., Stuparu, D., Schlumberger, J., de Ruiter, M., Tiggeloven, T., Torresan, S., Gottardo, S., Mysiak, J., Harris, R., Petrescu, E.-C., Girard, T., Khazai, B., Claassen, J., Dai, R., Champion, A., Daloz, A. S., … Ward, P. (2022, August 4). *D1.2 Handbook of Multi-hazard, Multi- Risk Definitions and Concepts* [Review of *D1.2 Handbook of Multi-hazard, Multi- Risk Definitions and Concepts*, by P. Ward & S. Hochrainer-Stigler]. https://www.myriadproject.eu/wp-content/uploads/2022/11/D1_2_Handbook.pdf

Gill, J. C., & Malamud, B. D. (2016). Hazard interactions and interaction networks (cascades) within multi-hazardmethodologies. *Earth System Dynamics*, *7*(3), 659–679. https://doi.org/10.5194/esd-7-659-2016

GIZ, & EURAC. (2017). *Risk Supplement to the Vulnerability Sourcebook: Guidance on how to apply the Vulnerability Sourcebook's approach with the new IPCC AR5 concept of climate risk*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

Glade, T. (2003). Landslide occurrence as a response to land use change: A review of evidence from New Zealand. *CATENA*, *51*(3–4), 297–314. https://doi.org/10.1016/S0341-8162(02)00170-4

Granger, K., Jones, T., Leiba, M., & Scott, G. (1999). *Community risk in Cairns: A multi-hazard risk assessment*. Australian Geological Survey Organisation (AGSO). https://pid.geoscience.gov.au/dataset/ga/33548

Greiving, S. (2006). Integrated Risk Assessment of Multi-Hazards: A New Methodology. *Geological Survey of Finland, Special Paper*, *42*, 75–82.

Greiving, S., Fleischhauer, M., & Lückenkötter, J. (2006). A Methodology for an integrated risk assessment of spatially relevant hazards. *Journal of Environmental Planning and Management*, *49*(1), 1–19. https://doi.org/10.1080/09640560500372800

Grünthal, G., Thieken, A. H., Schwarz, J., Radtke, K. S., Smolka, A., & Merz, B. (2006). Comparative Risk Assessments for the City of Cologne – Storms, Floods, Earthquakes. *Natural Hazards*, *38*(1–2), 21–44. https://doi.org/10.1007/s11069-005-8598-0

Hagenlocher, M., Renaud, F. G., Haas, S., & Sebesvari, Z. (2018). Vulnerability and risk of deltaic social-ecological systems exposed to multiple hazards. *Science of The Total Environment*, *631*, 71–80. https://doi.org/10.1016/j.scitotenv.2018.03.013

Han, R., Zhou, B., An, L., Jin, H., Ma, L., Li, N., Xu, M., & Li, L. (2019). Quantitative assessment of enterprise environmental risk mitigation in the context of Na-tech disasters. *Environmental Monitoring and Assessment*, *191*(4), 210. https://doi.org/10.1007/s10661-019-7351-1

Han, Z. Y., & Weng, W. G. (2011). Comparison study on qualitative and quantitative risk assessment methods for urban natural gas pipeline network. *Journal of Hazardous Materials*, *189*(1–2), 509–518. https://doi.org/10.1016/j.jhazmat.2011.02.067

Harp, E. L., & Wilson, R. C. (1995). Shaking intensity thresholds for rock falls and slides: Evidence from 1987 Whittier Narrows and superstition hills earthquake strong-motion records. *Bulletin of the Seismological Society of America*, *85*(6), 1739–1757. https://doi.org/10.1785/BSSA0850061739

He, Z., & Weng, W. (2020). Synergic effects in the assessment of multi-hazard coupling disasters: Fires, explosions, and toxicant leaks. *Journal of Hazardous Materials*, *388*, 121813. https://doi.org/10.1016/j.jhazmat.2019.121813

Hinkel, J. (2011). Indicators of vulnerability and adaptive capacity: Towards a clarification of the science–policy interface. *Global Environmental Change*, *21*(1), 198–208. https://doi.org/10.1016/j.gloenvcha.2010.08.002

Horsburgh, K., & Horritt, M. (2006). The Bristol Channel floods of 1607 – reconstruction and analysis. *Weather*, *61*(10), 272–277. https://doi.org/10.1256/wea.133.05

Huang, X., Liu, Y., & Huang, L. (2023). BIM and IoT data fusion: The data process model perspective. *Automation in Construction*.

Huggel, C., Kääb, A., & Salzmann, N. (2004). GIS-based modeling of glacial hazards and their interactions using Landsat-TM and IKONOS imagery. *Norsk Geografisk Tidsskrift - Norwegian Journal of Geography*, *58*(2), 61–73. https://doi.org/10.1080/00291950410002296

IPCC. (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC. https://reliefweb.int/attachments/44a8f598-303b-3782-9609-0a5e520ad09d/3B5B76515561CFC185257746006EC70F-ipcc-climate-change-2007.pdf

IPCC. (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. Cambridge University Press.

IPCC, I. P. on C. C. (2022). *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Ji, X., Weng, W., & Fan, W. (2008). Cellular Automata-Based Systematic Risk Analysis Approach for Emergency Response. *Risk Analysis*, *28*(5), 1247–1260. https://doi.org/10.1111/j.1539-6924.2008.01104.x

Jia, H., Wang, J., Yang, Y., Pan, D., & Yang, P. (2016). Analysis of natural disaster chain in Northwest China. *Journal of Catastrophology*, *31*(1), 72–77.

Joint Research Centre, J., & European Commission, E. (2008). *Handbook on Constructing Composite Indicators: Methodology and User Guide*. OECD Publishing. https://www.oecd-ilibrary.org/docserver/9789264043466-en.pdf?expires=1723726185&id=id&accname=guest&checksum=74E87440622F66059F17231622B083B1

Julià, P. B., & Ferreira, T. M. (2021). From single- to multi-hazard vulnerability and risk in Historic Urban Areas: A literature review. *Natural Hazards*, *108*(1), 93–128. https://doi.org/10.1007/s11069-021-04734-5

Kappes, M. S., Gruber, K., Frigerio, S., Bell, R., Keiler, M., & Glade, T. (2012). The MultiRISK platform: The technical concept and application of a regional-scale multihazard exposure analysis tool. *Geomorphology*, *151–152*, 139–155. https://doi.org/10.1016/j.geomorph.2012.01.024

Kappes, M. S., Keiler, M., Von Elverfeldt, K., & Glade, T. (2012a). Challenges of analyzing multi-hazard risk: A review. *Natural Hazards*, *64*(2), 1925–1958. https://doi.org/10.1007/s11069-012-0294-2

Kappes, M. S., Keiler, M., Von Elverfeldt, K., & Glade, T. (2012b). Challenges of analyzing multi-hazard risk: A review. *Natural Hazards*, *64*(2), 1925–1958. https://doi.org/10.1007/s11069-012-0294-2

Kappes, M. S., Papathoma-Köhle, M., & Keiler, M. (2012). Assessing physical vulnerability for multi-hazards using an indicator-based methodology. *Applied Geography*, *32*(2), 577–590. https://doi.org/10.1016/j.apgeog.2011.07.002

Keefer, D. K. (2002). Investigating Landslides Caused by Earthquakes – A historical Review. *Surveys in Geophysics*, *23*(6), 473–510. https://doi.org/10.1023/A:1021274710840

Kelly, C. (2009). Field note from Tajikistan Compound disaster-A new humanitarian challenge? *Jàmbá: Journal of Disaster Risk Studies*, *2*(3), 295–301.

Khakzad, N., Khan, F., Amyotte, P., & Cozzani, V. (2013). Domino Effect Analysis Using Bayesian Networks. *Risk Analysis*, *33*(2), 292–306. https://doi.org/10.1111/j.1539-6924.2012.01854.x

Khan, F., & Abbasi, S. (1998). DOMIFFECT (DOMIno eFFECT): User-friendly software for domino effect analysis. *Environmental Modelling and Software*, *13*(2), 163–177. https://doi.org/10.1016/S1364-8152(98)00018-8

Khan, S. (2012). Vulnerability assessments and their planning implications: A case study of the Hutt Valley, New Zealand. *Natural Hazards*, *64*(2), 1587–1607. https://doi.org/10.1007/s11069-012-0327-x

Khanmohammadi, S., Arashpour, M., & Bai, Y. (2020, October 14). *Applications of Building Information Modeling (BIM) in Disaster Resilience: Present Status and Future Trends*. 37th International Symposium on Automation and Robotics in Construction, Kitakyushu, Japan. https://doi.org/10.22260/ISARC2020/0191

Klein, J., Greiving, S., & Jarva, J. (2006). *Integrated natural risk legend and standard for harmonised risk maps for land use planning and management. Deliverable 3.2, ARMONIA*.

Kourniotis, S. P., Kiranoudis, C. T., & Markatos, N. C. (2000). Statistical analysis of domino chemical accidents. *Journal of Hazardous Materials*, *71*(1–3), 239–252. https://doi.org/10.1016/S0304-3894(99)00081-3

Lee, R., White, C. J., Adnan, M. S. G., Douglas, J., Mahecha, M. D., O'Loughlin, F. E., Patelli, E., Ramos, A. M., Roberts, M. J., Martius, O., Tubaldi, E., Van Den Hurk, B., Ward, P. J., & Zscheischler, J. (2024). Reclassifying historical disasters: From single to multi-hazards. *Science of The Total Environment*, *912*, 169120. https://doi.org/10.1016/j.scitotenv.2023.169120

Lee, Y.-J. (2014). Social vulnerability indicators as a sustainable planning tool. *Environmental Impact Assessment Review*, *44*, 31–42. https://doi.org/10.1016/j.eiar.2013.08.002

León, J., Ogueda, A., Gubler, A., Catalán, P., Correa, M., Castañeda, J., & Beninati, G. (2024). Increasing resilience to catastrophic near-field tsunamis: Systems for capturing,

modelling, and assessing vertical evacuation practices. *Natural Hazards*, *120*, 9135–9161. https://doi.org/10.1007/s11069-022-05732-x

Li, Y., Gong, J., Zhu, J., Song, Y., Hu, Y., & Ye, L. (2013). Spatiotemporal simulation and risk analysis of dam-break flooding based on cellular automata. *International Journal of Geographical Information Science*, *27*(10), 2043–2059. https://doi.org/10.1080/13658816.2013.786081

Lin, Y.-C., Chen, Y.-P., Yien, H.-W., Huang, C.-Y., & Su, Yu-Chih. (2018). Integrated BIM, game engine and VR technologies for healthcare design: A case study in cancer hospital. *Advanced Engineering Informatics*, *36*, 130–145. https://doi.org/10.1016/j.aei.2018.03.005

Liu, A., & Wu, C. (2015). Research on risk assessment method of disaster chain based on complex network. *Syst. Eng. Theory Pract*, *35*(2), 466–472.

Liu, W., & He, S. (2018). Dynamic simulation of a mountain disaster chain: Landslides, barrier lakes, and outburst floods. *Natural Hazards*, *90*(2), 757–775. https://doi.org/10.1007/s11069-017-3073-2

Ma, G., & Wu, Z. (2020). BIM-based building fire emergency management: Combining building users' behavior decisions. *Automation in Construction*, *109*, 102975. https://doi.org/10.1016/j.autcon.2019.102975

Mahendra, R. S., Mohanty, P., Kumar, T., Shenoi, S., & Nayak, S. (2010). Coastal Multi-Hazard Vulnerability Mapping: A Case Study Along The Coast of Nellore District, East Coast of India. *Italian Journal of Remote Sensing*, *42*, 67–76. https://doi.org/10.5721/ItJRS20104235

Marzocchi, W., Di Ruocco, A, Mastellone, M, Novelli, P., Romeo, E., & Gasparini, P. (2009). *Principles of multi-risk assessment: Interaction amongst natural and man-induced risks*. EC. https://data.europa.eu/doi/10.2777/30886

Marzocchi, W., Garcia-Aristizabal, A., Gasparini, P., Mastellone, M. L., & Di Ruocco, A. (2012). Basic principles of multi-risk assessment: A case study in Italy. *Natural Hazards*, *62*(2), 551–573. https://doi.org/10.1007/s11069-012-0092-x

Mascheri, G., Chieffo, N., Romão, X., & Lourenço, P. B. (2024). *COMPREHENSIVE MULTI-RISK ASSESSMENT FOR THE LISBON METROPOLITAN AREA*.

