multiclimact

D7.1 - MULTICLIMACT CREMA TOOL

Technical set-up and development

SEPTEMBER 2025 | RINA Consulting S.p.A. (RINA-C)

MULTICLIMACT
D7.1 – MULTICLIMACT CREMA TOOL TECHNICAL SET-UP AND DEVELOPMENT

Project Title	MULTI-faceted CLIMate adaptation ACTions to improve resilience, preparedness and responsiveness of the built environment against multiple hazards at multiple scales
Project Acronym	MULTICLIMACT
Contract Number	101123538
Project Coordinator	Rina Consulting S.p.A.
WP Leader:	National Center for Scientific Research “Demokritos”

Deliverable	D7.1 – MULTICLIMACT CREMA tool technical set-up and development
DoA	Task 7.1 - CREMA tool development - Assessment of the current resilience of built environment assets Task 7.2 - CREMA tool development - integration of the MULTICLIMACT toolkit of Design, Materials and Technologies, and Digital solutions
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Due date	30.09.2025
Report date	26.09.2025
Version	3.0

Document classification	PU Public

Co-funded by the European Union

REVISION TABLE

Version	Date	What
1.0	01.06.2025	Table of Contents (1st version)
2.0	30.07.2025	First draft ready for internal review (Partners added content to chapters – 1st version)
2.1	01.09.2025	Second draft ready for quality check by coordinator (All partners have added their final input)
3.0	26.09.2025	Final version as submitted

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ABBREVIATIONS AND ACRONYMS

ACRONYM	DESCRIPTION
API	Application Programming Interface
CCA	Climate Change Adaptation
CRUD	Create, Read, Update, Delete
CSRF	Cross-Site Request Forgery
DRM	Disaster Risk Management
DS	Damage State
EAL	Expected Annual Loss
EP	Exceedance Probability
FPM	FastCGI Process Manager
HTTP	HyperText Transfer Protocol
HTTPs	HyperText Transfer Protocol Secure
IM	Intensity Measure
IP	Internet Protocol
KPIs	Key Performance Indicators
OAuth	Open Authorization
ORM	Object-Relational Mapping
PGA	Peak Ground Acceleration
SPEI	Standardised Precipitation Evapotranspiration Index
Tr	Return period (time return)
UI	User Interface

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Executive Summary

This document presents the technical development and advancement of the CREMA tool, designed to address the urgent need for systematic, evidence-based approaches to resilience measurement within the built environment at multiple scales. As urban areas face mounting pressures from climate change, natural hazards, and socio-economic disruptions, the CREMA tool provides a robust, multi-scale framework for evaluating vulnerabilities and guiding cost-effective interventions to enhance resilience across diverse asset types and governance contexts.

The primary objective is to equip decision-makers with a comprehensive tool for assessing vulnerabilities and strengths in infrastructural assets, enabling targeted mitigation or adaptation actions in resilience. Mitigation aims to reduce risks from natural and climate hazards by strengthening systems or lowering emissions, while adaptation involves changing practices to handle these impacts, such as planning improvements or resource management. Both strategies seek to minimize harm and improve safety. The CREMA tool integrates physical, social, and economic considerations into a unified methodology, ensuring a holistic evaluation of infrastructure performance in the face of adverse events.

This deliverable is based on the work carried out within the activities of Tasks 7.1 and 7.2.
Task 7.1 deals with the technical development of the CREMA tool for assessing the current resilience of built environment assets. This task builds on the planning and design activities from T1.3 and draws from the ARCH disaster risk management framework. The tool is intended to support local authorities, practitioners, urban populations, and communities by guiding climate change adaptation planning and enabling the design of targeted, cost-effective interventions at multiple scales. Task 7.2 focuses on integrating the MULTICLIMACT toolkit of Design, Materials and Technologies, and Digital solutions into the CREMA tool. This integration allows the simulation of various resilience interventions and their quantitative impact assessment using KPI-based metrics. The approach follows the methodology defined in T1.2 and has been developed in close collaboration with T7.3 to ensure consistency and synergy across the project.

The implementation process has involved multiple iterations and collaboration, incorporating integration and synchronization with work from other tasks (mainly WP1, 7, and 11). This approach has promoted coordination and maintained consistency across project outcomes.

The CREMA tool’s design is underpinned by transparent assessment steps, adaptable criteria, and explicit guidance for use across various real-world scenarios. Methodological refinements in this phase have focused on granularity, practical application, and alignment with best practices, including comparative insights drawn from frameworks such as ARCH. Technical development has prioritized modular architecture, robust authentication, and clearly defined security protocols, thereby ensuring both functionality and integrity.

The comprehensive methodology has been updated, and technical development milestones have been met. The CREMA tool now stands as a practical, adaptable solution ready for demonstration tests, generating valuable outputs for other work packages and informing ongoing refinements.

1. INTRODUCTION

This deliverable addresses the increasing necessity for systematic approaches to resilience measurement within the built environment. As cities and communities contend with escalating risks, ranging from climate change and natural hazards to socio-economic disruptions, the need for robust, adaptable assessment tools has never been more pronounced.

Against this backdrop, the CREMA tool emerges as a response to the evolving demands of urban resilience planning. By bridging theory and practice, the tool empowers users to move beyond ad hoc evaluations and instead adopt a methodical, transparent process tailored to diverse asset profiles and contexts including but not limited to assessing cost-effective interventions. The integration of stakeholder perspectives and interdisciplinary expertise underpins the tool's design, ensuring its relevance across a spectrum of governance frameworks and operational realities.

Following the introductory sections, the document is organized into a clear progression, providing readers with both the overarching context and practical pathways for implementation. After the Executive Summary and Introduction, the next section outlines the Purpose and Target Group, clarifying the rationale for developing the CREMA tool and identifying its primary stakeholders.

Building on this foundation, the Methodology section, originally presented in D1.3, has now been significantly expanded. This update incorporates targeted improvements, greater detail, and a reinforced focus on practical application. The methodology now offers a more granular breakdown of assessment steps, enhanced criteria, and explicit guidance for adapting the tool across diverse real-world scenarios. To further enhance the CREMA tool, a brief comparison with the ARCH framework is proposed, focusing on stakeholder engagement during development. Examining ARCH's participatory practices reveals valuable lessons for fostering user involvement. Integrating such approaches may guide improvements in CREMA's stakeholder engagement strategy.

Furthermore, a dedicated section addresses the technical development of the CREMA tool itself. Here, readers will find detailed information on the underlying architecture, including the distinct layers that comprise the tool, as well as robust authentication mechanisms and clearly defined security criteria. This technical focus ensures that both the functionality and integrity of the tool are maintained throughout its implementation.

In addition, a dedicated section details the outputs generated for other work packages, spanning from the in-field demonstration test through to the subsequent tool revision phase.

1.1. PURPOSE AND TARGET GROUP

This deliverable centres on the development of the CREMA tool, an innovative solution crafted to help decision-makers and practitioners within local authorities, the urban population, and local communities systematically assess and strengthen the resilience of built environment. The purpose of the tool is to enable users to identify vulnerabilities and strengths across a diverse array of assets like building, urban and territorial, including cultural heritage, by providing a robust, evidence-based resilience score to guide cost-effective interventions.

At the heart of this development is a comprehensive methodology, which has been refined in this phase of the project. This methodology integrates physical, health, wellbeing and quality of life, technical, economic, environmental, and organisational dimensions, ensuring that the assessment captures the full spectrum of factors influencing resilience. By leveraging quantitative and qualitative analyses, the tool evaluates the ability of assets to withstand and recover from adverse events.

The primary target group for the CREMA tool comprises stakeholders with decision-making authority or a vested interest in the governance and management of different assets. This includes public authorities, policymakers, facility and infrastructure managers, investors, academic and research communities, as well as companies operating within the fields of architecture, engineering, construction, and facility operations.

1.2. CONTRIBUTIONS OF PARTNERS

The primary development and advancement of the CREMA tool were carried out by RINA-C, who led the main technical and methodological activities, ensuring the tool's comprehensive design and implementation. ICLEI contributed with expertise from the ARCH framework, enhancing resilience analysis. Furthermore, the partners' support was integrated into the development process, often conveyed through the work carried out in related project activities, in order to ensure methodological consistency throughout the process.

PARTNER (SHORT NAME)	CONTRIBUTION
RINA-C	Technical coordination, methodology development, engineering and risk analysis, overall CREMA tool architecture, integration of quantitative assessment methods
ICLEI EURO	Stakeholder engagement (ensuring collaboration with T7.3), ARCH framework expert
CMCC	Provision of climate data (by mean of data-clime platform) and support with KPIs
NCSRD	Scientific coordination with all tasks of WP and reviewer
UKA	Health and well-being expertise and reviewer
CYPE	Support and recommendations for user interfaces design of CREMA Tool

Table 1. Contributions of Partners

2. OBJECTIVES AND EXPECTED IMPACT

The primary objective of this deliverable is to document the progress achieved in the development of the CREMA tool, encompassing both methodological advancements and, above all, the concrete stages of the tool's development. The deliverable guides the reader through the main phases: from the definition of the system architecture to the back-end and front-end development activities, illustrating how each step contributes to building an integrated solution aligned with the identified requirements.

To frame the starting point, it is essential to highlight the outcomes of Task 1.3, which represented the core of the tool's planning and design activities, providing a solid methodological framework for the resilience approach. This framework was established through input from the preceding Tasks 1.1 and 1.2:

- Task 1.1: The most significant output was the development of the resilience score, a synthetic indicator designed to objectively and consistently measure the resilience level of the targeted assets and systems.
- Task 1.2: This task resulted in the definition of Key Performance Indicators (KPIs), selected to quantify and closely monitor the impacts of the solutions proposed by the MULTICLIMACT toolkit, thus offering coherent metrics suitable for various application contexts.

Both outcomes were integrated into Task 1.3, which combined the scoring and indicator dimensions into a unified design vision, serving as a foundation for the effective development of the CREMA tool.

This deliverable therefore aims to collect and systematically describe the work carried out in Tasks 7.1 and 7.2, which represent the core of the tool's development activities:

- Task 7.1: Focused on the analysis of resilience in the current state ("as is"), through data modelling and the development of information flows necessary to represent and assess the current conditions of the targeted assets and systems.
- Task 7.2: Centred on the operational implementation of KPIs to support the assessment of future scenarios ("to be"), thereby enabling a quantitative comparison of the potential impacts of adopted measures and solutions.

In addition, a fundamental objective is to ensure that the tool is specifically tailored to the selected case studies. To this end, data collection activities carried out in parallel within Tasks 11.1, 11.2, 11.3, and 11.4, each dedicated to one of the four pilot sites, have directly supported the development phase. The nature and structure of the data gathered for each pilot have significantly influenced the design and implementation of the back-end, as the availability, granularity, and format of these inputs determined both the information flows and the technical solutions adopted for effective data management and processing.

Figure 2-A graphically summarizes the interconnections between the tool and the various tasks that provide essential input. This diagram highlights the flow of methodological and operational information from the foundational design to the actual implementation steps, thus illustrating the integrated nature of the development process.

This deliverable aims to offer a clear and transparent overview of the progress achieved, the methodologies applied, and the future potential of the CREMA tool, thus laying the groundwork for subsequent test and validation phases (WP11).

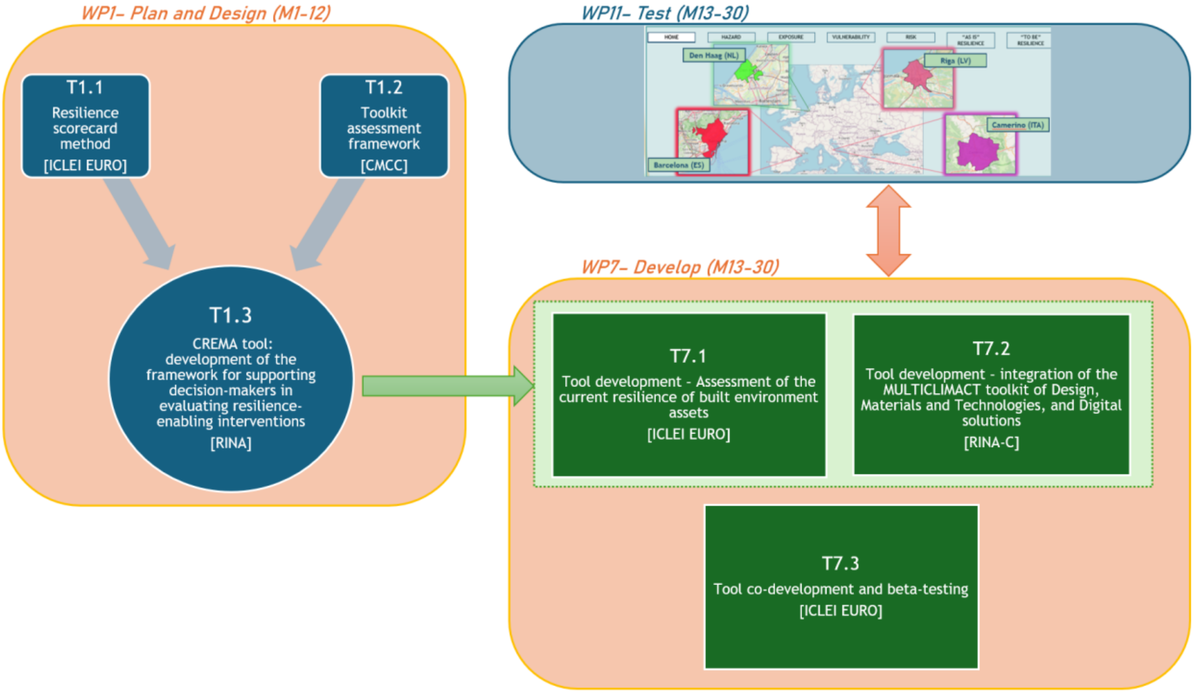

Figure 2-A. CREMA tool development process - input from tasks in WP1, WP7, WP11

2.1. EXPECTED IMPACT OF THE CREMA TOOL

The CREMA tool, developed through an integrated methodological and operational framework, is expected to make a significant impact in the field of resilience assessment and management. By merging a robust resilience scoring mechanism with targeted KPIs, it enables stakeholders to measure and monitor the resilience of assets and systems objectively, thus supporting transparent, evidence-based decisions and increasing the credibility of interventions. Its design, tailored by detailed data collection from diverse pilot sites, ensures that assessments are not only methodologically rigorous but also directly relevant to the unique needs and characteristics of each case study, enhancing the tool's versatility and practical value across various contexts and beyond the MULTICLIMACT project. Its scalable methodologies and technical solutions make it adaptable to additional assets, systems, or regions, multiplying its potential societal and environmental benefits. Furthermore, by systematically documenting results, methodologies, and lessons learned, the project establishes a solid foundation for ongoing testing, validation, and refinement, supporting continuous improvement and innovation in resilience assessment. In summary, the CREMA tool is expected to greatly enhance the ability of stakeholders and decision makers to assess, compare, and strengthen the resilience of assets and systems, ultimately fostering safer, more adaptive built environments in the face of evolving hazards and challenges.