Mazzorana, B., Picco, L., Rainato, R., Iroumé, A., Ruiz-Villanueva, V., Rojas, C., Valdebenito, G., Iribarren-Anacona, P., & Melnick, D. (2019). Cascading processes in a changing

environment: Disturbances on fluvial ecosystems in Chile and implications for hazard and risk management. *Science of The Total Environment*, *655*, 1089–1103. https://doi.org/10.1016/j.scitotenv.2018.11.217

Mendes, J. M. (2009). Social vulnerability indexes as planning tools: Beyond the preparedness paradigm. *Journal of Risk Research*, *12*(1), 43–58. https://doi.org/10.1080/13669870802447962

Mendes, J. M., Tavares, A. O., Cunha, L., & Freiria, S. (2011). A vulnerabilidade social aos perigos naturais e tecnológicos em Portugal. *Revista Crítica de Ciências Sociais*, *93*, 95–128. https://doi.org/10.1007/s13753-011-0005-5

Menoni, S. (2006). *Integration of harmonized risk maps with spatial planning decision processes* (No. Deliverable 5.1, ARMONIA).

Menoni, S., Molinari, D., Parker, D., Ballio, F., & Tapsell, S. (2012). Assessing multifaceted vulnerability and resilience in order to design risk-mitigation strategies. *Natural Hazards*, *64*(3), 2057–2082. https://doi.org/10.1007/s11069-012-0134-4

Meyenfeld, H. (2008). *Modellierung seismisch ausgelöster gravitativer Massenbewegungen für die Schwäbische Alb und den Raum Bonn und Erstellen von Gefahrenhinweiskarten*. University of Vienna.

Middelmann, M. H., & Granger, K. (2000). *Community risk in Mackay: A multi hazard risk assessment*. Australian Geological Survey Organisation (AGSO). https://pid.geoscience.gov.au/dataset/ga/35315

Mingguang, Z., & Juncheng, J. (2008). An improved probit method for assessment of domino effect to chemical process equipment caused by overpressure. *Journal of Hazardous Materials*, *158*(2–3), 280–286. https://doi.org/10.1016/j.jhazmat.2008.01.076

Mousavi, M., TohidiFar, A., & Alvanchi, A. (2022). BIM and machine learning in seismic damage prediction for non-structural exterior infill walls. *Automation in Construction*, *139*. https://doi.org/10.1016/j.autcon.2022.104288

Munich Re. (1998). *Weltkarte der Naturgefahren. Tech. Rep.* Münchner Rückversicherungs-Gesellschaft.

Munich Re. (2000). *Topics 2000: Natural catastrophes—The current position. Tech. Rep.* Münchner Rückversicherungs-Gesellschaft.

Murray, V., Abrahams, J., Ahmed, K., Davies, P., Douris, J., Golding, B., Kumar, A., Nagy, M., & Denis, M. (2022). *POLICY BRIEF: USING UNDRR/ISC HAZARD INFORMATION PROFILES*

TO MANAGE RISK AND IMPLEMENT THE SENDAI FRAMEWORK FOR DISASTER RISK REDUCTION.

MYRIAD-EU. (n.d.). *MYRIAD-EU*.

Necci, A., Argenti, F., Landucci, G., & Cozzani, V. (2014). Accident scenarios triggered by lightning strike on atmospheric storage tanks. *Reliability Engineering & System Safety*, *127*, 30–46. https://doi.org/10.1016/j.ress.2014.02.005

O'Brien, K. L., Eriksen, S., Schjolden, A., & Næss, L. O. (2005). What's in a word? Interpretations of vulnerability in climate change research. *Climate Policy*. https://doi.org/10.1080/14693062.2005.9685548

Ohgai, A., Gohnai, Y., Ikaruga, S., Murakami, M., & Watanabe, K. (2004). Cellular automata modeling for fire spreading as a tool to aid community-based planning for disaster mitigation. In *Recent advances in design and decision support systems in architecture and urban planning* (pp. 193–209). Springer.

Olfert, A., Greiving, S., & Batista, M. J. (2006). *Regional Multi-risk Review, Hazard Weighting and Spatial Planning Response to Risk-Results from European Case Studies*. *42*, 125–151.

Owolabi, T. A., & Sajjad, M. (2023). A global outlook on multi-hazard risk analysis: A systematic and scientometric review. *International Journal of Disaster Risk Reduction*, *92*, 103727. https://doi.org/10.1016/j.ijdrr.2023.103727

Papathoma-Köhle, M., Kappes, M., Keiler, M., & Glade, T. (2011). Physical vulnerability assessment for alpine hazards: State of the art and future needs. *Natural Hazards*, *58*(2), 645–680. https://doi.org/10.1007/s11069-010-9632-4

Paulik, R., Horspool, N., Woods, R., Griffiths, N., Beale, T., Magill, C., Wild, A., Popovich, B., Walbran, G., & Garlick, R. (2023). RiskScape: A flexible multi-hazard risk modelling engine. *Natural Hazards*, *119*(2), 1073–1090. https://doi.org/10.1007/s11069-022-05593-4

Paupério, E., Romão, X., & Costa, A. (2012). *A methodology for the vulnerability assessment of heritage buildings and contents under catastrophic hazard*. https://repositorio-aberto.up.pt/handle/10216/84581

Penn, R., Wild, S., & Mascarenhas, J. (1996). The Pombaline Quarter of Lisbon: An Eighteenth Century Example of Prefabrication and Dimensional Co-ordination. *Construction History*, *11*, 3–17.

Peters, K., Buzna, L., & Helbing, D. (2008). Modelling of cascading effects and efficient response to disaster spreading in complex networks. *International Journal of Critical Infrastructures*, *4*(1/2), 46. https://doi.org/10.1504/IJCIS.2008.016091

Puissant, A., Malet, J.-P., & Maquaire, O. (2006). *Mapping landslide consequences in mountain areas; a tentative approach with a semi-quantitative procedure*. https://api.semanticscholar.org/CorpusID:134502969

Rahman, M. (2019). Application of Bayesian methods in disaster risk assessment. *2019 IEEE 6th International Conference on Industrial Engineering and Applications (ICIEA)*, 318–322.

Risk Frontiers. (2008). *PerilAUS II—relative risk ratings for postcodes and CRESTA/ICA zones*. https://riskfrontiers.com/services/

RMS. (2009). *Risk management solutions*.

Romão, X., Paupério, E., & Pereira, N. (2016). A framework for the simplified risk analysis of cultural heritage assets. *Journal of Cultural Heritage*, *20*, 696–708. https://doi.org/10.1016/j.culher.2016.05.007

Samarakkody, A., Amaratunga, D., & Haigh, R. (2023). Technological Innovations for Enhancing Disaster Resilience in Smart Cities: A Comprehensive Urban Scholar's Analysis. *Sustainability*, *15*(12036), 1–22. https://doi.org/10.3390/su151512036

Schmidtlein, M. C., Deutsch, R. C., Piegorsch, W. W., & Cutter, S. L. (2008). A sensitivity analysis of the social vulnerability index. *Risk Analysis*, *28*, 1099–1114. https://doi.org/10.1111/j.1539-6924.2008.01072.x

Schmidt-Thomé, P. (Ed.). (2006). *Natural and technological hazards and risks affecting the spatial development of European regions: This volume is based on peer reviewed articles that reflect the results of the EPSON 1.3.1 project 'The spatial effects and management of natural and technological hazards in Europe'*. Geological Survey of Finland.

Schneiderbauer, S., & Ehrlich, D. (2006). Social levels and hazard (in)dependence in determining vulnerability. In J. Birkmann (Ed.), *Measuring vulnerability to natural hazards—Towards disaster resilient societies* (pp. 78–102). TERI Press.

Sedan, O., & Mirgon, C. (2003). *Application ARMAGEDOM. Notice utilisateur BRGM/RP-52759-FR, Bureau de recherches géologiques et minières (BRGM)*. https://infoterre.brgm.fr/rapports/RP-52759-FR.pdf

Shiau, Y.-C., Tsai, Y.-Y., Hsiao, J.-Y., & Chang, C.-T. (2023). *Development of Building Fire Control and Management System in BIM Environment*. 15–24.

Sun, D., Jiang, J., Zhang, M., & Wang, Z. (2015). Influence of the source size on domino effect risk caused by fragments. *Journal of Loss Prevention in the Process Industries*, *35*, 211–223. https://doi.org/10.1016/j.jlp.2015.05.005

Tapsell, S., McCarthy, S., Faulkner, H., & Alexander, M. (2010). *Social vulnerability to natural hazards*.

Tarvainen, T., Jarva, J., & Greiving, S. (2006). *Spatial pattern of hazards and hazard interactions in Europe*. 83–91.

Tate, E. (2012). Social Vulnerability Indices: A Comparative Assessment Using Uncertainty and Sensitivity Analysis. *Natural Hazards*, *63*(2), 325–347. https://doi.org/10.1007/s11069-012-0152-2

Tavares, A. O., Barros, J. L., Mendes, J. M., Santos, P. P., & Pereira, S. (2018). Decennial comparison of changes in social vulnerability: A municipal analysis in support of risk management. *International Journal of Disaster Risk Reduction*, *31*, 679–690. https://doi.org/10.1016/j.ijdrr.2018.07.004

Tilloy, A., Malamud, B. D., Winter, H., & Joly-Laugel, A. (2019). A review of quantification methodologies for multi-hazard interrelationships. *Earth-Science Reviews*, *196*, 102881. https://doi.org/10.1016/j.earscirev.2019.102881

Tobin, G. A., & Montz, B. E. (1997). *Natural Hazards: Explanation and Integration*. The Guilford Press.

UNDRR. (2015). *Sendai Framework for Disaster Risk Reduction 2015—2030*. United Nations Office for Disaster Risk Reduction. https://www.undrr.org/media/16176/download?startDownload=20241008

UNDRR. (2017). *DRR Glossary: Terminology*. United Nations Office for Disaster Risk Reduction. https://www.undrr.org/drr-glossary/terminology

UNDRR (Ed.). (2022). *Global Assessment Report on Disaster Risk Reduction 2022: Our World at Risk: Transforming Governance for a Resilient Future*. United Nations.

UN-ISDR. (2009). *Global assessment report on disaster risk reduction. Tech. Rep.* https://www.undrr.org/publication/global-assessment-report-disaster-risk-reduction-2009

Wan, H., Song, H., Zhu, C., & Zhang, M. (2017). Drought and flood disaster chain and its response to climate change in Baoji region during the Ming and Qing dynasties. *Acta Geogr Sin*, *72*(1), 27–38.

Wang, C., Li, H., & Kho, S. Y. (2018). VR-embedded BIM immersive system for QS engineering education. *Computer Applications in Engineering Education*, *26*, 626–641. https://doi.org/10.1002/cae.21915

Wang, J., Gu, X., & Huang, T. (2013). Using Bayesian networks in analyzing powerful earthquake disaster chains. *Natural Hazards*, *68*(2), 509–527. https://doi.org/10.1007/s11069-013-0631-0

Wang, J., He, Z., & Weng, W. (2020). A review of the research into the relations between hazards in multi-hazard risk analysis. *Natural Hazards*, *104*, 2003–2026. https://doi.org/10.1007/s11069-020-04259-3

Welch, D. P., Sullivan, T. J., & Filiatrault, A. (2014). Potential of building information modelling for seismic risk mitgation in buildings. *Bulletin of the New Zealand Society for Earthquake Engineering*, *34*(3), 253–263. https://doi.org/10.5459/bnzsee.34.3.214-236

Westen, C. J., Montoya, L., & Boerboom, L. (2002). *Multi-Hazard Risk Assessment using GIS in urban areas: A case study for the city of Turrialba, Costa-Rica*.

Wichmann, V., & Becht, M. (2003). Modelling of geomorphic processes in an alpine catchment. *7th International Conference on Geo Computation*. Martin D (ed), Southampton.

Wipulanusat, W., Nakrod, S., & Prabnarong, P. (2009). Multi-hazard risk assessment using GIS and RS applications: A case study of Pak Phanang Basin. *Walailak Journal of Science and Technology (WJST)*, *6*(1), 109–125.

Wisner, B. (2002). Who? What? Where? When? In an emergency: Notes on possible indicators of vulnerability and resilience by phase of the disaster management cycle and social actor. In *Environment and Human Security: Contributions to a Workshop in Bonn* (12th ed., pp. 7–12).

Wolfram, S. (1984). Computation theory of cellular automata. *Communications in Mathematical Physics*, *96*(1), 15–57. https://doi.org/10.1007/BF01217347

Xofi, M., Domingues, J. C., Santos, P. P., Pereira, S., Oliveira, S. C., Reis, E., Zêzere, J. L., Garcia, R. A. C., Lourenço, P. B., & Ferreira, T. M. (2022). On the Multi-hazard Risk Assessment of Urban Areas: Identification and Analysis of Exposure and Physical Vulnerability Indicators. *Advanced Nondestructive and Structural Techniques for Diagnosis, Redesign, and Health Monitoring for the Preservation of Cultural Heritage*, 146–155. https://doi.org/10.1007/978-3-031-03795-5_12

Zhao, L. (2008). *Study on the formation and prevention of geological hazards by human activity in Hunan Province*. *19*(2), 7–11.

Zheng, L., Wang, F., & Zheng, X. (2017). Complex network construction method to extract the nature disaster chain based on data mining. *2017 7th IEEE International Conference on Electronics Information and Emergency Communication (ICEIEC)*, 25–28.

Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R. M., Van Den Hurk, B., AghaKouchak, A., Jézéquel, A., Mahecha, M. D., Maraun, D., Ramos, A. M., Ridder, N. N., Thiery, W., & Vignotto, E. (2020). A typology of compound weather and climate events. *Nature Reviews Earth & Environment*, *1*(7), 333–347. https://doi.org/10.1038/s43017-020-0060-z

Annex A: RETIME glossary

Table 16 shows RETIME glossary resulting from the procedure described in *Section 3*.

Table 16. RETIME glossary.

A	Definition
Adaptation Tipping Point	An adaptation tipping point (ATP) is the moment when the magnitude of change is such that a current management strategy can no longer meet its objectives. As a result, adaptive management is needed to prevent or postpone these ATPs.
Architecture/architectural	Refers to the art of buildings and other physical structures. It involves both functional and aesthetic considerations, aiming to create spaces that are practical, safe, and visually pleasing. Architecture includes not only the design of individual structures but also the planning of entire environments, from cities to landscapes.
Automatic building monitoring system	Is a centralised system that monitors, controls, and automates various building functions such as HVAC (Heating, ventilation, and air conditioning), lighting, security, and energy management to optimise performance, reduce energy use, and improve comfort and safety.
B	**Definition**
Bayesian (Belief) Network	Graphical models that communicate causal information and provide a framework for describing and evaluating probabilities when we have a network of interrelated variables.
Building envelope	A building envelope is a barrier between the interior and exterior of a building designed to control the transference of air, water, heat, light, and noise. A building envelope includes the outer walls, roofing, and foundations.
Building characteristics	The physical and functional properties of a structure, including its size, shape, materials, and purpose.
Building resilience (assessment)	Ability to protect, maintain, or restore the functionality of, value of, and income generated by a building after a damaging event within a prescribed time frame.
C	**Definition**
Capacity	The combination of all the attributes, and resources available within an organisation, community, or society to manage and reduce disaster risks and strengthen resilience.
Capacity (Coping)	Coping capacity is the ability of people, organizations and systems, using available skills and resources, to manage adverse conditions, risk or disasters.
Cascades	Sequence of interconnected events where an initial incident or failure triggers subsequent risks or failures, often across different sectors or systems. This phenomenon is also known as "cascading effects" and is commonly observed in situations where the impact of one disaster leads to secondary events, amplifying the overall risk and complexity of the crisis. Processes in which an event or action triggers a chain reaction of subsequent events, each one building upon the previous.
Complexity	A causal chain with many intervening variables and feedback loops that do not allow the understanding or prediction of the system's behaviour on the basis of each component's behaviour.
Composite index	It is a statistical measure that combines multiple individual indicators or variables to create an overall score or representation. It is commonly used in finance, economics, and risk management to provide a single value that summarises a broader dataset or sector.

Composite vulnerability	Aggregated measure that combines multiple dimensions of vulnerability—such as social, economic, environmental, and infrastructural factors—into a single index. This index is used to assess the overall vulnerability of a system, community, or region to hazards or risks.
Confidence	The robustness of a finding based on the type, amount, quality and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and on the degree of agreement across multiple lines of evidence.
Criticality	Set of characteristics and behaviours of individuals that can contribute to the disruption of the system and community resources that allow them to respond to or deal with catastrophic scenarios.
D	**Definition**
Deterministic Event Modelling	Modelling of single, specific events (simulated or real observed) based on physical and analytical equations or other predefined rules.
Digital Twin	A Digital Twin in the context of the built environment and landscapes refers to a dynamic, virtual representation of physical assets, infrastructure, or entire landscapes, created using real-time data and simulations. It integrates geospatial data, sensors, Internet of Things (IoT) devices, and advanced modelling techniques to reflect the physical conditions and operations of buildings, cities, or natural environments.
Disaster	Serious disruption of the functioning of a community or society on any scale as a result of hazardous events, resulting in one or more of the following: human, material, economic, and environmental losses.
Disaster damage	It occurs during and immediately after a disaster. It is usually measured in physical units (e.g., square metres of dwellings, kilometres of roads, etc.) and describes the extent of destruction of physical assets, disruption of basic services and damage to livelihoods in the affected area.
Disaster Forensics	A process to understand the root causes of disasters (rather than focusing exclusively on the dynamics of individual disaster events and response efforts), often yielding 'systemic' strategies for managing disasters.
Disaster Impact	The total effect of a hazardous event or a disaster including economic, human and environmental impacts, and may include death, injuries, disease and other negative effects on human.
Disaster Recovery	The restoring or improving of livelihoods and health, as well as economic, physical, social, cultural and environmental assets, systems and activities, of a disaster-affected community or society, aligning with the principles of sustainable development and "build back better", to avoid or reduce future disaster risk.
Disaster Response	Actions taken directly before, during or immediately after a disaster to save lives, reduce health impacts, ensure public safety, and meet the basic subsistence needs of the people affected.
Disaster Risk	The potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society, or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity.
Disaster Risk Assessment	A qualitative or quantitative approach to determine the nature and extent of disaster risk by analysing potential hazards and evaluating existing conditions of exposure and vulnerability that together could harm people, property, services, livelihoods and the environment on which they depend.

Disaster Risk Drivers	Processes or conditions, often development-related, that influence the level of disaster risk by increasing levels of exposure and vulnerability or reducing capacity.
Disaster Risk Governance	The system of institutions, mechanisms, policy and legal frameworks and other arrangements to guide, coordinate and oversee disaster risk reduction and related areas of policy.
Disaster Risk Reduction	Preventing new and reducing existing disaster risk and managing residual risk, all of which contribute to strengthening resilience and therefore to the achievement of sustainable development.
Disasters (Consecutive)	Two or more disasters that occur in succession, and whose direct impacts overlap spatially before recovery from a previous event is completed.
Domino effect	A sequence of events triggered by initiating event. The occurrence of such effects significantly increases the severity of events that propagate in time and space. Events will occur in series, but also in parallel, if one of them affects several risk elements.
E	**Definition**
Ecosystem Services	Ecological processes or functions having monetary or non-monetary value to individuals or society at large. We can split them into use values (direct, indirect, option values) and non-use values (existence values).
Ecosystem-Based Adaptation (EbA)	The use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change. EbA aims to maintain and increase the resilience of ecosystems and people in the face of the adverse effects of climate change.
Ecosystem-Based Disaster Risk Reduction (Eco-DRR)	The sustainable management, conservation, and restoration of ecosystems to reduce disaster risk, with the aim to achieve sustainable and resilient development.
Emergency	Sudden, urgent, usually unexpected occurrence or event requiring immediate action.
Emergency protocols	Refer to a set of standardised procedures and guidelines designed to ensure safety and effective management during critical situations. These protocols outline the specific actions, roles, and communication strategies to be used during emergencies, such as natural disasters, accidents, or hazardous material spills.
Energy poverty	Situation where households or individuals cannot access essential energy services, such as heating, cooling, lighting, and the use of appliances, due to financial constraints or inadequate infrastructure. This results in adverse impacts on well-being, health, and social inclusion. This expands to broader issues of energy access, affordability, and efficiency.
Environmental Degradation	The reduction of the capacity of the environment to meet social and ecological objectives and needs. Degradation of the environment can alter the frequency and intensity of natural hazards and increase the vulnerability of communities. It could be also expressed as the most common anthropogenically caused reduction in the ecological stability of ecosystems and thus in the services they provide.
Event	Occurrence or change of a particular set of circumstances.
Exposure	The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas.
F	**Definition**
Feedback Loops	Part of a system in which some portion (or all) of the system's output is used as input for future operations. cyclical processes where the

	outcome or output of a system feeds back into the system itself, either amplifying or diminishing the original effect. These loops are critical in understanding how risks evolve, escalate, or stabilise over time. Positive feedback loop amplifies the original effect, leading to an increase in the intensity or frequency of a hazard or risk. For example, in climate change, melting polar ice reduces the Earth's albedo (the reflective capacity of the surface), meaning less solar radiation is reflected back into space, causing more warming, which leads to further ice melt. This amplifies global warming and escalates disaster risks like sea-level rise and extreme weather events. Another example in natural hazards might be deforestation, which can lead to increased landslides and flooding during heavy rains. The degradation of vegetation leads to more erosion, creating a positive feedback loop that increases the risk of these disasters. Negative Feedback Loops: In contrast, a negative feedback loop stabilises or dampens the original effect, reducing the intensity of a risk or hazard. For instance, in climate systems, increased cloud formation due to higher temperatures or volcanic ashes eruptions might block sunlight, cooling the surface and potentially mitigating further warming. In theory, this could create a stabilising effect, although such processes are more complex and likely not enough to counter global warming completely.
G	**Definition**
Governance	The structures, processes, and actions through which private and public actors interact to address societal goals. This includes formal and informal institutions and the associated norms, rules, laws, and procedures for deciding, managing, implementing, and monitoring policies and measures at any geographic or political scale, from global to local.
Greenhouse gas emission scenarios (RCPs)	RCPs are standardised pathways that describe different trajectories of greenhouse gas concentrations and their potential impact on radiative forcing by 2100. They include scenarios like RCP 2.6 (strong mitigation), RCP 4.5 (stabilization by mid-century), RCP 6.0 (stabilisation by end-century), and RCP 8.5 (high emissions), each leading to different levels of global warming.
H	**Definition**
Hazard (Cascading)	Cascading hazard processes refer to an initial hazard followed by a chain of interrelated hazards (e.g., earthquake triggering landslide, landslide triggering flooding, flooding triggering further landslides).
Hazard chain	A sequential process where one hazard triggers subsequent events or conditions, each contributing to an increased risk of harm or disruption. This chain of hazards could involve a cascading effect, where initial risks (e.g., equipment malfunction, natural disasters, or human errors) set off a series of subsequent failures or hazardous conditions, ultimately leading to a more significant event or risk scenario.
Hazard Interrelationships	The mode in which one hazard influences (directly or indirectly) another hazard.
Hazard networks	The interdependencies among the hazards in a system can be expressed by means of a hazard network, in which the nodes correspond to the hazards and the links indicate how they depend on one another.
Hazards (Anthropogenic)	Hazards that are induced entirely or predominantly by human activities and choices. This term does not typically include the occurrence or risk of armed conflicts and other situations of social instability or tension