3. APPLIED METHODOLOGICAL FRAMEWORK

The risk and resilience assessment within the MULTICLIMACT CREMA tool is a comprehensive, multi-step process designed to evaluate the vulnerability and preparedness of the built environment against multiple hazards. The approach supports decision-makers in identifying, quantifying, and improving resilience through evidence-based interventions.

During the development phase of the tool, numerous improvements and a higher level of detail in the procedures were introduced; these aspects will be illustrated in more detail in this chapter.

Steps of the risk and resilience assessment, as described in Deliverable 1.3, are:

1. **System, asset, and context characterization**
   This initial step collects and defines the physical, functional, and socio-economic characteristics of the system or area under study. Assets such as buildings, infrastructure, and populations are mapped and described in terms of their use, value, and criticality to the system.
2. **Hazard characterization**
   Multiple hazards (climate-related and natural) that may impact the system are identified and characterized. This step includes defining hazard intensity measures (IM), frequencies, and spatial distributions. Hazard curves depicting the probability of exceedance of given intensity levels are developed for each hazard.
3. **Vulnerability assessment**
   Vulnerability functions or fragility curves translate hazard intensities into probabilities or magnitudes of damage or loss. These reflect the susceptibility of assets to damage given certain hazard intensities, considering local conditions and material characteristics.
4. **Probability of damage occurrence**
   Combining hazard probabilities with vulnerability yields the likelihood of damage states across the system, allowing quantification of expected consequences at various hazard levels (see Figure 3-A).

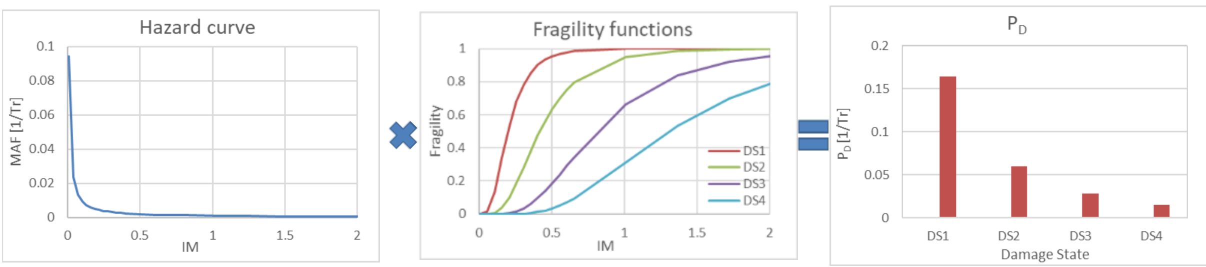

Figure 3-A. Example of damage probability evaluation per each DS

5. **Impact assessment**
   The tool aggregates damage probabilities to estimate overall impacts, including direct damages and functional disruptions. This stage links hazard exposure and vulnerabilities to tangible consequences.
6. **Risk assessment**
   Risk is quantified by integrating hazard likelihood, vulnerability, and impact into metrics such as Expected Annual Loss (EAL), expressing the average loss expected each year from hazards (Figure 3-B).

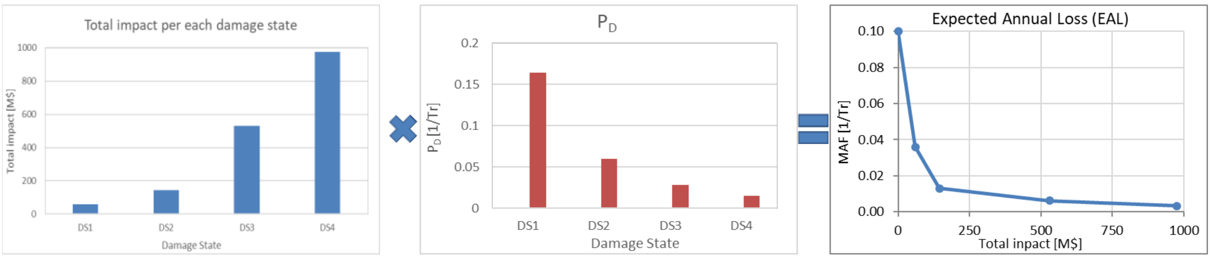

Figure 3-B. Example of EAL evaluation

7. **Resilience assessment**
   The assessment extends beyond risk by evaluating the system's capacity to resist, absorb, recover, and adapt to disruptions. Two scenarios are considered:
   - **"As-is" resilience**, representing current system capabilities;
   - **"To-be" resilience**, projecting the effect of resilience-enhancing interventions. Resilience curves visualize system performance over time during and after hazard events, indicating degradation and recovery phases.

Figure 3-C presents the conceptual workflow of the assessment tool, illustrating the sequential process by which hazard impacts and risks are evaluated. This diagram offers an at-a-glance overview of key methodological stages.

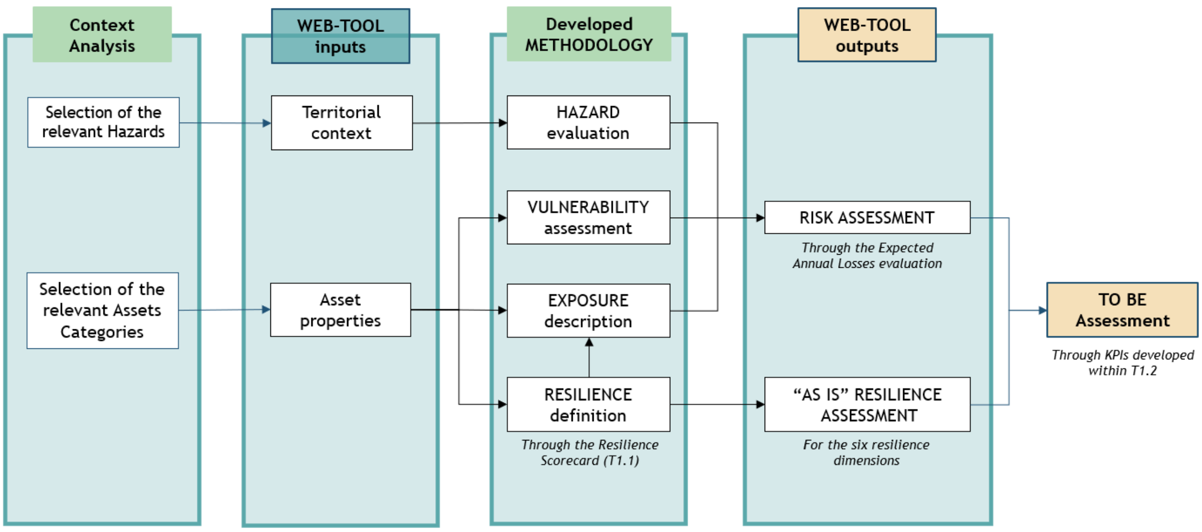

Figure 3-C. Conceptual workflow of the tool (source: D1.3)

3.1. IMPACT AND RISK ASSESSMENT AT MULTIPLE SCALES

The impact and risk assessment within the MULTICLIMACT project applies a structured, tailored methodology to evaluate how multiple climate-related and natural hazards affect the built environment across various European contexts. At this point, the methodology for the tool-application is outlined in broad terms to offer an overview of the framework supporting tool development. Comprehensive procedures, specific parameters, and case study outcomes will be detailed in deliverables 11.1, 11.2, 11.3, and 11.4.

Specifically, the approach:

- **characterizes hazards:** defines intensity-frequency relationships for hazards like floods, heatwaves, earthquakes;
- **defines exposure:** identifies and maps the system components such as buildings, infrastructure, cultural heritage, and populations subject to these hazards;
- **assesses vulnerability:** uses fragility and damage functions to translate hazard intensities into expected damage and loss probabilities for different asset types and conditions;
- **calculates impacts:** quantifies direct damages, functional disruptions, and socio-economic consequences through integrating hazard occurrence with vulnerability and exposure data;
- **quantifies risk:** computes metrics such as **EAL** to express average yearly economic impact from hazards.

The next stage in the workflow involves gathering and preparing the necessary data inputs for hazard, vulnerability and exposure characterization and subsequent analysis.

3.1.1. INPUT

An effective risk assessment begins with a clear specification of the required data types and sources. For **hazard data**, this means identifying datasets that capture both the magnitude and frequency of events across temporal and spatial scales. The process includes compiling historical records, remote sensing products, national or local hazard maps, and outputs from simulation models. For **vulnerability**, relevant information might encompass engineering studies, empirical fragility curves, or expert-elicited damage ratios for different asset typologies. **Exposure** datasets should incorporate up-to-date inventories of buildings, infrastructure, population distributions, and socio-economic indicators, often sourced from governmental databases, open-source platforms, or stakeholder-provided schematics.

A structured data inventory serves as a valuable reference for subsequent analysis stages. This inventory also highlights data gaps or uncertainties that may require supplementary field surveys, expert judgment, or proxy variables. Throughout, transparency regarding data provenance, processing steps, and quality control measures is crucial to ensure reproducibility and build trust with stakeholders and end-users.

A key aspect of the workflow is acknowledging that the collection and preparation of data form the foundation of the entire analytical process. The availability, quality, and specificity of data not only determine the accuracy of hazard, vulnerability, and exposure assessments, but also allow the methodology to be precisely adapted to the unique features and limitations of each case study. By gathering and harmonizing all relevant datasets at this early stage, we ensure that subsequent analyses are robust and context-sensitive, enabling the development of a risk assessment tool that reflects real-world complexities. This careful approach to data collection lays the groundwork for a methodology that is not only scientifically rigorous but also practically feasible, ensuring the tool will be ready for effective testing and demonstration at the pilot sites.

3.1.1.1. Hazard

For hazard characterization, four options are available, listed from the most detailed to the least detailed:

1) Hazard curve

Hazard curves represent a highly detailed method for assessing risk. These curves graphically illustrate the probability that specific levels of hazard intensity will be exceeded over a given period of time.

A general way to characterize the reported hazards is through the Intensity Measure (IM), which expresses the severity of the hazard in a given unit of measure. The selection of the intensity parameter is also related to the approach that is followed for the derivation of fragility curves and the typology of element at risk.

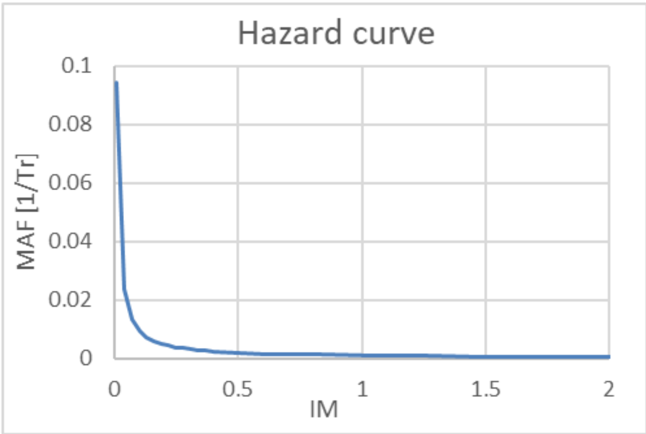

Figure 3-D. Standar hazard curve

HAZARD	IM
Earthquake	*Peak Ground Acceleration (PGA) [m/s²]*
Flood	*Water depth [m]*
Heat wave	*Daily maximum and minimum temperature [°C]*
Drought	*Standardised Precipitation Evapotranspiration Index (SPEI)*

Table 2. Intensity measure (IM) for each hazard

2) Mean annual frequency, for different scenarios

In the absence of the curve, intensity scenarios with their respective probability of occurrence (about 4 well-distributed scenarios) might be sufficient: it is possible to reconstruct the hazard curve through an exponential interpolation of these points.

When building hazard curves, uncertainties arise from limited data, model assumptions, and inherent variability of hazard events. Interpolation to estimate values between data points may introduce additional errors. To reduce these uncertainties, curve fitting techniques maximize the R-squared value (a statistic ranging from 0 to 1 that indicates how well the model explains data variance) and minimize residuals, which measure differences between observed and predicted values. High R-squared and low residuals ensure the model closely matches observations, improving hazard assessment accuracy and reliability by minimizing fitting errors and yielding more trustworthy hazard estimates (Iervolino, 2022; O'Reilly & Shahnazaryan, 2023).