	which are subject to international humanitarian law and national legislation.
Hazards (Biological)	Biological hazards are of organic origin or conveyed by biological vectors, including pathogenic microorganisms, toxins and bioactive substances.
Hazards (Environmental)	Environmental hazards may include chemical, natural, and biological hazards. They can be created by environmental degradation or physical or chemical pollution in the air, water, and soil.
Hazards (External)	Hazards originating from sources located outside the site area of interest.
Hazards (Geological / Geophysical)	Geological or geophysical hazards originate from internal earth processes.
Hazards (Hydrometeorological)	Hydrometeorological hazards are of atmospheric, hydrological, or oceanographic origin.
Hazards (Natural)	Hazards that are predominantly associated with natural processes and phenomena.
Hazards (Technological)	Technological hazards originate from technological or industrial conditions, dangerous procedures, infrastructure failures or specific human activities.
Human-induced (hazards)	Refer to risks that arise from human activities, either through deliberate actions or unintended consequences. These hazards include technological or industrial accidents, such as chemical spills, nuclear accidents, or infrastructure failures.
I	**Definition**
Impact-based Early Warning	Advanced approach in early warning systems that not only predicts the occurrence of a hazardous event (such as a storm or flood) but also focuses on forecasting the potential impacts of these events on people, infrastructure, and the environment.
Impacts (Cascading)	Cascading impacts are those in which the impact of a physical event or the development of an initial technological or human failure generates a sequence of events in human subsystems that results in physical, social or economic disruption.
Impacts (Cross-Boundary)	Cross-boundary impacts refer to the effects of events, actions, or policies that transcend political, geographic, or jurisdictional borders, impacting neighbouring regions, countries, or ecosystems. These impacts are crucial in fields like environmental issues, natural hazards, and climate change, where the consequences of actions often do not stop at administrative boundaries. Key areas where cross-boundary impacts are relevant: *Environmental Hazards:* Transboundary Pollution: Pollution (e.g., air or water pollution) from one region can affect neighbouring areas, such as air pollution traveling across national borders or water contamination in transboundary rivers. *Natural Disasters:* Disasters Crossing Borders: Hazards like earthquakes, wildfires, and floods often cross borders, affecting multiple regions or countries. An earthquake in one nation can cause widespread damage in neighbouring areas, and wildfires can spread across political boundaries depending on environmental conditions. *Climate Change:* *Climate-Induced Migration:* Environmental changes such as rising sea levels, droughts, or desertification can drive populations to migrate across borders, potentially leading to political tensions or resource competition in neighbouring areas.

	Cross-boundary Climate Policies: Climate mitigation strategies or policies in one region (e.g., carbon taxes) can have positive or negative economic impacts on neighbouring regions.
Incident	Event or situation that can be, or could lead to, a disruption, loss, emergency or crisis.
Index (Risk management)	A simplified tool used in risk management to aggregate multiple risk factors into a single measurable value, allowing for the comparison of risks across different scenarios or regions. It provides a standardised numeric representation of overall risk, which can be applied to both qualitative and quantitative assessments.
Indicators (Risk management)	These are measurable variables or metrics used to assess the performance, progress, or condition of a system or process. In risk management, indicators help monitor and evaluate potential risks, detect early warning signs, and track changes over time to inform decision-making and improve risk mitigation strategies.
Infrastructure	Fundamental systems and structures required for the functioning of a society, economy, or organization. It includes physical assets like transportation networks (roads, bridges, railways), utilities (water, energy, telecommunications), public institutions (hospitals, schools), and digital systems (cyber infrastructure).
Insurance	A family of financial instruments for sharing and transferring risk among a pool of at-risk households, businesses, and/or governments.
L	**Definition**
Litigation risk	Potential for legal action or lawsuits resulting from a company's actions, products, services, or decisions. This risk can lead to significant financial costs, including legal fees, settlements, and reputational damage.
Loss (Direct economic)	The monetary value of total or partial destruction of physical assets existing in the affected area. Direct economic loss is nearly equivalent to physical damage.
Loss (Economic)	Total economic impact that consists of direct economic loss and indirect economic loss.
Loss (Indirect economic)	A decline in economic value added as a consequence of direct economic loss and/or human and environmental impacts. Indirect economic loss includes microeconomic impacts (e.g., revenue declines owing to business interruption), mesoeconomic impacts (e.g., revenue declines owing to impacts on natural assets, interruptions to supply chains or temporary unemployment) and macroeconomic impacts (e.g., price increases, increases in government debt, negative impact on stock market prices and decline in GDP).
Loss (Non-economic)	Non-economic losses refer to a broad range of losses that are not in financial terms and not commonly traded in markets. They may impact individuals (e.g., loss of life, health, mobility), society (e.g. loss of territory, cultural heritage, indigenous or local knowledge, societal or cultural identity) or the environment (e.g. loss of biodiversity, ecosystem services).
M	**Definition**
Man-made (hazards)	Are risks or disasters that are caused entirely or predominantly by human activities or choices. These include accidents such as chemical spills, explosions, transportation accidents, and environmental contamination.
Mitigation (Climate Change)	Human intervention to reduce GHG emissions, environmental impacts or increase sinks of greenhouse gases to prevent a worsening of the climate crisis.

Mitigation (Hazard Impact)	The reduction of the potential adverse impacts of a hazardous event (including those that are human-induced) through actions that reduce hazard, exposure, and vulnerability.
Mitigation measure	In climate policy, mitigation measures are technologies, processes or practices carried out to mitigate the effect of a disaster.
Modelling	The process of creating a simplified representation or simulation of a system to predict or analyse its behaviour under different scenarios. In risk management, modelling is used to forecast potential outcomes of various hazards, assess vulnerabilities, and develop strategies to mitigate risks. This process often involves mathematical or computational tools to simulate complex interactions and outcomes.
Multi-Hazard Event Sets	A list of multi-hazard events over a given time period.
Multi-Layer Single Hazards	More than one hazards are considered, but not the interrelationships between these (i.e., they are treated as discrete, independent).
(Multi-)vulnerability	Refers to (i) a variety of exposed sensitive targets (e.g., population, infrastructure, cultural heritage) with possible different vulnerability degree against the various hazards; (ii) time-dependent vulnerabilities, in which the vulnerability of a specific class of exposed elements may change with time as consequence of different factors (e.g. the occurrence of other hazardous events).
N	**Definition**
NATECH Events	Technological accidents triggered by a natural hazard or disaster which result in consequences involving hazardous substances (e.g., fire, explosion, toxic release).
Natural Resources	Actual or potential sources of wealth that occur in a natural state, such as timber, water, fertile land, wildlife and minerals.
Nature-Based Solutions	Actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits. Their characteristic feature is the provision of benefits without the need to maintain them or to supply energy or other resources for their functionality (e.g. greenery cools a space without the need to supply electricity as in the case of air conditioning).
O	**Definition**
Occurrence (Risk management)	The event or instance of something happening. In risk management, occurrence is used to describe the frequency or probability of a specific hazard or risk event taking place within a given time frame.
Opportunity Tipping Points	Points at which a particular action becomes feasible or attractive, for example because of lower costs of actions or technical developments.
P	**Definition**
Paired Disaster Study	A type of empirical case study, that analyses changing conditions, and changes in the impacts of consecutive disasters that occurred in the same region over time.
Pathway	The temporal evolution of natural and/or human systems towards a future state.
Physical vulnerability	Physical factors which increase the susceptibility of assets, buildings or systems to the impacts of hazards.
Pilot Area	A specific, designated location where new methods, technologies, or processes are tested and evaluated before wider implementation.
Pilot object (Building)	Building that is used to test new technologies, processes, or systems in a real-world and controlled environment before broader implementation.

Preparedness	The knowledge and capacities developed by governments, response and recovery organizations, communities, and individuals to effectively anticipate, respond to, and recover from the impacts of likely, imminent, or current disasters.
Probabilistic Event Modelling	Modelling approach where multiple simulations are run with slightly varying initial conditions or parameters to capture a range of possible outcomes.
Probable Maximum Loss	The maximum loss that an insurer would be expected to incur on a policy.
R	**Definition**
Relationship (Amplification)	The occurrence of one hazard can increase the likelihood and/or magnitude of additional hazards in the future (e.g., forest fires can amplify the triggering of debris flows during heavy rain).
Relationship (Triggering)	One hazard causing another hazard to occur Any natural hazard might trigger zero, one, or more secondary natural hazards, with these being either the same or different from the primary hazard.
Relationships (Compound)	Two different natural hazards that impact the same time period and spatial area. Compound hazards can have a footprint with spatial and temporal characteristics that differs from the component single hazards.
Resilience Knowledge Hub	A comprehensive collection of online tools, resources and publications to support professionals working in resilience.
Risk "understanding"/ risk "equation"	It refers to the comprehensive awareness and analysis of potential risks, including their nature, likelihood, impact, and interconnections. It involves identifying hazards, assessing vulnerabilities, and recognising how different factors may influence the outcome of certain events. Proper risk understanding is crucial for informed decision-making in risk management and mitigation strategies.
Risk (Deterministic)	Deterministic risk considers the impact of a single risk scenario (as opposed to probabilistic risk).
Risk (Emergent)	A risk that arises from the intersection of phenomena in a complex system.
Risk (Individual)	Risk of individual elements within a system (a bottom-up perspective).
Risk (Probabilistic)	The consideration of all possible scenarios, their likelihood, and associated impacts.
Risk (Residual)	The disaster risk that remains in unmanaged form, even when effective disaster risk reduction measures are in place, and for which emergency response and recovery capacities must be maintained.
Risk (Systemic)	Process marked by strong interconnections and interdependencies between systems, giving rise to cascading effects, capable of causing disruptions and propagating losses and damages in complex systems.
Risk Dynamics	A term used to encompass the interrelationships between and evolution through time of hazard, exposure, and vulnerability, and underlying risk drivers.
Risk Perception	The subjective judgment that people make about the characteristics and severity of a risk.
Robustness	The insensitivity [of a system] to future conditions and the ability to perform satisfactorily over a broad range of future conditions.
Robustness (Societal)	Robustness of a system of systems might be maximised using different perspectives: a 'social planner's perspective' might want to maximise the welfare for the entire system, while a 'pragmatists perspective' might be accounting for the power dynamics.
Robustness Conflicts	The existence of unacceptable compromises to some cooperating actors in a strategy (e.g., for risk management).
S	**Definition**