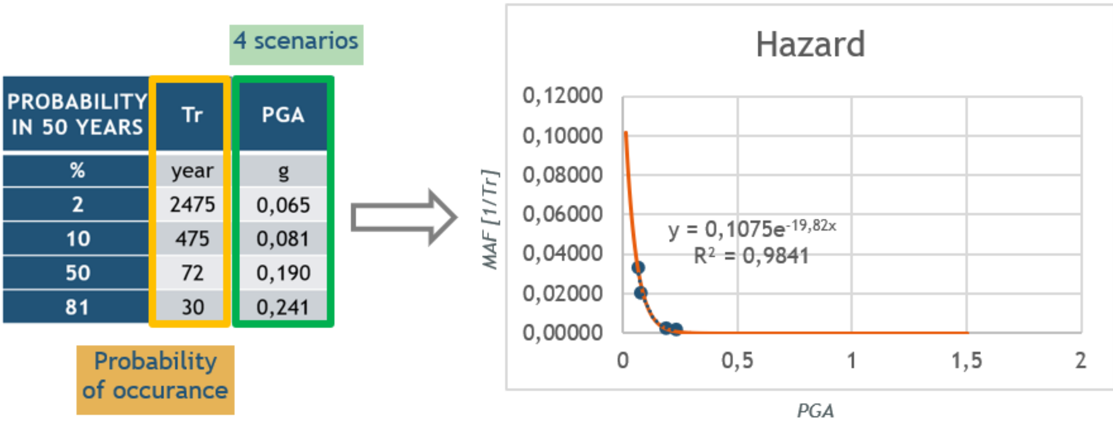

Figure 3-E. Example earthquake hazard curve showing 4 probabilities of exceeding PGA (in g) over 50 years

3) IM for each day (GEOTIFF/CSV) (historical data series)

Alternatively, daily hazard intensity values collected over a multi-year time window could be utilized. These data can enable an approximate reconstruction of the probability of events of comparable magnitude occurring.

An essential component in characterising hazards—particularly those related to climate events—is the selection of appropriate climate data sources. These sources may include global and regional meteorological archives, remote sensing products, as well as reanalysis datasets, which reconcile observational data with physical models to improve spatial and temporal coverage. For site-specific studies, data from national meteorological agencies or local weather stations can provide higher-resolution records, while satellite-derived datasets offer consistent measurements across broader areas (University of Oxford, Environmental Change Institute, 2024).

Figure 3-F presents an example of daily maximum and minimum temperature data. This parameter serves as a valuable indicator for identifying heatwave events, as it captures both the peak and trough temperatures experienced within a 24-hour period, thereby reflecting the intensity and persistence of extreme heat conditions (Alemaw and Simalenga, 2015).

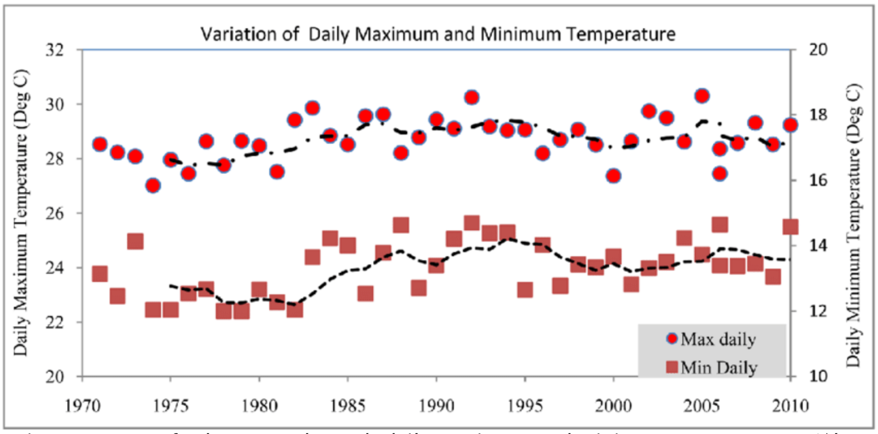

Figure 3-F. Illustrative parameter for heatwave hazard: daily maximum and minimum temperatures (Alemaw and Simalenga, 2015)

4) Maps from literature

If none of the above options are available, open-source maps from literature or CSV data may be utilized for hazard characterisation.

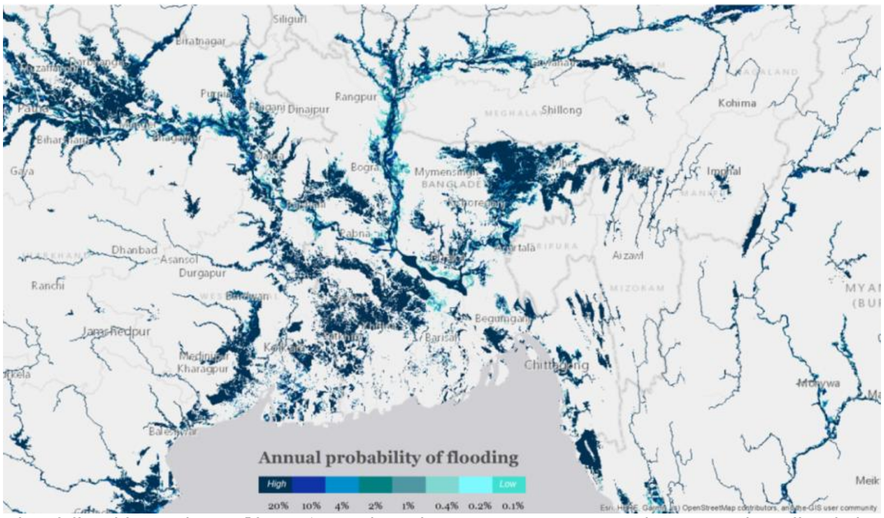

Figure 3-G. Example of flood hazard map [from Acqueduct: https://www.wri.org/data/aqueduct-floods-hazard-maps]

3.1.1.2. Fragility

To quantify vulnerability, fragility curves are utilized that have an intensity measure (IM) consistent with what was previously used for the hazard curve.

The development of a fragility curve requires the collection of empirical data from historical events, numerical modelling of structural and thermal behaviour, and the simulation of damage scenarios. Subsequently, the probability of exceeding various damage thresholds is calculated based on the event's intensity.

1) **Fragility curve**

If fragility curves are already available for investigated assets (e.g., buildings, roads, infrastructures), it would be ideal to have 4 damage states, following the Hazus classification (FEMA,2013a). Alternatively, at least 3 damage states would be necessary.

DAMAGE STATE		MEAN VALUE	STANDARD DEVIATION
DS1	Slight	0,09	0,78
DS2	Moderate	0,18	0,74
DS3	Extensive	0,30	0,73
DS4	Complete	0,42	0,73

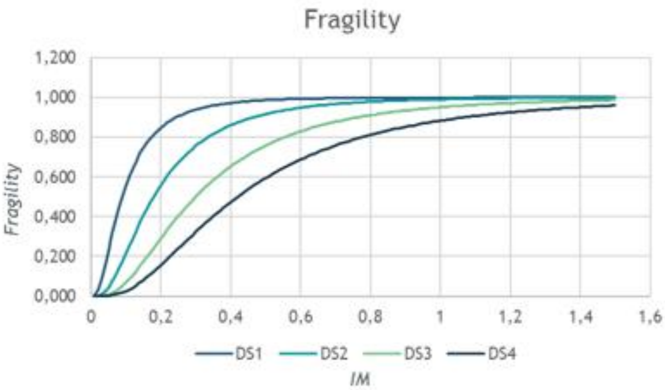

Figure 3-H: Example of fragility curve

2) **Fragility curve from database**

If fragility curves are not available, they can be researched in the bibliography. It is necessary to gather information on the characteristics of the exposed asset to identify the most representative curves.
The principal attributes of each asset, which inform the selection of the appropriate fragility function—regardless of whether they are obtained from established databases, existing literature, or custom-developed models—are detailed below:

Earthquake and *Flood*

- Primary construction material
- Construction typology
- Year of construction
- Seismic design code applied
- Number of storeys
- Typical asset dimensions (length, width, pier dimensions, etc.)

Heatwave

- Thermal transmittance (U-value) and thermal mass
- Window and wall (opaque) surface areas
- Population distribution (by age, spatial density, etc.)
- Vulnerable populations (individuals over 65 and under 15)

Drought

- NDVI (Normalized Difference Vegetation Index) of surrounding rural areas influencing the local market

3.1.1.3. Exposure

The necessary information to characterize the asset is described below, and formats such as **Shapefile**, **GeoTIFF**, and **CSV** (with coordinate information) are preferred:

- Maps indicating the boundaries of the area for analysis;
- Building information such as location, height, materials, age of construction, storeys, and usage destinations (residential, commercial, industrial);
- Information on main and secondary roads;
- Population (age groups, distribution density...);
- Agricultural areas influencing the offerings of the local market.

To collect specific information, an asset data model has been shared, as shown below, that serves as a structured framework for organizing, integrating, and analyzing information about assets within a defined area.

Instructions

- identify the asset: determine if the asset is a building or an open space, and specify the category

Asset ID	Sector	Category
B_T13_1	building	sidential/commerc
	building	
	open_space	

Figure 3-I. Instruction to fill in the Asset data model sheet - part 1

-enter required information about location, coordinate, history and value

location			coordinate	
State	Region	Municipality	Latitude	Longitude
			(WGS84)	(WGS84)
Italy	Marche	Camerino	40,25	35,4

history		value	
year of construction	structural retrofit (year)	structural value	non structural value
		€	€
1942-1968	1998	5.616.160,00 €	1.000.000,00 €

Figure 3-J. Instruction to fill in the Asset data model sheet - part 2

-enter capacity and physical information: based on the asset type, provide the relevant details

service			
people/day	capacity 1	capacity 2	capacity 3
600			

Physical						
physical 1	physical 2	physical 3	physical 4	physical 5	physical 6	physical 7
rc	4	3	1	400	14	500

Figure 3-K. Instruction to fill in the Asset data model sheet - part 3

The following tables present an overview of the relevant asset data requested for the designated area of analysis. Each entry is organized by sector and category, with associated capacity indicators that detail the specific characteristics and potential uses of buildings or open spaces within the region.

SECTOR	CATEGORY	CAPACITY 1	CAPACITY 2	CAPACITY 3
building	residential/commercial	-	-	-
	industrial	production [goods/days]	product value [€/goods]	-
	educational	-	-	-
	hospital	n. of beds	n. of operating theatres	n. of staff
	transportation system buildings	n. of journeys	-	-
open space	roads	n. of vehicles	-	-
	railways	n. of route	-	-
	green areas	trees height [m]	-	-
	agricultural	crop type	crop value	-

Table 3. Asset data model: capacity properties

SECTOR	CATEGORY	PHYSICAL 1	PHYSICAL 2	PHYSICAL 3	PHYSICAL 4	PHYSICAL 5	PHYSICAL 6	PHYSICAL 7
building	all	main material	number of storeys (basement included)	inter-storey height [m]	n. of basement	floor area [m^2]	height [m]	avg. glazing area [m^2]
open space	roads	length [m]	width [m]	carriageway	-	-	-	-
	railways	length [m]	width [m]	n. of tracks	-	-	-	-
	green areas	area [m^2]	-	-	-	-	-	-
	agricultural	area [m^2]	-	-	-	-	-	-

Table 4. Asset data model: physical properties

<u>Please note that the information requested in this section represents the optimum for proceeding with the analysis. In cases where it is not possible to collect or achieve this level of detail, the analysis will be simplified using the data available for each pilot.</u>

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3.1.2. EXPECTED OUTPUT

The MULTICLIMACT CREMA tool provides two key outputs relevant to risk and impact evaluation: **Impact Assessment** and **Expected Annual Loss (EAL)**.

- **Impact Assessment** in the tool involves the evaluation of potential damages or consequences caused by various climate-related and natural hazards on the built environment. This is done through a systematic methodology that considers the characterization of the system/assets, hazard intensity and frequency, vulnerability, and the probability of damage occurrence. The tool integrates these components to assess the expected damage or impact that hazards may inflict, often using fragility and vulnerability functions to quantify damage states and consequences.
- **EAL** represents a quantitative metric that estimates the average annual loss due to hazards. It is calculated by integrating the hazard probability distribution with vulnerability functions and damage consequences over time, effectively providing an economic expectation of damage losses per year. This metric supports decision-makers by quantifying the financial risk under current or projected hazard conditions and can be used to evaluate the cost-effectiveness of resilience-enhancing interventions.

Both outputs serve the purpose of supporting resilience assessment and planning by providing clear, actionable data: Impact Assessment details the expected physical and functional disruptions from hazards, while EAL quantifies these impacts economically to aid prioritization and investment decisions in climate adaptation and disaster risk reduction interventions within the built environment

3.1.2.1. Impact assessment

Impact assessment is a core element in climate and risk analysis, systematically identifying and quantifying the consequences of hazardous events on systems, assets, and populations. Within the MULTICLIMACT framework, impact assessment distinguishes between:

- **direct impacts**: immediate physical damage resulting from hazard exposure;
- **indirect impacts**: secondary effects that arise as a consequence of direct damage, often manifesting through disruptions in connected systems or socioeconomic processes;
- **impact on people**: effects on human health, safety, and well-being, extending beyond structural or economic losses.

	EARTHQUAKE	FLOOD	HEAT WAVE	DROUGHT
DIRECT IMPACT	Cost of reconstruction	Cost of reconstruction	-	Loss of asset value
INDIRECT IMPACT	Economic loss due to inaccessibility and the need to find alternative locations	Economic loss due to inaccessibility and the need to find alternative locations	Consumption of facilities; Decrease in productivity	Increase in sale prices
IMPACT ON PEOPLE	Possibility of death or injury	Possibility of death or injury	Possibility of death or injury	-

Table 5. Economic losses by impact type and hazard

By integrating direct, indirect, and people-centred impacts, the assessment ensures a comprehensive understanding of hazard consequences, supporting better decision-making for risk reduction and resilience planning in the built environment.