Scenario	A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change (TC), prices) and relationships.
Scenario (Current)	A hazard or risk scenario using the historical baseline or current data, for the current conditions.
Scenario (Future)	A hazard or risk scenario using the historical baseline or current data, and/or modelled climate change metrics presented in the future (after present day), for example for 2050 or 2080.
Sensitive buildings/infrastructure	Structures and facilities that are crucial for maintaining societal functions, public safety, and economic stability, and which require heightened protection due to their vulnerability to various threats. These threats can include physical attacks, natural disasters, or cyber intrusions.
Site Area	A geographical area that contains assets at risk.
Social vulnerability	Level of resilience or resistance of individuals and communities when exposed to harmful processes or events.
Structural system	The arrangement of interconnected structural elements within a building or structure that supports and transmits applied loads safely to the ground. The system ensures that a building can withstand forces such as gravity, wind, and seismic activity throughout its lifespan. Common structural systems include frame systems (interconnected columns and beams), braced frames, and shear wall systems, each designed to resist various loads while maintaining the building's stability and safety.
Support Capacity	The ability of stakeholders, including local authorities, public institutions, and private entities, to provide resources, expertise, or infrastructure that aids in mitigating risks and enhancing resilience in vulnerable urban areas. This capacity includes both human resources (e.g., knowledge and experience) and technical resources (e.g., tools and systems).
Sustainability	Involves ensuring the persistence of natural and human systems, implying the continuous functioning of ecosystems, the conservation of high biodiversity, the recycling of natural resources and, in the human sector, successful application of justice and equity, promote stable economic growth without harming the environment
Sustainable (or Healthy) Ecosystems	Ecosystems that are largely intact and functioning where human demand for ecosystem services does not affect their conservation for future generations.
Sustainable Development	Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.
System	A set of (partly) interconnected elements.
System of systems	A system where the individual elements of the system are treated again as systems.
Systemic Perspective	A focus on interactions between elements within a ‘System’ or Systems.
T	**Definition**
Territorial	Spatial organization and management of land use, natural resources, and human activities across a specific geographic area that is under the jurisdiction or control of a specific entity, such as a government, state, or organization. It often carries political or administrative significance and includes land, waters, and airspace.
Territorial vulnerability	Susceptibility of a territory to various hazards, shaped by factors such as its physical, social, economic, and environmental characteristics.
Threshold	The level of magnitude of a system process at which sudden or rapid change occurs. A point or level at which new properties emerge in an

	ecological, economic or other system, invalidating predictions based on mathematical relationships that apply at lower levels.
Tipping Point	A critical threshold beyond which a system reorganises, often abruptly and/or irreversibly.
Tool	A resource or technique designed to carry out a particular function to solve a particular problem.
Totem (Hardware)	A digital display unit, often installed in public spaces such as town squares, that visually presents data collected from various sensors. These sensors can monitor environmental conditions such as weather, air quality, temperature, and pollution. The totem then displays this data in numerical, graphical, or textual formats, providing real-time information to the public.
Trade-off	A decision between two desired outcomes where a gain in one requires a loss in another.
Transition risk	The financial risks that arise as organizations and economies shift toward more sustainable and low-carbon practices. These risks can result from changes in policies, technologies, and market dynamics as efforts to mitigate climate change and reduce carbon emissions intensify.
U	**Definition**
Uncertainty	A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, incomplete understanding of critical processes, or uncertain projections of human behaviour.
Uncertainty (Deep)	Exists when experts do not know or the parties to a decision cannot agree upon (i) the external context of a system, (ii) how a system works and its boundaries, and/or (iii) the outcomes of interest from a system and or their relative importance. Deep uncertainty also arises from actions taken over time in response to unpredictable evolving situations.
Urban (Area)	Region surrounding a city that is highly developed with dense human structures, such as houses, commercial buildings, roads, and bridges.
Urban resilience	Ability of any urban system, with its inhabitants, in a changing environment, to anticipate, prepare, respond to and absorb shocks, positively adapt and transform in the face of stresses and challenges, while facilitating inclusive and sustainable development.
V	**Definition**
Vulnerability	Characteristic of coherent groups of objects, people, areas or systems that expresses their susceptibility to be negatively affected by hazards. It is determined by physical, social, economic and environmental factors or processes.
Vulnerability assessment	The process of identifying, assessing, and prioritising the vulnerabilities within a system or geographic area. It typically involves several steps, such as identifying assets, determining their value, identifying and analysing potential threats, and assessing how vulnerable these assets are to various risks. The goal is to determine both the direct and indirect impacts of vulnerabilities, allowing organizations or authorities to develop strategies to mitigate or eliminate these risks.
Vulnerability hotspots	Geographic areas that are particularly prone to risk due to a combination of exposure to hazards (such as natural disasters) and underlying socio-economic vulnerabilities. These hotspots are regions where the likelihood of damage and the inability to cope with the effects of events like droughts, floods, or storms are especially high.

Annex B: Overview of review papers on vulnerability and risks assessment methodologies

Table 17 presents a database of 33 scientific journal publications, including 22 reviews, which focus on multi-risk, social vulnerability, and resilience. It was created as a side product of the process that led to the identification of the most relevant papers overview in *Section 5*. Table 17 indicates authors, title, and publication year, followed by the selection criteria:

- It is a review paper
- The topic of the review is multi-risk assessment or multi-hazard risk assessment
- Natural hazards, both hydrometeorological (e.g., flood) and solid earth and surface process hazards (e.g., earthquakes) are covered.

Afterwards qualitative assessment of the covered types of risk assessment methodologies /main topics in the publication, gaps in the publication or identified gaps in current research, and major findings are displayed.

Table 17. Overview of publications on vulnerability and risk assessment methodologies.

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
Büyüközkan et al.	A review of urban resilience literature	2022	yes	no	no	N.A.	No multi-risk assessment provided.	Main factors affecting resilience: 1) climate change, 2) urban planning, 3) urban hazards and disaster risks, 4) urban sustainability and green infrastructure, 5) the adaptation solutions and 6) smart technologies.
Chuvieco et al.	Towards an Integrated Approach to Wildfire Risk Assessment: When, Where, What and How May the Landscapes Burn	2023	no	no	no	Only single-hazard: Integrated Wildfire Risk-Assessment.	Only single hazard is considered.	Propose an integrated fire risk system being developed under the FirEUrisk European project, as an example of how the different risk components (including danger, exposure and vulnerability) can be generated and combined into synthetic risk indices to provide a more comprehensive wildfire risk assessment, but also to consider where and on what variables reduction efforts should be stressed and to envisage policies to be better adapted to future fire regimes.

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
Curt	Multirisk: What trends in recent works? – A bibliometric analysis	2021	yes	yes	yes	Various risk assessment methods are overviewed.	Bibliometric approach, no discussion of methods quality.	Identified seven main themes of research in the literature: three concern Domino Effects (46.6% of the articles), two are dedicated to the assessment of Multi-(hazard/vulnerability) Risk (28.7%), one deals with NATECH issues (13.5%) and one concerns Cascade Effects in critical infrastructures (11.2%).

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
Drakes & Tate	Social vulnerability in a multi-hazard context: a systematic review	2022	yes	no	yes	This systematic review utilises correlations and hierarchical clustering to determine how social vulnerability is assessed in the context of the three most common classifications of 'multi-hazard': aggregate, cascading and compound.	Future research should focus on the cascading and compound classifications of multi-hazards, which are more suited to interrogating how human-(multi)hazard interactions shape social vulnerability.	Results reveal these classifications of 'multi-hazard' each focus on different aspects of social vulnerability. Studies in the aggregate classification of multi-hazard were more likely to represent social vulnerability as an outcome of hazard events, while those in the cascading and compound classifications more often addressed social vulnerability as a preexisting condition. Further, knowledge of social vulnerability to multi-hazards comes mainly from the aggregate classification and the mitigation phase of the disaster cycle.

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
Fekete	Social Vulnerability (Re-)Assessment in Context to Natural Hazards: Review of the Usefulness of the Spatial Indicator Approach and Investigations of Validation Demands	2019	yes	no	yes	This article analyses, by means of a literature review of 63 articles, if and in which aspects such an indicator approach is regarded as useful by scientific studies.	A need for more research on the validation and justification of indicators.	This article supports the conceptual development of SVA by adding to reflection about advancements and applications, but also shortcomings. The main advancement area discussed is validation and the demand for establishing benchmark criteria for vulnerability.
Felicioni et al.	Exploring the Common Ground of Sustainability and Resilience in the Building Sector: A Systematic Literature Review and Analysis of Building Rating Systems	2023	yes	no	yes	Overlaps between sustainability and resilience.	No multi-risk assessment provided.	Examine the commonalities between the sustainability and resilience of buildings using two different approaches: (i) a systematic literature review, taking into consideration a 10-year period for selecting records, and (ii) an analysis of five green building rating systems and five resilience rating systems and guidelines selected according to their popularity and number of certified buildings

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
Gallina et al.	A review of multi-risk methodologies for natural hazards: Consequences and challenges for a climate change impact assessment	2016	yes	yes	yes	This article provides an overview of the different methodologies used to assess several types of natural hazards, including earthquakes, floods, landslides and hurricanes. The focus is on combined risk and vulnerability assessment.	Lack of integrated approaches that combine different types of hazards into a single assessment framework. Need for better data and analytical tools for more accurate risk assessment. Insufficient consideration of socio-economic factors and their impact on vulnerability to natural hazards.	Multi-risk methodologies are essential for a comprehensive risk assessment that encompasses different types of natural hazards. Effective risk assessment requires a combination of different analytical approaches and data sources.

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
Gentile et al.	Scoring, selecting, and developing physical impact models for multi-hazard risk assessment	2022	yes	no	yes	This article focuses on the selection and development of physical impact models that are key to effective risk assessment.	A detailed description of the methodologies used to assess different types of risks in specific geographical and social contexts is lacking. Further, it would be useful to focus on the inclusion of socio-economic factors in risk assessment models.	The development and selection of physical impact models is key to effective risk assessment. Scoring systems allow you to compare and evaluate different models based on their accuracy, complexity and usability.
Gill & Malamud	Hazard interactions and interaction networks (cascades) within multi-hazard methodologies	2016	no	no	no	Focusses on the importance of hazard interactions for multi-hazard methodologies.	Multi-hazard consideration is included, but only from vulnerability perspective; building vulnerability is missing.	Better characterisation and integration of interactions and networks of interactions into multi-hazard methodologies
Gill & Malamud	Reviewing and visualising the interactions of natural hazards	2014	yes	no	yes	1. Qualitative descriptions and classifications 2. Hazard matrices and diagrams.	No quantification, focus only on hazard.	4 types of multi-hazardsmulti-hazard matricesgood visualisation4 step Multihazard framework

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
						Probability/scenario trees.		
Hochrainer-Stigler et al.	Toward a framework for systemic multi-hazard and multi-risk assessment and management	2023	no	yes	yes	Presents a new framework, systemic approach.	No review paper.	Good overview of Multi-Hazard, Multi-Hazard risk etc.

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
Jamshed et al.	A bibliometric and systematic review of the Methods for the Improvement of Vulnerability Assessment in Europe framework: A guide for the development of further multi-hazard holistic framework	2023	yes	no	N.A	Natural hazards and climatic change under MOVE (Methods for the Improvement of Vulnerability Assessment in Europe) - as developed within the context of the European Commission FP7 research project – MOVE. In terms of hazard type, assessment approach, context and spatial scale.	Assessing (pros and cons) of the MOVE framework Even though these frameworks have been widely cited in research, the range and context of application and contextual use of such frameworks have rarely been explored.	MOVE (Methods for the Improvement of Vulnerability Assessment in Europe) Buildings are not involved The hazards considered by MOVE may be natural, socio natural and anthropogenic hazards.
Julià & Ferreira	From single- to multi-hazard vulnerability and risk in Historic	2021	yes	yes	yes	Physical vulnerability analysis.	Social vulnerability.	Seismic, flood, and fire physical vulnerability assessment methodologies and overview on multi-risk assessment methodologies

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
	Urban Areas: a literature review							
Kappes et al.	Challenges of analysing multi-hazard risk: a review	2012	yes	yes	yes	Three steps of a multi-hazard risk analysis, namely the analysis of multi-hazard (2.1), vulnerability of elements at risk for multiple processes (2.2) and multi-hazard risk (2.3) event trees	Social vulnerability not covered.	Detailing the difficulties and challenges associated with multi-hazard risk analysis. Overview of existing approaches that meet these challenges. not only multi-hazard strategies, but also those studies that deal with more-than-one-hazard coherent overview of all steps in multi-hazard analysis.