ANNEX A examines methods for evaluating economic, direct, and indirect impacts resulting from adverse events, focusing on the immediate consequences for structures and services as well as effects on people.

3.1.2.2. Expected annual loss (EAL)

EAL is a key risk metric representing the average annual economic loss due to hazards, typically expressed in monetary terms (e.g., dollars). It estimates how much loss, on average, can be expected per year considering all possible hazard events weighted by their annual frequency and severity (FEMA, 2025).

EAL is computed by integrating the losses over a range of hazard intensity levels, each multiplied by the annual probability of its occurrence:

$$EAL = Exposure \times Annualized\ Frequency \times Historic\ Loss\ Ratio$$

The calculation involves three factors:

- exposure: value of assets or population at risk;
- annualized frequency: the probability or expected frequency per year that a hazard of a given intensity will occur;
- historic loss ratio: the fraction of exposed value expected to be lost at a certain hazard intensity, based on vulnerability.

These factors are multiplied to compute expected losses at different hazard levels, and then summed to give an average annual loss figure (FEMA, 2025).

The EAL is often derived and visualized via a Loss Exceedance Probability (EP)-Curve, which plots the annual frequency (or probability) that losses will exceed various thresholds (Figure 3-Ls). The curve shows the likelihood of different sizes of losses occurring in any given year.

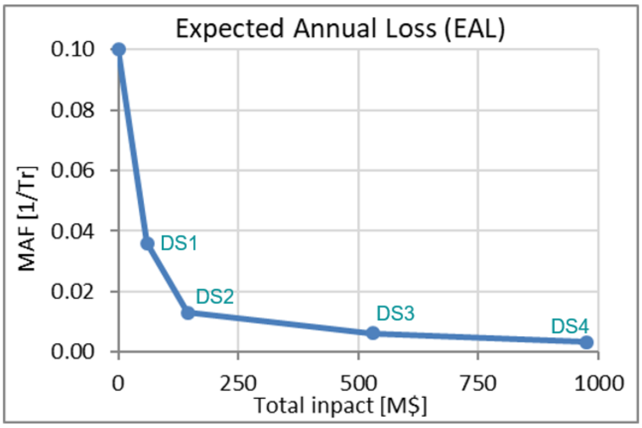

Figure 3-L. EAL curve (Exceedance probability curve)

For a given loss value on the x-axis, the corresponding y-axis value shows how often (e.g., per year) losses equal or exceed that value. The area under the curve corresponds to the EAL. In other words, EAL is the expected value (mean) of the loss distribution represented by the EP curve.

For example, a steep curve indicates a high probability of small losses, while a flatter tail represents low-probability but high-impact events, both contributing to the overall EAL differently depending on the hazard type.

EAL acts as a practical summary of risk, capturing the average yearly loss from all potential hazards as a single, actionable number. This makes it easier for decision-makers to compare risks and prioritise where to invest in adaptation interventions. EAL can be calculated for different hazard types or categories—like buildings or urban areas and then combined for an overall risk picture.

More than just a statistic, EAL helps weigh the cost of risk reduction efforts against the benefits. It also distinguishes between hazards with similar average loss but different patterns of frequency and severity, as reflected in their Loss Exceedance Probability (EP) curves. Recognising these differences is crucial for designing effective, targeted risk management strategies.

3.2. ASSESSMENT OF THE CURRENT RESILIENCE OF BUILT ENVIRONMENT TO CLIMATE CHANGE AND NATURAL HAZARDS

The assessment of resilience within the MULTICLIMACT project is grounded in a comprehensive methodology that aims to capture the multi-dimensional nature of urban and infrastructural adaptability. By employing a systematic evaluation tool, the project addresses the complexity of resilience in the face of diverse hazards and evolving socio-economic challenges. This approach not only measures existing capacities but also identifies critical areas for improvement, providing a robust foundation for informed decision-making and strategic planning.

3.2.1. RESILIENCE SCORE

The resilience score index within the MULTICLIMACT project is determined by multiplying resilience factors—each defined through responses to one or more targeted questions from the Resilience Scorecard—by their associated weights. This approach offers a systematic and quantitative mean to represent the significance of various resilience dimensions. Each resilience factor corresponds to a core element identified in the scorecard, and its final weight, which ranges from 0 to 3, reflects the extent of relevance or achievement associated with that factor. The use of this weighted product methodology enables the index to effectively consolidate qualitative feedback into a comprehensive and comparable metric for evaluating resilience.

Resilience factors are organized into three macro-categories:

- Preparation (advance planning)
- Internal resourcefulness (effectiveness and availability of resources)
- External resourcefulness (agreements and coordination with external parties)

To clarify the relationship between each resilience factor and its associated questions from the Resilience Scorecard (Angelone et al., 2024),Table 9. *Resilience interview* (see §9.1) summarizes this correspondence. Each resilience factor is mapped to the most relevant questions within the scorecard, illustrating how these targeted items contribute to the assessment and quantification of resilience within the MULTICLIMACT framework.

3.2.2. RESILIENCE COEFFICIENT

Resilience factors, in addition to the assignment of a resilience score, are incorporated into impact analysis. Certain resilience coefficients are defined to include these factors within the analysis framework. A detailed description of their estimation is reported in ANNEX A.

Table 6 presents the relationships between factors for each macro-category, their effects on the asset, and the corresponding questions from the Resilience Scorecard (Angelone et al., 2024).

Resilience indicators				*Resilience coefficient*			*Scorecard questions*
				Peop.	Phys.	Serv.	
Preparation		P1	Existence and status of emergency plans	δ_t			9.2.1
		P2	Frequency of training course/exercise	δ_t			6.1.5 - 6.1.6; 9.5.1- 9.5.2
		P3	Insurance cover				3.2.3
		P4	Existence of backup systems			δ_{rec}	8.2.3; 8.3.3; 8.4.3; 8.5.3; 8.7.2; 8.8.2- 8.8.3
		P5	Community experienced a significative hazardous event	δ_p			6.1.1- 6.1.2
		P6	Warning time before the hazardous event	δ_p			9.1.2
		P7	Specific countermeasures	δ_{S1}	δ_{S2}	δ_{S3}	8.1.1 - 8.1.4
Resourcefulness	*Internal*	Int1	Early warning system			δ_{rec}	9.1.1
		Int2	Available material to offset the loss			δ_{rec}	9.3.3; 9.4.1- 9.4.2
	External	Ext1	Mutual agreements and exercises with relevant institutions and organizations			δ_{E1}	6.3.1-6.3.2
		Ext2	Coordination with public units and local government institutions			δ_{E1}	9.3.1
		Ext3	Coordination with hospitals with special treatment units.	δ_{E2}			8.8.1- 8.8.2

Table 6. Summary of resilience coefficient

3.3. INTEGRATION OF MULTICLIMACT TOOLKIT OF DESIGN, MATERIALS AND TECHNOLOGIES, AND DIGITAL SOLUTIONS

The **MULTICLIMACT Toolkit** presents a curated selection of 18 innovative solutions aimed at enhancing climate resilience across **buildings**, **urban spaces**, and **territorial** environments. Designed for public authorities, planners, engineers, and decision-makers, the toolkit addresses the multifaceted challenges posed by climate change and natural hazards through a strategic approach.

These solutions fall into three main domains:

- **Design Practices and Methods** – Guidelines and strategies for climate-adaptive planning and policy-making.
- **Materials and Technologies** – Novel construction materials and sensor-based systems to boost structural and environmental performance.
- **Digital Solutions** – Data-driven platforms and monitoring tools that enable predictive analysis, early warning, and integrated planning.

The MULTICLIMACT toolkit assessment framework is designed to quantitatively evaluate resilience-enabling design practices and methods in the built environment against multiple natural and climatic hazards at various scales, from individual buildings to urban and territorial levels (Ricciardi, 2024). Central to this framework are Key Performance Indicators (KPIs) that serve to identify, understand, and measure resilience aspects as aligned with the MULTICLIMACT Resilience Scorecard (Angelone et al., 2024), ensuring that the measurement of toolkit performance directly supports the broader resilience assessment framework. KPIs are quantitative metrics that assess essential aspects of resilience such as robustness, redundancy, resourcefulness, and rapidity, enabling systematic evaluation of a system's ability to withstand, recover, and adapt to disturbances (Bruneau et al., 2003). By measuring how well these solutions mitigate risks, support preparedness, and enhance responsiveness, stakeholders can simulate, estimate, and compare their impacts across various natural and climatic hazards and at different scales.

3.3.1. ASSESSMENT OF RESILIENCE-ENHANCING SOLUTIONS

In the MULTICLIMACT framework, effective assessment of resilience-enhancing solutions relies on a complementary combination of qualitative and quantitative approaches. Initially, qualitative evaluation is facilitated through a structured scorecard system, where stakeholders respond to targeted questions that probe the presence, consistency, and maturity of resilience strategies across relevant domains. These scorecard questions not only capture nuanced, context-specific insights into current practices and needs, but also guide users in identifying gaps and opportunities for improvement. The qualitative process empowers decision-makers to discern the readiness and appropriateness of interventions before moving to more data-intensive analyses.

Once potential solutions are identified and tailored via the qualitative scorecard, the focus transitions to a quantitative assessment anchored in KPIs. This stage employs a set of standardized, objectively measurable metrics that capture the concrete impacts of each intervention on critical dimensions of resilience, such as robustness, adaptability, and operational continuity. By combining the interpretive depth of qualitative inquiry with the precision of KPI-based measurement, the toolkit ensures that resilience planning is both informed by stakeholder perspectives and substantiated by empirical evidence. This dual approach supports transparent, data-driven decision-making, allowing stakeholders to compare, prioritize, and implement climate adaptation solutions with confidence.

3.3.2. QUALITATIVE EVALUATION OF INTERVENTIONS BASED ON RESILIENCE QUESTIONS

Stakeholders engaging with the MULTICLIMACT Toolkit will find that some specific response provided within the resilience scorecard seamlessly unlocks tailored solutions that address their specific climate adaptation needs. Once these solutions are identified, a rigorous evaluation follows, measuring their effectiveness through a suite of targeted KPIs. This methodology transforms user input into actionable insights, allowing decision-makers to trace a direct line between their choices, the toolkit’s interventions, and the quantifiable improvements in resilience that are ultimately achieved.

To further support transparent and informed decision-making, Table 7 presents a matrix that maps toolkit solutions to the specific questions within the scorecard. Through these two questions—one relating to "Materials and Technologies" and the other to "Digital Solutions"—a package of specific solutions is activated. The impacts of these solutions are then analysed in detail using a suite of KPIs, which make it possible to quantify the effectiveness of the strategies implemented against resilience objectives. The questions not only guide the selection process for the most suitable solutions but also formally incorporate them into the resilience score, ensuring that each intervention is evaluated both qualitatively and quantitatively for adaptive, transparent, and comparable planning.

CATEGORY	TOOLKIT SOLUTION	SCORECARD QUESTION
Design Practices and Methods	Guideline to political policies	4.4.1
	Guideline to supply chains	
	Life cycle approach	
	Guideline to thermal comfort	
	Human-centredness	
	Cultural heritage protection	
Materials and technologies	Fiber optics flood monitoring	8.1.1
	Recycled cool pavements	
	Sensorized concrete (ECCS)	
	Eco-friendly mortar	
	Wearable signs sensors	
	Passive system for housing	
	NBS to reduce urban floods	
Digital solutions	Energy & heat evaluation	8.1.4
	Early-warning of floods	
	Extreme weather prevention& damage estimation	
	Energy solution planning	
	Environmental and structural monitoring of building	

Table 7. Toolkit solutions with resilience-related questions

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3.3.3. QUANTITATIVE (KPI-BASED) ASSESSMENT OF INTERVENTIONS IMPACT

The selection of the most suitable KPIs to assess the impact of MULTICLIMACT toolkit solutions followed a multi-criteria approach integrating technical relevance, stakeholder needs, and practical measurability (Ricciardi, 2024). The process began with a comprehensive review of the project's objectives and the diverse climatic, geographic, and socio-economic contexts addressed in its four pilot sites. The goal was to identify KPIs that reliably capture the improvements linked to each specific solution—whether material, technological, or digital—across scales from building components to urban systems. For a comprehensive and detailed overview of the KPIs and applicability across each pilot site, please refer to the annex (§9.2).

A core feature of the toolkit is its integration of measurable outcomes, ensuring that each solution can be objectively evaluated through a set of tailored KPIs and performance-based questions. To ensure relevance, KPIs were chosen based on their ability to quantitatively reflect core resilience dimensions including physical robustness, environmental benefits, human health and comfort, and operational continuity. Through systematic monitoring and scoring, users can identify the most effective interventions and prioritize resources according to contextual needs and vulnerabilities.

To provide a clear overview of the relationship between each MULTICLIMACT toolkit solution and its measurable impact, Table 8 presents a summary associating each toolkit intervention with its relevant KPIs, a typical range observed for each KPI, and the anticipated quantitative benefit derived from implementing the solution. These benefits are initially estimated based on theoretical data, but will be subject to comprehensive validation during the upcoming beta-test and test phases. This approach ensures that stakeholders have a transparent, data-driven reference to guide decision-making, compare interventions, and prioritise actions based on measurable resilience outcomes.

	TOOLKIT SOLUTION	ASSOCIATED KPI(S)	KPI RANGE / CLASSES (LITERATURE)	SOURCE OF RANGE / CLASSES	ESTIMATE BENEFIT	POSSIBLE SOURCE OF MULTICLIMACT BENEFIT VALUE	NOTES / QUALITATIVE BENEFITS
Materials and Technologies							
	Recycled cool pavements	Cool surfaces in proportion to number of dwellings	Proportion varies; higher % better	Tuomimaa et al. (2023)	Cool surface area increased by 15-20%	Urban heat mapping data	Natural surfaces reduce urban heat island, improving liveability
	Sensorized concrete (ECCS)	Robustness Index	0 to 1 scale, >0.8 indicates high robustness	Chee Yin et al. (2022)	Robustness improvement by approx. 10%	Structural test results within the project	Self-sensing concrete detects damage early, extends lifespan, improves seismic resistance
		Damages for building materials	Measured as % damage or repair cost	General engineering assessments	Damage reduction up to 15%	Project case studies	Durable and sensorized concrete reduces repair frequency
	Eco-friendly mortar	Practical Moisture Buffer Value (?)	Typical values 0.1-1.0 g/(m²·%RH)	Rode et al. (2005)	Moisture buffer increased approx. 20%	Lab experiments	Enhances indoor moisture regulation, improves building hygrothermal comfort

TOOLKIT SOLUTION		ASSOCIATED KPI(S)	KPI RANGE / CLASSES (LITERATURE)	SOURCE OF RANGE / CLASSES	ESTIMATE BENEFIT	POSSIBLE SOURCE OF MULTICLIMACT BENEFIT VALUE	NOTES / QUALITATIVE BENEFITS
Materials and Technologies	Wearable signs sensors	Psychological distress	Scale 0 (none) to high distress	Lee EKO & Tran TV (2008)	Distress reduction estimated 10-15%	Field studies	Real-time health monitoring reduces anxiety and enhances response to heat stress
		Sweat rate	Normal range 0.3-2.0 L/h depending on conditions	Narocki (2021)	Improved heat stress management by ~10%	Sensor data from pilot projects	Monitors physical strain in workers for heatwave resilience
	Passive system for housing	Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD)	PMV: -3 to +3; optimal near 0; PPD < 10-20%	Matzarakis & Amelung (2008)	Achieves PMV ~0 (neutral) and PPD <15%	Field measurements	Passive design maintains comfort with minimal energy use
		Reduction in Peak Site Power Demand Intensity	Percentage reduction, typical goals 10-30%	Holzer et al. (2024)	Peak demand reduced by ~15-20%	Digital tool outputs	Reduces stress on grids, lowers energy costs, supports renewable integration
		Recovery Time Indicator (RTI) for Extreme Heat	Hours/days for habitat recovery, shorter is better	International Building Code (2021)	Recovery time reduction 20-30%	Modelling results	Reduces indoor heat strain during heatwaves without active cooling

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TOOLKIT SOLUTION		ASSOCIATED KPI(S)	KPI RANGE / CLASSES (LITERATURE)	SOURCE OF RANGE / CLASSES	ESTIMATE BENEFIT	POSSIBLE SOURCE OF MULTICLIMACT BENEFIT VALUE	NOTES / QUALITATIVE BENEFITS
	NBS to reduce urban floods	Drainage system capacity	System capacity increased 10-30%	Laskar et al. (2021)	Capacity increase 20-25%	Multi-site monitoring	Green infrastructure improves stormwater absorption and reduces runoff
		Insurance policies covering catastrophic risks	Percentage coverage varies	Interreg ALCOTRA - ARTACLIM (2019)	5-10% improvement in flood insurance uptake	Survey data	NBS reduces perceived risk, increasing insurance participation
Digital solutions	Energy & heat evaluation	Permeability and infiltration rate	Varies with material, 10^{-6} to 10^{-4} m/s	Zamora-Sànchez et al. (2024)	Real-time detection of increased permeability events	Sensor network data	Detects degradation or blockage in drainage and building envelopes
		Ambient temperature, Global solar radiation	Typical ambient range 5-35°C; Global solar radiation 0-1000 W/m²	Zamora-Sànchez et al. (2024)	Monitoring accuracy +/-2°C; enables responsive cooling strategies	System test data	Provides real-time environmental data for adaptive building management
		Surface temperature of pavement	Typical urban pavement: 25°C to 50°C	Zamora-Sànchez et al. (2024)	Surface temp reduction 5-10°C	MULTICLIMACT experimental tests	Reduces urban heat island effect, enhances pedestrian comfort
	Early-warning of floods	Mean Lead Time	Minutes to hours; higher better	Verkade & Weber (2011)	Lead time extended by 20-50%	System performance logs	Allows more time for flood preparation and evacuation
		Probability of Detection (POD), False Alarm Ratio	POD >0.9 ideal; False Alarm Ratio <0.1	WWRP/WGNE verification guides	POD ~0.85; False alarm ~0.15	Operational validation	Maintains high detection confidence, limiting unnecessary alerts

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	TOOLKIT SOLUTION	ASSOCIATED KPI(S)	KPI RANGE / CLASSES (LITERATURE)	SOURCE OF RANGE / CLASSES	ESTIMATE BENEFIT	POSSIBLE SOURCE OF MULTICLIMACT BENEFIT VALUE	NOTES / QUALITATIVE BENEFITS
Digital solutions		Structural redundancy	Index typically 0 to 0	Ghosn et al. (2016)	Design and monitoring support improve redundancy index by 0.1–0.1	Inspection reports	Supports resilient building design and ensures multiple load paths
	Extreme weather prevention & damage estimation	Occurrence probability of certain consequences	0 to 1 (probability scale)	Matassoni et al. (2017)	Accurate probability modelling within ±0.1 range	Validation with historical data	Supports decision making on risk mitigation and emergency response
		Inventory of Assets	Number of assets monitored varies	Golparvar-Fard et al. (2012)	Expanded asset monitoring coverage by ~30%	Project delivery reports	Comprehensive asset data improves damage estimation and prioritization
	Energy solution planning	Thermal transmittance (U-value)	0.1 to 1.5 W/m²K (building envelope values)	Verbeke & Audenaert (2018)	Real-time deviation detection of +/-0.1 W/m²K	Monitoring trial results	Enables verification of insulation performance and energy efficiency
		Hours outside comfort temperature	0 to 200+ hours/year	Level(s) indicator 4.2 (JRC)	Reduction of hours outside comfort by ~20-30%	Pilot building measurements	Optimizes HVAC and energy usage, improving occupant comfort during heat events
		Energy demand and consumption of the systems	kWh/m²/year typically 100-300	Attia et al. (2021)	Energy demand reduced by 15-25%	Field operational data	Enhanced energy efficiency through monitoring and control
		Thermal transmittance (U-value)	0.1 to 1.5 W/m²K (building envelope values)	Verbeke & Audenaert (2018)	Real-time deviation detection of +/-0.1 W/m²K	Monitoring trial results	Enables verification of insulation performance and energy efficiency

TOOLKIT SOLUTION		ASSOCIATED KPI(S)	KPI RANGE / CLASSES (LITERATURE)	SOURCE OF RANGE / CLASSES	ESTIMATE BENEFIT	POSSIBLE SOURCE OF MULTICLIMACT BENEFIT VALUE	NOTES / QUALITATIVE BENEFITS
Digital solutions	Environmental & structural monitoring of building	Fire resistance rating	Usually rated by hours of resistance (e.g., 30-120 min)	Guay (2019)	Early smoke and temperature detection leads to 10-15% faster alerts	Field tests and simulations	Enhances fire safety through early warning
		Seismic resistance	Rated scale or code-specific (e.g., 1-5)	Musella et al. (2020)	Real-time structural monitoring improves response time by ~25%	Project pilot studies	Allows fast damage assessment post-earthquake
		Hours Outside Comfort Temperature	0 to 200+ hours/year	Level(s) indicator 4.2 (JRC)	Reduction of hours outside comfort by ~20-30%	Pilot building measurements	Optimizes HVAC and energy usage, improving occupant comfort during heat events
		Energy demand and consumption of the systems	$kWh/m^2/year$ typically 100-300	Attia et al. (2021)	Energy demand reduced by 15-25%	Field operational data	Enhanced energy efficiency through monitoring and control

Table 8. Preliminary estimate of quantitive (KPI-based) assessment of toolkit impact

4. RESILIENCE ASSESSMENT THROUGH ARCH DISASTER RISK MANAGEMENT FRAMEWORK

A comparative analysis of the CREMA tool framework developed in T1.3 and the ARCH Disaster Risk Management (DRM) framework from the ARCH project identified opportunities to integrate specific elements from ARCH into the tool. These enhancements aim to strengthen the CREMA tool both during its development and future implementation. In particular, CREMA stands to benefit from ARCH's structured and iterative approach to stakeholder and community engagement.

4.1. OVERVIEW OF ARCH FRAMEWORK

The ARCH Disaster Risk Management Framework (DRMF) is a comprehensive, cyclical process designed to enhance the resilience of historic areas facing both sudden-onset disasters and slow-onset climate-related risks. Developed under the EU-funded ARCH project, the framework integrates Disaster Risk Management (DRM) and Climate Change Adaptation (CCA) into a unified strategy specifically tailored to historic urban environments.

The ARCH DRMF supports asset managers, urban planners, and decision-makers in developing and implementing integrated DRM/CCA strategies. It frames historic areas as social-ecological systems (SES) and highlights the importance of cultural heritage, social justice, and community identity in resilience planning.

The framework comprises ten interconnected steps, structured across three operational phases:

Pre-Disaster (Normal Operation):

- Prepare the ground
- Assess vulnerabilities and risks
- Identify risk prevention, adaptation, and emergency response options
- Assess and select measures
- Implement selected measures
- Establish monitoring, evaluation, and learning procedures

During and Post-Disaster (Emergency Operation):

- Conduct emergency response procedures
- Assess needs and impacts
- Stabilize the situation
- Recover and Build Back Better (including revision of steps 1–6)

A defining feature of the ARCH framework is its emphasis on monitoring, evaluation, and learning (Step 6), which replaces a simple return to the beginning of the cycle. Instead, it introduces feedback loops to track not only implementation progress but also the effectiveness of DRM and CCA strategies. This adaptive approach fosters continuous improvement and sustained resilience over time (ARCH Project, 2020).

4.2. INTEGRATING ARCH CO-CREATION STRATEGY INTO CREMA DEVELOPMENT

Through the comparative analysis, it was identified that the CREMA tool has significant potential to enhance co-creation mechanisms in its development phase. While it provided strong methodological guidance for resilience assessment, incorporating structured stakeholder engagement and co-creation processes can further broaden its applicability in diverse local contexts.

To address this, ARCH co-creation strategies will be incorporated into the CREMA tool, including:

- Early and continuous involvement of diverse stakeholders
- Iterative feedback loops and joint validation of outputs
- Inclusive engagement across both technical and non-technical user groups
- Embedding participation throughout all phases of tool development

These principles are being actively applied in Task 7.3 through participatory workshops and collaborative design sessions. The workshops support the validation of the tool interface, clarify user roles, and ensure that the tool’s outputs are accessible, relevant, and actionable for end users.

4.3. KEY STEPS FOR INTEGRATION

The integration of co-creation principles from the ARCH Disaster Risk Management Framework (DRMF) into the development of the CREMA tool has been guided by a comparative analysis of the two approaches. While both frameworks support climate resilience through structured assessment and action planning, ARCH places stronger emphasis on stakeholder engagement and iterative learning throughout the full disaster risk management and climate adaptation cycle.

These integration steps aim to bridge the technical and participatory dimensions of resilience planning and are informed both by ARCH’s normal operation phase and by early co-creation activities piloted within Task 7.3 of MULTICLIMACT.

A visual comparison between the ARCH DRM Framework and the CREMA tool is presented in Figure X. This diagram served as a reference for identifying integration opportunities, particularly in relation to stakeholder engagement and co-creation strategies at different stages of the resilience cycle.

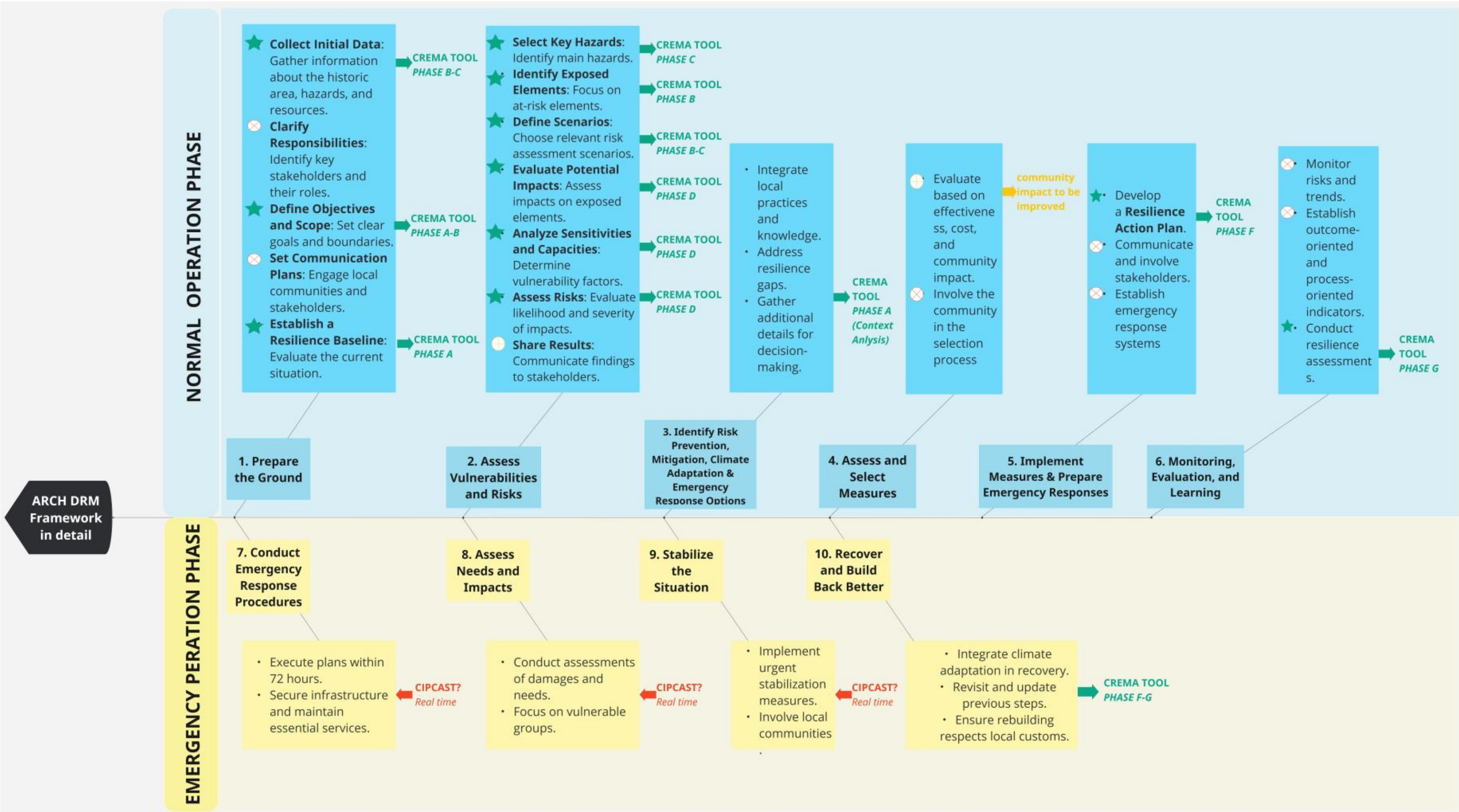

Figure 4-A. Comparative mapping of ARCH DRM Framework phases and CREMA tool components (Source: Miro board created by ICLEI)

1. **Stakeholder Mapping**

The first step involves the early identification and classification of relevant actors, including public authorities, infrastructure managers, local communities, and academic or technical partners. This aligns with the "Prepare the Ground" phase of the ARCH framework, where understanding the local context and mapping stakeholder ecosystems is essential for meaningful engagement.