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
Kuhlicke et al.	Spinning in circles? A systematic review on the role of theory in social vulnerability, resilience and adaptation research	2023	yes	no	yes	No multi-risk assessment method. Role of theories in SVRA research by systematically scanning 2716 and reading 413 articles to understand overall trends and patterns.	The absence of a theoretical basis not only undermines the development of a more robust evidence base in SVRA research, but also hampers the generation of policy recommendations.	Regarding the hazard types, most articles addressed floods (47.9%), followed by earthquakes (27.8%) and droughts (17.0%) (Fig. 3B). relatively small proportion of articles explicitly articulate their theoretical underpinning. Among articles with an explicit theoretical framework, most follow the idea of methodological individualism.
Urbina Leal et al.	A Systematic Review of Integrated Frameworks for Resilience and Sustainability Assessments for Critical Infrastructures	2023	yes	no	yes	Provides a state-of-the-art review of integrated assessments for resilience and sustainability in critical infrastructure, examining concepts, indicators, frameworks, and	Call to action for researchers, practitioners, and policymakers to collaborate and develop more integrated and adaptable assessment frameworks.	This study emphasises the relevance of establishing common metrics for a convergent frame for the resilience and sustainability assessment.

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
						methodologies. Additionally, a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis was performed.		

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
Lee et al.	Reclassifying historical disasters: From single to multi-hazards	2023	no	no	yes	Assessment of historical disasters, identification of multi-hazards with historical data is presented.	Based on EM-Dat data, poor resolution, but interesting approach is presented.	Interactions between various combinations of natural hazard pairs are explored, reclassifying them into four categories: preconditioned/triggering, multivariate, temporally compounding, and spatially compounding multi-hazard events. The results show, globally, approximately 19 % of the 16,535 disasters recorded in EM-DAT can be classified as multi-hazard events. However, the multi-hazard events recorded in EM-DAT are disproportionately responsible for nearly 59 % of the estimated global economic losses.
Limongi & Galderisi	Twenty years of European and international research on vulnerability: A multi-faceted concept for better dealing with	2021	no	no	yes	Vulnerability analysis.	Risk and Hazard are not covered.	Literature review on vulnerability

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
	evolving risk landscapes							
Mah et al.	Social vulnerability indices: a scoping review	2023	yes	no	yes	Social vulnerability indexes	One limitation in the search and selection of articles was the prevalence of SVI, which may have led to the loss of other studies that were not called SVI but included factors determining social vulnerability.; "Indices that may be made on social resilience factors were not part of the search, yet is one area of future exploration as it is unclear if an index of social strengths (i.e., a strengths-based resilience index) would yield comparable results to a social vulnerability index".	Overview of SVIs in the literature up to December 2021summary of commonly used variables for social vulnerability indicesdemonstrate that SVIs are commonly used in several fields of research, especially since 2010: disaster planning, environmental science or health sciences, the SVIs are composed of similar items and domains.

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
Meldrum et al.	Parcel-Level Risk Affects Wildfire Outcomes: Insights from Pre-Fire Rapid Assessment Data for Homes Destroyed in 2020 East Troublesome Fire	2022	no	no	no	Wildfire risk-assessment methodology is presented.	Only wildfire risk is considered.	Validation of wildfire risk index was provided.
Navarro et al.	Territorial vulnerability to natural hazards in Europe: a composite indicator analysis and relation to economic impacts	2023	no	no	no	Vulnerability and capacity assessment via principal component analysis (PCA) is provided.	Multi-hazard, only vulnerability perspective building vulnerability is missing.	Shows vulnerability distribution to natural hazards throughout EU.
Nguyen & Akerkar	Modelling, Measuring, and Visualising Community Resilience: A Systematic Review	2020	yes	no	yes	No risk assessment, but resilience assessment is provided.	Systematic Review of Community Resilience is not focused on hazards.	Overview of multiple perspectives for modelling, measuring, and visualising community resilience derived from related and emerging studies, projects, and tools.

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
Owolabi & Sajjad	A global outlook on multi-hazard risk analysis: A systematic and scientometric review	2023	yes	yes	yes	Multi-hazard risk methodologies (natural hazards and climate change). Methodologies regarding landslides risk assessment are the most frequent.	No international collaboration is identified for the scholars in the south Asian region, Australia, and South America despite being impacted by multiple hazards and climate change. The major focus of the MHRA field remained on landslide hazards highlighting an under-representation of other geophysical, meteorological, and hydrological hazards.	Even though the number of published articles gradually increased between 2019 and 2022, the major focus of the MHRA field remained on landslide hazards highlighting an under-representation of other geophysical, meteorological, and hydrological hazards.

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
Rezvani et al.	A Systematic Literature Review on Urban Resilience Enabled with Asset and Disaster Risk Management Approaches and GIS-Based Decision Support Tools	2023	yes	no	yes	Urban Resilience, Multicriteria decision making, analytic hierarchy process, multi-attribute utility theory. Multi-Criteria Decision Analysis, UNDRR approach, Multicriteria Decision Making approaches are presented.	Lack of a common resilience definition and multidisciplinary analysis - a need for a unified scalable and adoptable UR (Urban Resilience) model, margin for an increased application of GIS-based multidimensional tools,stochastic analysis of virtual cities, and scenario simulations to support decision making processes.	Urbanization and climate change in all its facetsEfficient decision making is important hereUrban resilience model is discussed.
Šakić Trogrlić et al.	Challenges in assessing and managing multi-hazard risks: A European stakeholders perspective	2024	no	no	yes	Stakeholder involvement through workshops to identify challenges in the use of multi-hazard assessments	Only observes challenges, not review of existing approaches is provided.	Challenges for moving towards multi-hazard risk management through the perspective of European stakeholders: i) governance, ii) knowledge of multi-hazards and multi-risks, iii) existing approaches to disaster risk management, iv) translation of science to policy and practice, and v) lack of data

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
Stolte et al.	VulneraCity–drivers and dynamics of urban vulnerability based on a global systematic literature review	2024	yes	no	yes	Conducting a systematic literature review on the peer-reviewed scientific literature. Out of an initial set of 3168 studies, 462 studies were included for in-depth analysis. VulneraCity, the urban vulnerability drivers database, in which are record the drivers and classify them based on topic and acquisition method is presented.	Further research into multi-hazard (instead of multiple hazards') vulnerability and vulnerability dynamics as next steps is proposed towards more comprehensive urban disaster risk studies.	The article lists 1460 unique drivers of vulnerability in VulneraCity, of which 37.3 % are empirically acquired in the source studies. Other drivers are either modelled (7.9 %), theorized (22.9 %), adopted (27.0 %), or acquired with an unknown method (5.0 %). Furthermore, the relationships between drivers and impact are often assumed to be linear. Six types of directional dynamics - one-directional, bidirectional, transferable, asynergies, conditional, and compound were identified. They describe the complexities in these relationships to show that the linearity assumption is regularly violated.

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
Sutanto et al.	Heatwaves, droughts, and fires: Exploring compound and cascading dry hazards at the pan-European scale	2020	no	no	no	None	No complete review, only dry hazards are addressed.	Investigate spatio-temporal patterns of compound and cascading hazards using historical data for dry hazards, namely heatwaves, droughts, and fires across Europe.
Tilloy et al.	A review of quantification methodologies for multi-hazard interrelationships	2019	yes	no	yes	Uses grey- and peer-review literature to identify and compare current research available for the quantification of hazard interrelations, focussing on 14 different natural hazards	Cross-disciplinary approaches for better understanding potential risk related to multi-hazard events are missing.	Identifies 19 different modelling methods to quantify natural hazard interrelationships which were clustered into three broad modelling approaches: stochastic, empirical, and mechanistic

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
Wang et al.	A review of the research into the relations between hazards in multi-hazard risk analysis	2020	yes	yes	yes	Different risk assessment methods	Presents challenges, but no solution approaches.	Summarises the progress of the risk analysis of mutually amplification hazards; namely, NATECH events (Sect. 3.1), human-induced disasters (Sect. 3.2), disaster chains (Sect. 3.3), the domino effect (Sect. 3.4), and concurrent hazards (Sect. 3.5).
Ward et al.	Review article: Natural hazard risk assessments at the global scale	2020	yes	no	yes	Review of risk assessments at global scale	Includes only reviews of single hazard assessments and only on global scale.	Review of natural hazard risk assessments at the global scale, specifically discussing whether and how overviewed studies have examined future projections regarding hazard, exposure, and/or vulnerability

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
Ward et al.	Invited perspectives: A research agenda towards disaster risk management pathways in multi-(hazard-)risk assessment	2022	no	no	yes	From multihazards to multirisk assessment and management.	Only natural hazards are included, MYRIAD-EU project statement: "We explicitly do not aim to develop a unified method or model for navigating the framework, as it is our conviction that there is no one-size-fits-all model for addressing multi-(hazard) risk management. Continuous learning across projects and disciplines is needed to break the silos in which natural hazard risk science operates."	Outline several key developments in multi-(hazard-) risk research in the last decade, with a particular focus on the EU. Present challenges for multi-(hazard-)risk management as outlined in several research projects and papers. Presented is a research agenda for addressing these challenges. They argue for an approach that addresses multi-(hazard-)risk management through the lens of sustainability challenges that cut across sectors, regions, and hazards.
Zhai et al.	Investigating Vulnerability, Adaptation, and Resilience: A Comprehensive Review within the Context of Climate Change	2024	yes	no	yes	Systematic literature search, analysis of case studies, statistical methods to assess vulnerability and resilience.	Need for more detailed empirical data to confirm some of the conclusions, possible complexity of implementing the recommendations in practice.	Examination of their definitions and the interrelationships among vulnerability, adaptation, resilience, and climate-related disasters. Additionally, it explores the impact of climate change on future disaster risk reduction efforts by analysing the nexus between climate change adaptation and disaster risk reduction

Publication information			Publication assessment					
Authors	**Title**	**Year**	**Review?**	**Multi-(hazard) risk assess-ment?**	**Hydro-meteoro-logical and solid earth and surface process hazards**	**Type of risk assessment/Main topics**	**Gaps in the publication or current research**	**Major findings in the publication**
Zscheischler et al.	A typology of compound weather and climate events	2020	no	no	no	Regression techniques and event compositing correlation coefficient, Copula-based approaches, Poisson process, extremal coefficient and the semivariogram	No tectonic hazards (earthquakes, landslides, tsunamis) are considered.	Typology of compound weather and climate events, with the aim of providing a coherent framework for compound-event analysis. They propose four key compound-event types based on an assessment of the literature: preconditioned, multivariate, temporally compounding and spatially compounding.

Annex C: Description of potential OA datasets and e-tools suitable for RETIME

Table 15,Table 17,Table 18 show potential Data Portals Supporting RETIME tasks.

Table 18. Copernicus Land Monitoring Service.

Data portal	**Copernicus Land Monitoring Service**
Link to online source	https://land.copernicus.eu/en
Access rights	Open access
Authorising organisation	Copernicus
Spatial coverage	Global, European
Update frequency	-
Potential usage in RETIME	Exposure and vulnerability database
Data format	Vector data (WFS, shapefile), Raster data (WMS, GeoTIFF)
API access	https://land.copernicus.eu/en/how-to-guides/how-to-download-spatial-data/how-to-download-m2m

Table 19. Risk Data Hub.

Data portal	**Risk Data Hub**
Link to online source	https://drmkc.jrc.ec.europa.eu/risk-data-hub#/dataviewer
Access rights	Open access
Authorising organisation	Joint Research Centre (JRC)
Spatial coverage	Europe
Spatial resolution	• Country • NUTS2 • NUTS3
Update frequency	-
Potential usage in RETIME	Hazard identification; exposure and vulnerability
Data format	Vector data (.SHP), Raster data (WMS)
API access	https://drmkc.jrc.ec.europa.eu/risk-data-hub-api/docs/

Table 20. ESPON Database.