In CREMA, this step has already been piloted through initial workshops with stakeholders from the four case study regions. These exercises applied a stakeholder typology similar to ARCH, ensuring representation across sectors and governance levels. This mapping forms the foundation for targeted participation in subsequent tool development stages.

2. **Developing a Communication and Engagement Strategy**

ARCH structured its engagement through recurring stakeholder interactions—via workshops, co-design sessions, and feedback loops. Inspired by this approach, CREMA is adopting a phased engagement strategy to ensure transparency, inclusivity, and continuity of stakeholder input throughout the tool's development.

For example, Workshop #2 in Task 7.3 introduced participants to a CREMA prototype, focusing on asset registration, hazard scenario selection, and resilience scoring. Stakeholders provided structured feedback through live polling and guided discussion, which helped identify key usability challenges—such as confusion around hazard-scenario combinations, the need for clearer role definitions (e.g., admin vs. client), and preferences regarding the order of asset and pilot creation. These findings directly informed improvements to the user interface and functionality, following the ARCH model of continuous stakeholder validation and adaptation.

3. **Embedding Participation Across the Development Cycle**

Rather than confining co-creation to the initial design phases, the ARCH project demonstrated the value of stakeholder input throughout all stages—from risk assessment and option appraisal to implementation and monitoring. CREMA is adopting a similar approach by embedding engagement touchpoints across its full development lifecycle.

Workshops #2 and #3 focused not only on improving the user interface but also on refining scenario logic and interpreting results, ensuring that outputs are understandable and actionable for a diverse range of users. Participants provided feedback on interface clarity, role distinctions (e.g., admin vs. client), and the readability of outputs—insights that directly shaped both the tool's functionality and its communication strategy.

This reflects ARCH's emphasis on usability, accessibility, and the integration of non-technical perspectives in tool refinement.

5. CREMA TOOL TECHNICAL SET-UP

The development of the CREMA tool represents the core of this deliverable, integrating insights from participatory engagement with robust technical architecture to support urban resilience. Building upon the collaborative groundwork established through iterative stakeholder workshops and co-design sessions, the tool's evolution is grounded on principles of transparency, inclusivity, and adaptability. This section provides an in-depth overview of the technical framework and implementation strategies underlying CREMA, while bridging the outcomes of prior engagement activities with the architectural choices that define its core functionalities.

From the outset, CREMA's design philosophy has been shaped by continuous feedback from a diverse range of stakeholders. Early workshops, as detailed above, highlighted the importance of clarity, usability, and actionable outputs—needs that directly inform the tool's technical structure. These findings steered the team towards solutions that facilitate both expert and non-expert participation, ensuring that the platform remains accessible and responsive to evolving user requirements.

Technically, the CREMA tool adopts a layered application model, with each layer tailored to optimize specific aspects of user experience and system performance. The Presentation Layer, or frontend, leverages Livewire—a framework supporting interactive, real-time user interfaces without the need for full-page reloads. Livewire acts as a bridge between the server and the client, employing AJAX and Alpine.js to handle dynamic form submissions, real-time filtering, modal dialogues, and dashboard widgets. This approach not only enhances responsiveness but also simplifies the development of complex interactive elements, making the tool intuitive and efficient for end users.

On top of Livewire, the Filament Admin Panel provides a comprehensive management interface built with Tailwind CSS. Filament offers preconfigured components and plugins, such as Filament Forms, Tables, and Notifications, streamlining the creation and administration of backend resources—users, roles, settings, and other core entities. Its modular structure supports rapid prototyping and iterative refinement, aligning with the co-creation ethos established through the project's stakeholder engagement activities.

Subsequent sections will delve deeper into each application layer, detailing both frontend and backend components, data management processes, and the logic that drives scenario modelling and resilience assessment. By weaving together participatory insights and technical best practices, this deliverable aims to demonstrate how CREMA's architecture is purpose-built to support continuous development, stakeholder empowerment, and meaningful resilience outcomes.

5.1. TOOL ARCHITECTURE

At a high level, the CREMA application architecture is divided into distinct but interconnected layers, each responsible for a key facet of the system's operation. This layered approach ensures scalability, maintainability, and the flexibility to respond rapidly to user feedback and evolving project needs. This approach ensures that changes in one layer—for example, updating the user interface (UI)—have minimal unintended consequences elsewhere.

The primary layers include the Presentation Layer (Front-end), which governs user interaction; the Application Layer (Back-end), which encapsulates business logic; and the Data Layer, which manages storage, retrieval, and integrity of information. Each is designed to work seamlessly together, creating a cohesive ecosystem that supports collaborative workflows and robust data-driven insights.

To further clarify the system's structure and illustrate these interdependent components, Figure 5-A presents a visual overview of the CREMA tool architecture. This diagram maps out the key application layers and their respective roles, offering a concise reference point for understanding how user interactions, business logic, and data management are orchestrated within the platform. As depicted, the architecture not only delineates functional boundaries but also highlights the pathways that connect each layer, underscoring the tool's emphasis on modularity and cohesive system design.

Following, the functionalities of each layer are outlined in detail.

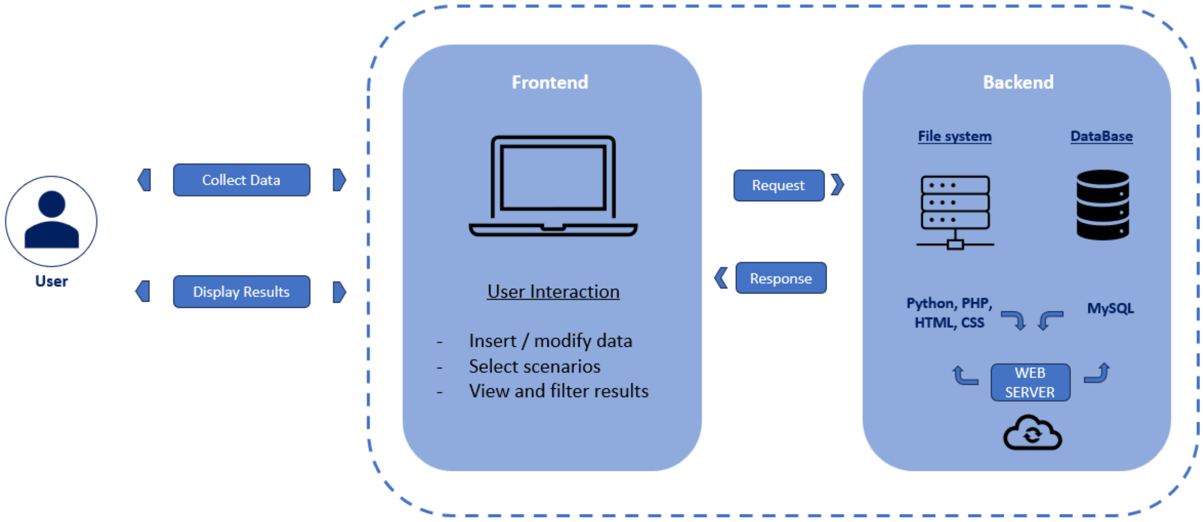

Figure 5-A. CREMA tool architecture

5.1.1. PRESENTATION LAYER (FRONT-END)

The front-end of the CREMA tool is engineered to provide users with an intuitive, flexible, and visually engaging environment. Recognizing that both expert analysts and community stakeholders will engage with the platform, the front-end prioritizes clarity, accessibility, and responsiveness. Through a careful balance of interactive elements and streamlined design, users are empowered to explore scenarios, input data, and make informed decisions without being encumbered by technical barriers. This user-centric approach is achieved through the integration of advanced frameworks and component libraries, which together enable rapid development of sophisticated interfaces while maintaining seamless performance.

Central to this architecture are two modern technologies: Livewire and Filament.

- **Livewire** is a dynamic framework designed for building rich, interactive user interfaces within Laravel applications. Unlike traditional front-end frameworks that rely heavily on client-side JavaScript, Livewire enables developers to create reactive components using familiar server-side logic. By leveraging AJAX requests under the hood, Livewire efficiently synchronizes data between the server and client, allowing elements such as forms, filters, and modals to update in real time—without requiring full-page reloads. Alpine.js is often paired with Livewire to enhance client-side interactivity and handle lightweight UI behaviours, resulting in interfaces that feel both immediate and smooth.
- **Filament**, on the other hand, serves as a robust administrative panel layered atop Livewire and styled with Tailwind CSS. It provides a suite of prebuilt components and management tools tailored specifically for backend resource administration. With Filament, CRUD (Create,

Read, Update, Delete) operations for users, roles, settings, and other key entities can be implemented rapidly, using intuitive interfaces that minimize development overhead. The modular plugin system includes features like Filament Forms for advanced user input, Tables for data display, Notifications for real-time feedback, and custom widgets to visualize critical metrics or workflows. By coupling these technologies, the CREMA front-end achieves a high degree of flexibility, making it easy to customize and extend administrative functions as project requirements evolve.

To effectively illustrate the platform's functionality and user experience, this section presents a selection of key user interface (UI) images. These visuals have been carefully chosen to provide a comprehensive overview of the primary interaction points and data presentation methods. Specifically, the included images showcase:

- The Landing Page: As the introductory interface to the platform, this visual serves to convey the core objective of the project and strategically highlights the various study pilots through an accessible visualization (Figure 5-B).

Figure 5-B. CREMA tool – Landing page

- The "AS-IS" Scenario Visualization: This crucial display demonstrates how the platform represents the current, baseline risk and resilience assessment of the pilot under selected hazards. It is vital for establishing the initial conditions against which analyses and future adaptation actions are evaluated. For illustrative purposes, the "AS IS" scenario for the Carmelitane building under earthquake conditions is presented (Figure 5-C).