Data portal	**ESPON Database**
Link to online source	https://database.espon.eu/
Access rights	Open Access
Authorising organisation	• University of Geneva, Switzerland (lead contractor) • Universitat Autonòma de Barcelona, Spain

	• Spatial Foresight GmbH, Luxembourg • MCRIT SL, Spain
Spatial coverage	• EU28+Iceland, Liechtenstein, Norway, and Switzerland • Some indicators for: Albania, the Republic of North Macedonia, Montenegro, Serbia, Turkey, Bosnia and Herzegovina, Kosovo. • Areas in the EU macro-regional strategies defined by the European Council and Transnational Cooperation Areas
Spatial resolution	Depending on the indicator: • NUTS levels (0, 1, 2, 3) • Functional Urban Area (FUA) • CITIES • LAU (3, 5) • Grid data (1km)
Temporal coverage	Depending on the indicator
Temporal resolution	Depending on the indicator
Climate scenario	• RCP2.6 • RCP4.5 • RCP8.5
Update frequency	Updates are given as new data are available from ESPON projects, periodically and project specific updates.
Potential usage in RETIME	Hazard identification in the three pilot areas, Exposure and vulnerability database
Data format	Numerical tabular data (.XLS, .CSV), Vector data (.SHP), Software tools and libraries (JSON)
API access	REST WEB Service: https://database.espon.eu/api/

Table 19, Table 20, Table 21, Table 22, Table 23, Table 24, Table 25, and Table 26 show the potential Datasets Supporting Hazard Identification (T3.1).

Table 21. River Flood Hazard Maps Europe dataset.

Datasets	**River Flood Hazard Maps Europe**
Link to online source	https://data.jrc.ec.europa.eu/dataset/1d128b6c-a4ee-4858-9e34-6210707f3c81
Access rights	Open Access
Authorising organisation	European Commission, Joint Research Centre
Spatial coverage	• Europe

	• Mediterranean Basin
Spatial resolution	Grid resolution: 90m (3 arcseconds)
Latest version release	2021
Temporal resolution	(daily river flow: 1990-2016)
Return periods	• 10 years • 20 years • 50 years • 100 years • 200 years • 500 years
Update frequency	Irregular
Data format	Raster data (GeoTIFF)
API access	The following API are currently available: • CKAN action API, RPC-style API that exposes some legacy features to existing API clients. • ODCAT action API, RPC-style API that we recommend using by new API clients.

Table 22. Extreme precipitation risk dataset.

Datasets	**Extreme precipitation risk**
Link to online source	https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-european-risk-extreme-precipitation-indicators?tab=overview
Access rights	Open access
Authorising organisation	Copernicus Climate Change Service
Spatial coverage	Europe
Spatial resolution	• ERA5: 0.25° x 0.25° • E-OBS: 0.1° x 0.1° • ERA5-2km: 0.02° x 0.02° • ECA&D: 0.1° x 0.1°
Latest version release	2021
Temporal coverage	1950-2019
Temporal resolution	Daily, monthly, yearly, and 30-year statistics
Return Period	• 5 year • 10 year • 25 year • 50 year • 100 year

Update frequency	No updates expected
Data format	Raster data (NetCDF)
API access	CDS API (https://cds.climate.copernicus.eu/api-how-to)

Table 23. Earthquake Hazard dataset.

Datasets	**Earthquake Hazard**
Link to online source	http://hazard.efehr.org/en/home/
Access rights	Open Access for online view
Authorising organisation	European Facilities for Earthquake Hazard and Risk (EFEHR)
Spatial coverage	• Europe • Middle East
Spatial resolution	About 50km
Latest version release	-
Temporal resolution	-
Return Period	475 years
Update frequency	-
Data format	-
API access	EFEHR tries to leverage pre-existing formats (e.g., QuakeML, NRML) and service standards (RESTful web services, OGC standards) where adequate, and will propagate "simple" ad-hoc solutions in other cases. EFEHR provides access services for hazard results (maps, curves, and uniform hazard spectra), and for the ESHM13 (SHARE) model offer OGC WMS for the input data sets Active Faults, Seismic Source Zones, and the SHEEC seismic catalogue.

Table 24. European Forest Fire Risk dataset.

Datasets	**European Forest Fire Risk**
Link to online source	https://forest-fire.emergency.copernicus.eu/apps/fire.risk.viewer/
Access rights	Open Access
Authorising organisation	European Commission, EFFIS
Spatial coverage	• European • Middle Eastern • North African regions
Spatial resolution	About 0.11º

Latest version release	2022
Data format	Raster Data (GeoTIFF)
API access	-

Table 25. Landslide Susceptibility map dataset.

Datasets	**Landslide Susceptibility Map**
Link to online source	https://esdac.jrc.ec.europa.eu/content/european-landslide-susceptibility-map-elsus-v2
Access rights	Open Access upon request
Authorising organisation	Bundesanstalt für Geowissenschaften und Rohstoffe (BGR, Hannover, Germany), Istituto di Ricerca per la Protezione Idrogeologica (CNR-IRPI, Perugia, Italy), Institut de Physique du Globe de Strasbourg (CNRS-EOST, Strasbourg, France), and the Joint Research Centre (JRC, Ispra, Italy), and the European Centre on Geomorphological Hazards (CERG)
Spatial coverage	All European Union member states except Malta, in addition to Albania, Andorra, Bosnia and Herzegovina, Croatia, FYR Macedonia, Iceland, Kosovo, Liechtenstein, Montenegro, Norway, San Marino, Serbia, and Switzerland
Spatial resolution	200m
Latest version release	2018
Update frequency	Irregular
Data format	Raster data (ARC GRID)
API access	-

Table 26. Coastal risk dataset.

Datasets	**Coastal Risk**
Link to online source	https://coastal.climatecentral.org/
Access rights	Open access for online view and JPEG download; further options for students and researchers available upon request otherwise only payable solutions
Authorising organisation	Climate Central
Spatial coverage	Global
Spatial resolution	30m, 90m
Water level scenario	0-10m
Data format	Image (.jpg)

API access	-

Table 27. Thermal comfort dataset.

Datasets	**Thermal comfort**
Link to online source	https://cds.climate.copernicus.eu/cdsapp#!/dataset/derived-utci-historical?tab=overview
Access rights	Open Access
Authorising organisation	European Centre for Medium-range Weather Forecasts
Spatial coverage	Global except for Antarctica (90N-60S, 180W-180E)
Spatial resolution	0.25° x 0.25°
Latest version release	2024
Temporal coverage	From January 1940 to near real-time
Temporal resolution	Hourly
Update frequency	Intermediate dataset updated daily in near real time. Consolidated dataset monthly updates with 2–3-month delay behind real time.
Data format	Raster data (NetCDF)
API access	CDS API (https://cds.climate.copernicus.eu/api-how-to)

Table 28. Air quality dataset.

Datasets	**Air quality**
Link to online source	https://ads.atmosphere.copernicus.eu/#!/search?text=
Access rights	Open Access
Authorising organisation	Copernicus Atmosphere Monitoring Service
Spatial coverage	Global, Europe
Spatial resolution	0.1°
Temporal coverage	Three-year rolling archive
Temporal resolution	Hourly
Update frequency	Daily
Data format	Raster data (NetCDF)
API access	https://ads.atmosphere.copernicus.eu/api-how-to

Table 27, Table 28, Table 29, Table 30, Table 31, Table 32, Table 33, Table 34 Table 35, an Table 36 show potential Datasets Supporting the Exposure and Vulnerability Database (T3.3).

Table 29. Land cover, land use, and infrastructure dataset.

Datasets	Land cover, land use & infrastructure
Link to online source	https://export.hotosm.org/v3/
Access rights	Open access
Authorising organisation	HOT OpenStreetMap
Spatial coverage	Global
Spatial resolution	At best 2m
Temporal resolution	-
Update frequency	Frequent updates through community users
Data format	Vector data (.SHP, .KML)
API access	Overpass API

Table 30. Health sites dataset.

Datasets	Health sites
Link to online source	https://healthsites.io/#about
Access rights	Open access
Authorising organisation	Healthsites.io
Spatial coverage	Global
Spatial resolution	-
Temporal resolution	-
Update frequency	Frequent updates through community users
Data format	Vector data (GeoJSON, .SHP, .KML), Numerical tabular data (.CSV)
API access	https://github.com/healthsites/healthsites/wiki/API

Table 31. GISCO dataset.

Datasets	GISCO
Link to online source	https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Geographical_information_system_of_the_Commission_(GISCO)#What_is_GISCO.3F
Access rights	Open access
Authorising organisation	Eurostat
Spatial coverage	European Union
Spatial resolution	• Country • NUTS1

	• NUTS2
Temporal resolution	from real-time data (e.g., live traffic data) to annual updates (e.g., census data)
Update frequency	Some datasets may be updated daily, weekly, monthly, or annually
Data format	Shapefile, GeoJSON, KML, or CSV
API access	e.g., RESTful

Table 30, Table 31, Table 32, Table 33, Table 34, Table 35, and Table 36 show potential Forecasts and Real-time Observations Supporting Impact-based (Trigger) Alerting (T3.2 and T4.1).

Table 32. European Drought Observatory.

Name	**European Drought Observatory**
Link to online source	https://drought.emergency.copernicus.eu/tumbo/edo/map/
Access rights	Open access
Authorising organisation	Copernicus
Spatial coverage	Europe
Spatial resolution	5km
Temporal resolution	Daily
Update frequency	Daily
Data format	Raster data (GeoTIFF, NetCDF)
API access	WMS & WCS services

Table 33. European Forest Fire Information System.

Name	**European Forest Fire Information System**
Link to online source	https://forest-fire.emergency.copernicus.eu/about-effis
Access rights	Open access
Authorising organisation	European Forest Fire Information System (EFFIS)
Spatial coverage	• European • Middle Eastern • North African regions
Spatial resolution	ECMWF (~8 km), MeteoFrance (~10 km) and NASA Geos-5 (~28 km) deterministic models, 250m (MODIS Burnt Areas) and 375m (VIIRS Burnt Areas), 1km (VIIRS Active fires)
Temporal resolution	Daily, 10 days lead time
Update frequency	Daily

Data format	Raster data (GeoTIFF)
API access	https://gwis.jrc.ec.europa.eu/applications/data-and-services

Table 34. European Flood Forecasting System.

Name	**European Flood Forecasting System**
Link to online source	https://www.copernicus.eu/en/european-flood-forecasting-system
Access rights	Restricted to official authorities, Open access forecast older than 30 days
Authorising organisation	JRC, Copernicus
Spatial coverage	Europe
Spatial resolution	1 arcmin (ensemble forecast), 100m (rapid impact assessment)
Temporal resolution	6 hourly
Update frequency	2-times daily
Data format	Raster data (NetCDF)
API access	WMS

Table 35. MeteoAlarm – Early Warnings for Europe.

Name	**MeteoAlarm: Early Warnings for Europe**
Link to online source	https://meteoalarm.org/en/live/page/about-meteoalarm#list
Access rights	Open access
Authorising organisation	GeoSphere Austria
Spatial coverage	38 European National Meteorological and Hydrological Services
Spatial resolution	Municipality level
Temporal resolution	Daily
Update frequency	Daily/Instantaneous
Data format	CAP/Atom
API access	MeteoAlarm Feeds

Table 36. Global Disaster Alert and Coordination System.

Name	**Global Disaster Alert and Coordination System**
Link to online source	https://gdacs.org/
Access rights	Open Access
Authorising organisation	United Nations, European Commission

Spatial coverage	Global
Spatial resolution	Depending on product/service
Temporal resolution	Depending on product/service
Update frequency	Depending on product/service
Data format	Depending on product/service
API access	Depending on product/service

Table 37. CLIMA EXTREMO.

Datasets	**CLIMA EXTREMO**
Link to online source	CLIMA EXTREMO – Risk Warning to Building Occupants During Extreme Weather Events (Portugal)
Access rights	Open Access
Authorising organisation	FCT
Spatial coverage	Portugal
Latest version release	DSAIPA/DS/0111/2019
Temporal coverage	1950 – today
Update frequency	Each 6 days
Data format	Raster data (NetCDF-4), Vector data (GeoJSON)
API access	CDS API (https://cds.climate.copernicus.eu/api-how-to)

Table 38. UrbClim (SImulator).