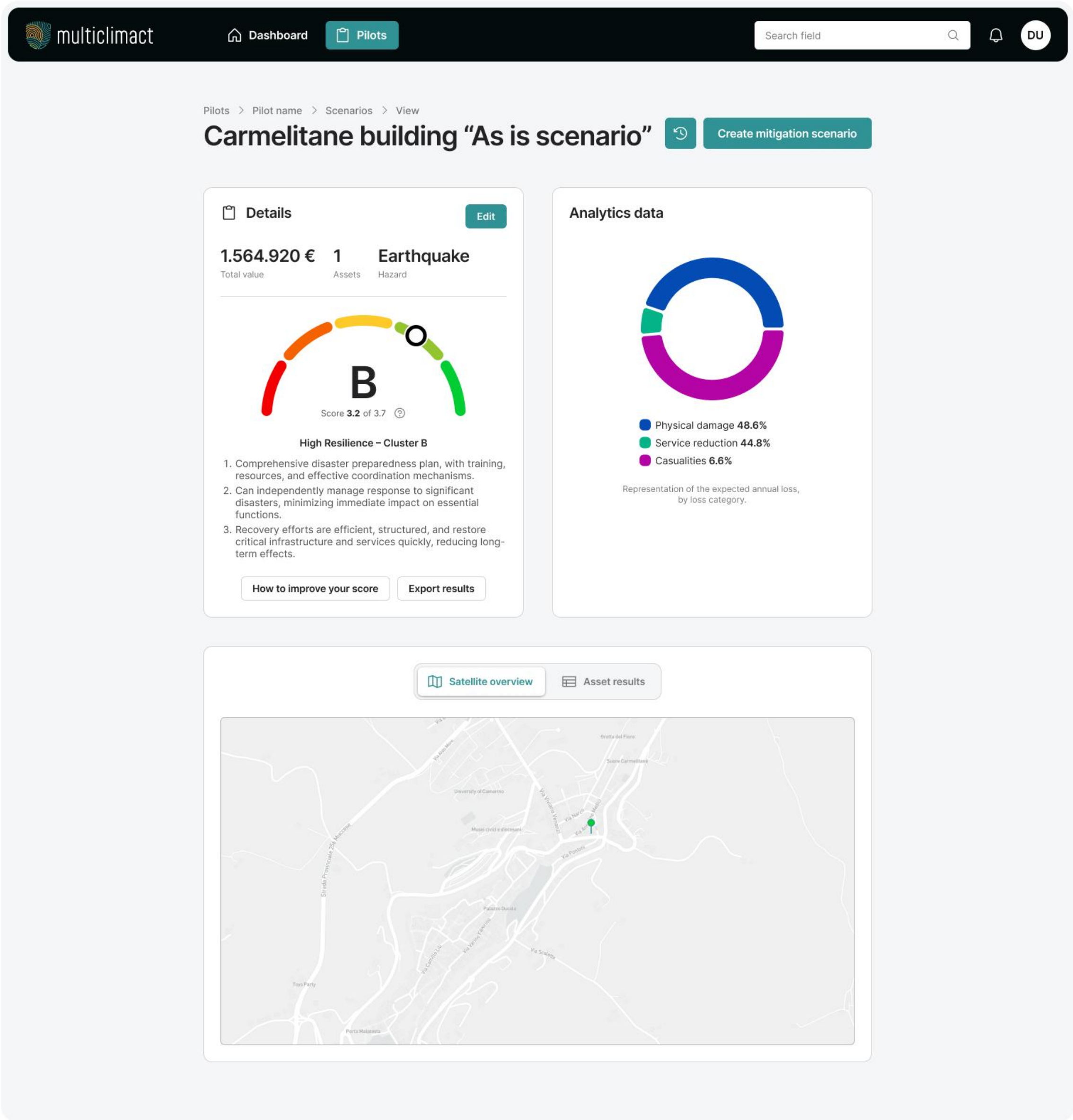

Figure 5-C. CREMA tool – "As is" scenario output visualization

- <u>Single Asset Output Visualization</u>: These screens highlight the detailed way analytical results pertinent to individual assets are presented. This granular output visualization is designed to facilitate clear interpretation of data, aid in the identification of critical areas, and support informed decision-making. Specifically, this visualization presents a breakdown of the economic impacts, differentiating between direct losses, indirect losses, and potential casualties. It also includes the comprehensive results of the risk and resilience assessment performed.

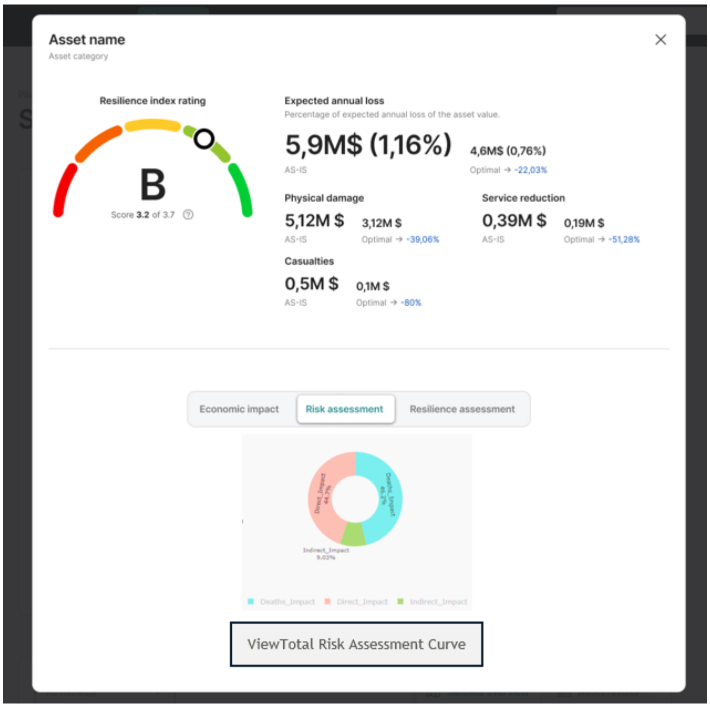

Figure 5-D. CREMA tool – Risk results of a specific asset

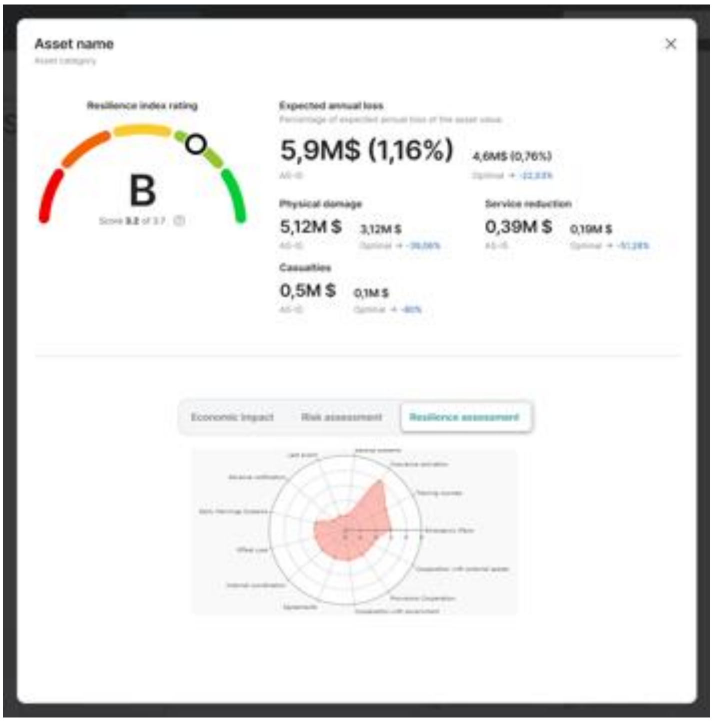

Figure 5-E. CREMA tool – Resilience results of a specific asset

5.1.2. APPLICATION LAYER (BACK-END)

The Application Layer, commonly referred to as the backend, serves as the core of the CREMA platform's architecture. Its primary function is to interpret, validate, and execute all instructions originating from the user interface, while orchestrating the system's internal logic and ensuring seamless collaboration among platform components. All components of the applied methodology, detailed in the preceding sections, are visually represented in the accompanying Figure 5-F. This comprehensive diagram illustrates the interconnected elements that form the core of the calculations, encompassing both the "AS IS" (current state) and "TO BE" (mitigated state) scenarios, along with their crucial linkage to various databases.

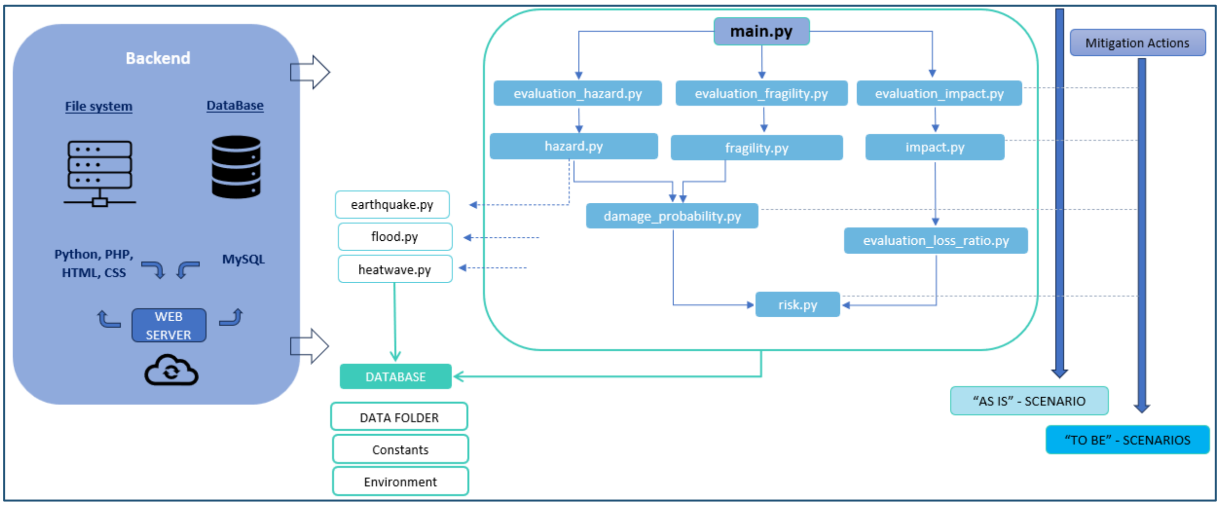

Figure 5-F. CREMA tool - back-end architecture

This visual representation highlights the layered structure and key interactions that underpin the system's reliability, scalability, and extensibility. The calculation's scalability for each asset type and hazard is a core design principle, achieved through the robust logic embedded within the backend architecture. As Figure 5-G illustrates, this architecture's core starts from the central main.py file. From there, it orchestrates a series of calculations, precisely tailoring them to the chosen asset, hazard type, and desired scale of study, all the way to the final risk.py script (Figure 5-H).

```python
@resplat.route('/calculate', methods=['POST'])
def calculate():
    """ Endpoint to handle the calculation request.
    :return: JSON response with the results of the calculation
    """

    try:
        assets: pl.DataFrame = __read_request(request)
        results = __cira(assets)

        if results is not None:
            res = __results2json(results)
            response = resplat.response_class(mimetype= MIMETYPE, response=res)
        else:
            response = resplat.response_class(mimetype= MIMETYPE, response=dumps(NO_RESULTS_ERROR))
    except ValueError as ve:
        response = resplat.response_class(mimetype= MIMETYPE, response=dumps({"err": f"value error: {str
    except Exception as e:
        response = resplat.response_class(mimetype= MIMETYPE, response=dumps({"err": e.args[0]}))
    return response
```

Figure 5-G. CREMA tool Backend - main.py

Co-funded by the European Union

```python
def eal (rcr ,rcr_max, maf_min, maf):

    if len(rcr)==4:
        eal=maf[3]*(rcr_max-rcr[3])*0.5\
            +(maf[3]+maf[2])*(rcr[3]-rcr[2])*0.5\
            +(maf[2]+maf[1])*(rcr[2]-rcr[1])*0.5\
            +(maf[1]+maf[0])*(rcr[1]-rcr[0])*0.5\
            +(maf[0]+ maf_min)*rcr[0]*0.5
    if len(rcr)==3:
        eal=maf[2]*(rcr_max-rcr[2])*0.5+(maf[2]+maf[1])*(rcr[2]-rcr[1])*0.5+(
                maf[1]+maf[0])*(rcr[1]-rcr[0])*0.5+(maf[0]+ maf_min)*rcr[0]*0.5
    elif len(rcr)==2:
        eal=maf[1]*(rcr_max-rcr[1])*0.5+(maf[1]+maf[0])*(rcr[1]-rcr[0])*0.5+(
                maf[0]+ maf_min)*rcr[0]*0.5
    elif len(rcr)==1:
        eal=maf[0]*(rcr_max-rcr[0])*0.5+(maf[0]+ maf_min)*rcr[0]*0.5

    eal=round(eal,5)
    eal_d=eal*100
    eal_d=round(eal_d,6)
    return eal_d
```

Figure 5-H. CREMA tool Backend - risk.py

At its foundation, this layer is built upon **Laravel 12 Core**, a powerful and extensible PHP framework. Laravel's structure encourages clean separation of concerns and maintainable code architecture, which is critical for a complex, evolving platform such as CREMA tool. The framework is organized around key components:

- **routing**: manages how HTTP requests are dispatched to the appropriate controllers, ensuring each user action—from scenario exploration to data submission—triggers the correct backend process;
- **controllers**: act as the command centres for processing requests, coordinating business logic, retrieving or updating relevant records, and formatting responses for the frontend;
- **middleware**: handles pre- and post-processing of requests, including input validation, permission checks, logging, and response formatting. This allows for systematic enforcement of policies such as access control and audit tracing;
- **service providers**: bootstrap both core and custom services, facilitating integration of domain logic and event listeners. This modular approach makes it easy to expand the platform's capabilities;
- **dependency injection**: promotes decoupled, testable code by providing services and utilities wherever they are needed, rather than hardwiring dependencies.

A defining feature of the backend is its robust capacity to manage complex business logic. The Application Layer takes responsibility for validating incoming data and enforcing business rules, which helps preserve workflow integrity and ensures that the system adheres to intended behaviours. It orchestrates multi-step processes, including scenario simulations, dynamic report generation, and workflow automation—often requiring coordination across various internal services.

User permissions, roles, and access to sensitive features are meticulously monitored and regulated, with comprehensive audit trails providing transparency and accountability. The system supports asynchronous operations through **Laravel's Job Queues**, which relocate resource-intensive or time-consuming tasks—such as sending notifications, processing integrations, or executing batch computations—into background workers. This approach maintains system responsiveness, even as operational demands increase.

Additionally, the Application Layer facilitates centralized configuration for environment settings, feature toggling, and plugin management, all accessible via secure administrative interfaces. To maintain high reliability, it incorporates robust error handling, logging, and monitoring, making it possible to swiftly diagnose issues, recover from failures gracefully, and ensure consistent system performance.

In summary, CREMA's Application Layer delivers a highly modular, scalable, and secure backend—capable of evolving with the platform's needs. By abstracting complexity away from the frontend, it empowers users to interact with sophisticated features intuitively, while guaranteeing that all actions, processes, and data flows are handled with integrity, speed, and reliability.

5.1.3. DATA LAYER (BACK-END)

The primary objective of the Data Layer is to ensure that all critical data is stored, organized, and retrieved with the highest levels of reliability and security. This commitment to data integrity extends through every stage of the application's lifecycle—encompassing not only the initial capture and storage of information, but also its accurate retrieval and consistent management during subsequent operations. Key data elements such as user credentials, workflow states, configuration settings, and audit trails are all handled with meticulous care, reinforcing the system's reliability and traceability.