Data portal	**UrbClim (Simulator)**
Link to online source	https://www.urban-climate.eu/form/time?bounds=0.9108786443331383%2C35.85795935685509%2C37.30780329708776%2C51.095351951113116
Access rights	Paid
Authorising organisation	VITO
Spatial coverage	Global
Spatial resolution	• Global • National • NUTS2 • NUTS3 • Local Administrative Units (LAU)
Latest version release	15. 08. 2024
Update frequency	Daily

Potential applicability for RETIME	amplifying climate extremes such as excessive heat and flooding. simple urban physics, coupled to a 3D atmospheric boundary layer module
Data format	10.1.1.1.1.1. Software tools and libraries (SSP)
API access	-

Table 37 and Table 38 shows the potential hazard identification e-tools.

Table 39. Risk Data Hub – Data viewer.

E-tool	**Risk Data hub – Data viewer**
Links to online information	https://drmkc.jrc.ec.europa.eu/risk-data-hub/#/dataviewer
Licensing requirements and access rights	Unless otherwise indicated (e.g., in individual copyright notices), content owned by the EU on this website is licensed under the CC BY 4.0. This means that reuse is allowed, provided appropriate credit is given and changes are indicated.
Authorising organisation	This site is managed by JRC
Description of relevant functionality	Available map layers (version 1.3 – 2024-07-16): • Administrative division (NUTS Level 0 – Level 3, local administrative units); • Exposure (power plants, police stations, education, Healthcare, Fire stations; Corine Land Cover [CLC 2018 raster], Land use based integrated sustainability assessment [LUISA 2018], Natura 200 Sites, Global human settlement [population raster, build-up residential surface raster, build-up non-residential surface raster]) • Vulnerability layers at low resolution (2005, 2010, 2015, 2020, 2025, 2030) • Hazard high resolution layers (from 10-year to 10000-year return periods) (Tsunami, Coastal Floods, River Floods, Forest Fires, Extreme heat, Seismic hazard, Windstorms, Landslides)
Applicability	Spatial coverage varies across map layers from country level to high resolution (dozens of meters) Layers are attached to a period (typically a year). Temporal coverage varies across map layers.
Usage	Policy support

Potential applicability for RETIME	Hazard identification at pilot sites Vulnerability analyses at pilot sites (low resolution
Notes	-

Table 40. Think Hazard!.

E-tool	**Think Hazard!**
Links to online information	https://thinkhazard.org/en/
Licensing requirements and access rights	Open access; GNU General Public Licence, Version 3, 29 June 2007; Text content is licenced under CC-BY-SA. Classified hazard levels are licenced under CC-BY.
Authorising organisation	Global Facility for Disaster Reduction and Recovery (GFDRR)
Description of relevant functionality	ThinkHazard! provides a general view of the hazards, for a given location, that should be considered in project design and implementation to promote disaster and climate resilience. The tool highlights the likelihood of different natural hazards affecting project areas (very low, low, medium, and high), provides guidance on how to reduce the impact of these hazards, and where to find more information.
Applicability	The tool offers a (global) location search function and provides in hazard levels for up to 11 hazards. In addition, the tool provides some general information for each hazard.
Usage	The tool shall support projects in hazard identification.
Spatial resolution	• National • Regional • Municipality
Indicators	Hazards: River flood, earthquake, drought, cyclone, coastal flood, tsunami, volcano, and landslide.
Potential applicability for RETIME	Hazard identification at municipal level
Notes	-

Table 39, Table 40, Table 41, Table 42, and Table 43 show potential Tools Supporting Multi-(hazard) Risk Assessment (T3.3).

Table 41. INFORM Index.

E-tool	**INFORM Index**
Links to online information	https://drmkc.jrc.ec.europa.eu/inform-index/INFORM-Risk
Licensing requirements and access rights	Open access

Authorising organisation	JRC
Description of relevant functionality	The INFORM Risk Index is a global, open-source risk assessment for humanitarian crises and disasters.
Applicability	They provide global annual multi-risk indices at national level. The risk assessment is based on set indicators and not adjustable. However, in the dashboard view, it is possible to explore the indicators and how they add up to the national risk.
Usage	It supports humanitarian decision-making about disaster prevention, preparedness and response.
Spatial resolution	National
Indicators	Hazard: earthquake, flood, tsunami, tropical cyclone, drought, epidemic, current conflict intensity, projected conflict risk Vulnerability: development and deprivation, inequality, aid dependency, uprooted people, other vulnerability groups Lack of coping capacity: DRR, governance, communication, physical infrastructure, access to health system
Potential applicability for RETIME	The methodology can be adopted for multi-risk assessment.
Notes	-

Table 42. RiskScape – Multi-hazard risk modelling.

E-tool	**Multi-hazard Risk Modelling**
Links to online information	https://riskscape.org.nz
Licensing requirements and access rights	Distributed for research purposes only (v1.6.0 from 2024) via: https://riskscape.org.nz/docs/intro/downloads.html
Authorising organisation	RiskScape (Copyright Institute of Geological and Nuclear Sciences Limited & National Institute(INE) of Water and Atmospheric Research Limited)
Description of relevant functionality	RiskScape integrates various input layers geospatially. For instance, it can analyse a building portfolio alongside a flood hazard map to determine the flood depth each building faces. Users can provide custom Python functions to compute impacts, like repair costs, or analyse the flood's consequences for individual buildings. RiskScape can then compile the results, including summing losses for buildings in specific regions.

Applicability	Supports various geospatial data formats, such as ArcGIS fformat, GeoTIFF, ASC, NetCDF, OpenQuake, PostGIS, WFS. RiskScape provides a wizard to help users build a simple risk model initially, by answering a series of questions relating to their input data and what is being modelled. Users 'run' their models from the command-line. It is compatible with open-source software (packages) and OGC compliant. Supports python as plugins. Modelling can be done at any geographical location or scale. 2-dimensional modelling. Require Java version 17 or higher.
Usage	Deterministic and probabilistic modelling; Impact-based modelling; multi-hazard risk modelling
Applicability for initial hazard, vulnerability, and multi-risk analysis at pilot sites	RiskScape is a modelling software for multi-hazard risk analysis. It quantifies risk from the evolving and uncertain complex interactions between hazards and socio-economic elements.
Potential applicability for RETIME	It works along with the formula R=fc(H,E,V) (Eq. (1), *Section 2*). It can be used for multi-hazard risk assessment in T4.6.
Notes	Paulik et al. (2023)

Table 43. CLIMANDA – Probabilistic Risk Analysis.

E-tool	**CLIMANDA – Probabilistic Risk Analysis (Python)**
Links to online information	https://github.com/CLIMADA-project/climada_python?tab=readme-ov-file
Licensing requirements and access rights	Open Access; Free use and access under GNU GPL3; Data freely available under CC BY 4.0
Authorising organisation	ETH Zürich
Description of relevant functionality	CLIMADA stands for CLIMate ADAptation and is a probabilistic natural catastrophe impact model, that also calculates averted damage (benefit) thanks to adaptation measures of any kind (from grey to green infrastructure, behavioural, etc.). CLIMADA is divided into two parts (two repositories): 1. the core climada_python contains all the modules necessary for the probabilistic impact, the averted damage, uncertainty and forecast calculations. Data for hazard, exposures and impact functions can be obtained from the

	data API. Litpop is included as demo Exposures module, and Tropical cyclones is included as a demo Hazard module. 2. the climada_petals contain all the modules for generating data (e.g., TC_Surge, WildFire, OpenStreeMap). Most development is done here. The petals builds-upon the core and does not work as a stand-alone.
Applicability	The tool is primarily designed for national level but by inputting own data, the tool could probably go to neighbourhood scale.
Usage	(Economic) impact simulation of hazard events on assets and people taking into account their vulnerabilities. Analysis of costs and benefits of adaptation to support decision makers.
Indicators	Hazards: Drought, heatwaves, floods, storms, wildfires. Exposure& vulnerability: infrastructure, environmental assets, people
Applicability for initial hazard, vulnerability, and multi-risk analysis at pilot sites	The main aim of the tool is to assess economic impact of extreme weather and assess the cost-benefits of adaptation measures (e.g., NBS) but it could be difficult to get to building scale. Therefore, the main purpose would be the hazard assessment
Potential applicability for RETIME	Provides climate-related extreme-weather hazards (river flood, drought, winter storms) at high resolution (4x4km) via a data API. (Economic) impact assessment in T1.4.
Notes	Infographic explaining the tool: https://wcr.ethz.ch/research/climada.html [Accessed: 20.08.2024]

Table 44. Probabilistic Risk Assessment Platform.

E-tool	**Probabilistic Risk Assessment Platform** (e.g., CAPRA)
Links to online information	https://ecapra.org/topics/capra-gis
Licensing requirements and access rights	Open Access
Authorising organisation	Universidad de los Andes (Colombia)
Description of relevant functionality	CAPRA-GIS is a geographic information system developed by ERN-AL, which is oriented to probabilistic risk calculations.
Applicability	No information
Usage	The tool strengthens the institutional capacity for assessing, understanding and communicating disaster risk, with the

	ultimate goal of integrating disaster risk information into development policies and programs.
Applicability for initial hazard, vulnerability, and multi-risk analysis at pilot sites	Risk assessment
Potential applicability for RETIME	Multi-hazard or risk assessment in WP3 (T3.3)
Notes	The website does not provide any further information. The website also offers other tools and platforms regarding hazard, exposure, vulnerability and risk assessment.

Table 45. Open Quake – Seismic risk assessment.

E-tool	**OpenQuake – Seismic risk assessment**
Links to online information	https://www.globalquakemodel.org/product/openquake-engine
Licensing requirements and access rights	Open access under AGPL-3.0 license via https://github.com/gem/oq-engine/tree/master/demos/risk
Authorising organisation	Global Earthquake Model (GEM) Foundation
Description of relevant functionality	The OpenQuake Engine software provides calculation and assessment of seismic hazard, risk and decision-making tools via the data, methods and standards
Applicability	Can be calculated at multiple scales from global to site-specific locations. It has an open-source code (python) with quality assurance and end-to-end testing.
Usage	Application examples: Regional and national analysis; near real-time ground shaking assessment; site specific studies (e.g., of a power plant).
Applicability for initial hazard, vulnerability, and multi-risk analysis at pilot sites	Seismic hazard and risk probabilistic and deterministic calculation. It can output hazard curves, maps, spectra and ruptures.
Potential applicability for RETIME	Hazard, exposure, vulnerability and risk assessment
Notes	More information, guidance, etc: https://docs.openquake.org/oq-engine/manual/latest/

Table 44 and Table 45 show potential Tools for Increasing Building Resilience (T4.6).

Table 46. Heat Action Platform.

E-tool	**Heat Action Platform**

Links to online information	https://heatactionplatform.onebillionresilient.org
Licensing requirements and access rights	Open Access
Authorising organisation	Atlantic Council
Description of relevant functionality	The Heat Action Platform is a living, engagement-oriented tool for city officials, practitioners, and financial institutions to find guidance, both existing resources and tailor-made solutions, on reducing the human and economic impacts of extreme heat at the regional or municipal level. The platform guides municipalities through different phases from risk assessment, adaptation planning, and implementation and monitoring of adaptation measures.
Potential applicability for RETIME	It is an information source for tasks in WP4 related to building resilience to heatwaves.

Table 47. Climate Resilient Cities ToolBox.

E-tool	**Climate Resilient Cities Toolbox**
Links to online information	https://crctool.org/en/
Licensing requirements and access rights	Open Access
Authorising organisation	Deltares
Description of relevant functionality	The map-based tool asks to select an area, a hazard, scale (city, neighbourhood, street, building), land uses, and much more information. Based on this information it offers a list of adaptation measures.
Potential applicability for RETIME	It can be used within WP4 related to building resilience to heatwaves, drought, pluvial flooding, and water safety.