To achieve these standards, CREMA utilizes **MySQL** as its principal database management system. MySQL is chosen for its robust performance characteristics and its ability to scale efficiently as the platform evolves. Within this environment, essential records, including user accounts, roles, permissions, content, and application states, are securely managed and maintained. The transactional fidelity of MySQL ensures that even under conditions of high concurrency and demand, data remains accurate, consistent, and accessible. For each pilot study, a comprehensive set of "AS IS" and "TO BE" scenarios are securely stored in the central database. Users can easily access these scenarios for comparison and download, enabling detailed analysis of different conditions and proposed adaptation scenarios.

The integration with **Laravel's Eloquent Object-Relational Mapping (ORM)** system is central to the effectiveness of the Data Layer. Eloquent streamlines the process of linking application logic to the underlying database, allowing developers to interact with data structures through expressive models. This approach not only simplifies development but also minimizes the risk of inconsistencies or errors by ensuring that changes in data representation are systematically reflected across the application.

Maintaining a robust and adaptable database structure is facilitated by Laravel's migrations system. Migrations provide a controlled, version-based mechanism for updating the database schema, allowing teams to introduce, modify, or revert structural changes efficiently. This capability is critical in collaborative development environments, supporting both agility and discipline as the platform's requirements evolve.

Furthermore, the Data Layer leverages Laravel's seeders and factories to accelerate development and testing processes. Seeders enable the introduction of initial or sample datasets, which are essential for validating new deployments or testing updates.

The Data Layer's architectural design is intentionally built to anticipate future growth. This proactive approach ensures the existing database of analytical parameters can readily expand, while also accommodating evolving business requirements. Its modular structure supports the integration of new data types, external system connections, and increased operational scale, all while upholding rigorous security measures, such as encryption, access controls, and continuous monitoring. Sensitive information, including user credentials and audit logs, is managed in accordance with best practices and industry standards.

In summary, the Data Layer is a foundational component of the CREMA platform, underpinning its ability to deliver secure, consistent, and high-performance services. Its careful design and integration with advanced data management tools ensure that the platform remains reliable and scalable, capable of supporting both current operational needs and future innovation.

5.2. AUTHENTICATION & AUTHORIZATION

Authentication and authorization are fundamental pillars in the architecture of any modern digital platform, serving as the primary mechanisms that safeguard sensitive data and regulate access to system resources. Together, these processes form the first line of defense against unauthorized entry, ensuring that only legitimate users and services can interact with protected assets within the application environment. In the context of CREMA, where the integrity and confidentiality of user data are paramount, the careful implementation of authentication and authorization protocols is not merely a security requirement, but a core design principle that permeates the entire system.

Authentication is the process by which a system verifies the identity of a user or entity attempting to gain access. This verification typically involves checking credentials, such as usernames, passwords, or tokens, against known records. By confirming that an individual is indeed who they claim to be, authentication establishes trust at the very outset of any user interaction. The robustness of this process is critical; weak authentication mechanisms can open the door to malicious actors and jeopardize the security of the platform. In sophisticated environments like CREMA, authentication is often delegated to trusted external providers using protocols such as OAuth. This procedure not only enhances user convenience by enabling single sign-on capabilities but also leverages the provider's advanced security measures to reduce the risk of compromise.

Authorization, on the other hand, determines what authenticated users are permitted to do within the system. Once a user's identity has been established, authorization policies define their range of actions, what data they can view or modify, which features they can access, and what operations they can trigger. These policies are typically governed by a combination of user roles, permissions, and contextual rules that reflect organizational needs and regulatory requirements. By enforcing strict boundaries around sensitive operations, authorization mitigates the risk of inadvertent data exposure or misuse, helping to maintain compliance and protect the interests of all stakeholders.

In a comprehensive system like CREMA, authentication and authorization are not isolated components but are deeply integrated into the application's lifecycle and user journey. Their collaboration ensures that security is enforced seamlessly, without impeding user experience or operational agility. Advanced frameworks, such as Laravel, offer middleware and policy-driven architectures that simplify the implementation of these controls while maintaining high standards of reliability and adaptability. The following sections delve into the specific mechanisms adopted by CREMA for authentication and authorization, elucidating how these core security functions are realized in practice to uphold the platform's commitment to safe, efficient, and scalable digital operations.

5.2.1. AUTHENTICATION

The authentication process within the CREMA platform is meticulously engineered to balance robust security, operational efficiency, and user convenience—each a cornerstone of modern digital infrastructure. Recognizing the critical role authentication plays as the gateway to sensitive data and system resources, CREMA adopts a layered approach that leverages both industry standards and advanced technological integrations.

At its core, the authentication workflow is built around OAuth, a widely adopted protocol for secure, token-based user verification. When a user initiates a login attempt, they are seamlessly redirected from CREMA's interface to a trusted **external OAuth provider**, in this case, RINA. This delegation of authentication to an established third-party provider introduces several advantages. Firstly, it capitalizes on RINA's comprehensive security infrastructure, which includes sophisticated threat detection, encryption at both transit and rest, and continuous monitoring for anomalous activities. This greatly reduces the risk of credential compromise within the CREMA ecosystem itself.

The authentication journey unfolds as follows: after the user is directed to the RINA login portal, they are prompted to present their credentials. Upon a successful validation, RINA generates a secure authentication token, which is transmitted back to the CREMA platform via a designated **callback endpoint** (typically **/auth/callback**). This endpoint acts as the bridge between CREMA and RINA, verifying the authenticity of the token and extracting essential user information—such as name and email address. Importantly, only minimal and non-sensitive data is stored in CREMA's local database, adhering to the principle of data minimization and further reducing the attack surface.

Once the token is validated, the user's session is established and bound to their identity within CREMA. **Middleware guards**, implemented through Laravel's framework, play a critical role at this stage, enforcing authentication requirements on all relevant routes and APIs. These middleware components inspect each request to ensure a valid, active session exists before granting access, thereby preserving the platform's integrity against unauthorized access attempts.

Additionally, the authentication framework is carefully integrated with CREMA's broader **authorization logic (**user binding logic in AuthServiceProvider**)**, ensuring that user identity and access privileges are tightly coupled throughout the lifecycle of a session. By externalizing authentication, maintaining strict **session handling**, and employing policy-driven access controls, CREMA achieves a security posture that is both resilient against evolving threats and attuned to the expectations of seamless user experience.

In summary, the authentication process in CREMA reflects a best-practice paradigm, delegating identity verification to a trusted external provider, validating authentication tokens securely, storing only essential user details, and rigorously enforcing access controls at every step. This ensures that only legitimate users gain entry, while organizational data and critical system functions remain protected at all times.

5.2.2. AUTHORIZATION

Authorization is a critical aspect of system security, defining what authenticated users are permitted to do within an application. After a user's identity has been verified, authorization policies come into play to determine their level of access — specifying which data they can view or modify and which features or operations they can use. These rules are commonly governed by user roles, permissions, and contextual factors that reflect both organizational needs and regulatory standards.

In Laravel, robust authorization is achieved through the framework's **built-in policies and gates**. Gates are closures that determine if a user is authorized to perform a given action, often used for simple authorization logic. Policies, on the other hand, are classes that organize authorization logic around a particular model or resource, making it easy to manage complex permission structures. By leveraging these tools, developers can centralize and clearly define access rules, ensuring a scalable and maintainable approach to security. Middleware further enforces these policies by checking permissions before users can access certain routes or APIs.

In comprehensive platforms such as CREMA, authorization is deeply integrated with authentication, ensuring only the right individuals perform sensitive actions. Advanced frameworks like Laravel streamline this process through policy-driven architectures and middleware, enabling precise, scalable control over each user’s capabilities. By strictly enforcing boundaries around critical operations and data, authorization minimizes the risk of accidental or malicious misuse, safeguards sensitive information, and helps maintain compliance. Ultimately, robust authorization systems are essential for protecting both the digital assets of an organization and the privacy of its users.

5.2.2.1. Role of ADMIN and CLIENT user

In CREMA, user roles are foundational to the platform’s authorization model, with the ADMIN and CLIENT roles representing distinct sets of privileges and responsibilities.

The ADMIN role is endowed with the highest level of system access. Administrators have the authority to manage users, configure platform settings, and oversee critical operations across the application. Their permissions typically include creating or modifying resources, assigning or revoking user roles, monitoring platform activity, and intervening in system processes when necessary. This comprehensive access ensures that ADMIN users can maintain platform integrity, enforce organizational policies, and respond swiftly to incidents or operational needs. The admin interface offers robust capabilities for managing multiple clients independently, allowing for the assignment of unique analytical needs and specific project/pilot particularities. This ensures a tailored approach to each client's requirements, accommodating their distinct operational contexts and data characteristics.

Conversely, the CLIENT role is designed for end users who interact with the platform’s core features within boundaries defined by their permissions. CLIENT users can typically view and manage their own data, engage with services offered by CREMA, and perform risk and resilience analysis relevant to their specific use case. However, their access is intentionally limited, protecting sensitive system functions and information from unauthorized modification or exposure. This ensures that CLIENT users enjoy a seamless and secure experience while upholding the platform’s broader security and compliance objectives.

By clearly delineating the capabilities of ADMIN and CLIENT users through role-based policies and middleware enforcement, CREMA creates a controlled environment where each individual’s access aligns precisely with their role, reducing risk and supporting both operational efficiency and robust data protection.

5.3. HARDWARE AND SOFTWARE REQUIREMENTS

A robust and reliable deployment of CREMA depends not only on strong authorization mechanisms but also on well-defined hardware and software requirements. The underlying infrastructure plays a critical role in ensuring optimal performance, scalability, and security of the platform. Thoughtful selection of hardware and software components enables seamless integration with the application’s architecture, while supporting the demands of concurrent users, background processing, and secure data management. From the choice of web and application servers to the configuration of databases, session storage, and caching solutions, each layer of the environment must be carefully aligned with best practices and platform needs. The following outlines the essential hardware and software prerequisites for deploying CREMA, offering guidance for administrators and engineers seeking to establish a solid operational foundation.

5.3.1. DEPLOYMENT & HOSTING

When deploying CREMA, it is crucial to consider a meticulously designed infrastructure that supports both the immediate and future needs of the platform. The synergy between hardware and software components underpins CREMA’s ability to deliver seamless user experiences, maintain high availability, and uphold rigorous security standards. Below, we provide a comprehensive overview of the recommended technology stack and deployment considerations for CREMA, highlighting the roles and benefits of each system component.

At the foundation of CREMA's web architecture lies the choice of **web server**, with **Nginx** or **Apache** serving as the preferred options. Both servers are capable of handling modern PHP applications efficiently; however, Nginx is often favoured for its performance and ability to manage high levels of concurrent traffic, while Apache offers extensive configurability and compatibility with legacy systems. Regardless of the selection, running **PHP 8.3** or newer is essential. PHP 8.3 brings significant performance improvements and security enhancements, ensuring that the underlying application layer operates reliably and efficiently. The use of **PHP-FPM** (FastCGI Process Manager) further optimizes request handling, allowing for faster execution and better resource management, which is particularly beneficial when scaling to meet increased user demand.

The core application logic for CREMA is powered by **Laravel**, a robust PHP framework renowned for its elegant syntax, modularity, and comprehensive ecosystem. Laravel's architecture facilitates rapid development, clear separation of concerns, and seamless integration with various backend services. Coupled with PHP-FPM, Laravel delivers optimal performance while maintaining flexibility for future enhancements. This combination empowers development teams to push updates and implement new features with minimal disruption to users.

To support asynchronous processing and enhance overall responsiveness, CREMA employs a **queue worker** system. Background jobs, such as processing uploads, or handling data synchronization, are offloaded to dedicated queue workers utilizing **Redis** or a database queue driver. Redis, an in-memory data structure store, is particularly well-suited for high-throughput queue management due to its low latency and robust pub/sub capabilities. In scenarios where Redis is unavailable, the database queue driver offers a reliable alternative, though with some trade-offs in performance. This architecture ensures that resource-intensive operations do not impede the user experience, allowing for smooth and scalable service delivery.

Data persistence and integrity are cornerstones of any enterprise platform. CREMA relies on a **self-hosted MySQL 8.x** database, which provides advanced capabilities such as improved security, better performance, and enhanced support for JSON and spatial data types. Self-hosting the database offers organizations greater control over configuration, backup strategies, and compliance requirements, allowing for fine-tuned optimizations tailored to CREMA's unique workload.

Session management and caching are vital for application speed and user experience. **Redis** is the preferred solution for both session storage and caching due to its exceptional performance, atomic operations, and support for advanced data structures. By leveraging Redis, CREMA can efficiently manage user sessions, cache frequently accessed data, and reduce database load, collectively contributing to faster page loads and improved scalability. Where Redis is not feasible, **file-based or database-backed session** and cache storage options are available, offering flexibility across a range of deployment environments.

Authentication and authorization remain at the heart of platform security. CREMA integrates with an **external OAuth provider (RINA)** to enforce modern authentication flows, including secure token management and delegated access. This externalization of authentication not only streamlines user management but also supports single sign-on (SSO) capabilities, allowing organizations to centralize identity and access control while reducing administrative overhead.

On the frontend, CREMA harnesses a modern build process powered by **Vite**, which enables rapid asset compilation, hot module replacement, and efficient bundling for production. This approach ensures that static assets, such as CSS and JavaScript, are delivered quickly and reliably to end users, regardless of their device or network conditions. JavaScript interactivity is further enhanced through **Livewire**, a Laravel framework that facilitates dynamic UIs without extensive client-side scripting. By rendering components on the server and transmitting only the necessary updates, Livewire simplifies development and reduces the potential for frontend vulnerabilities.

File **storage** represents another critical aspect of CREMA's operational blueprint. The platform provides flexible storage options, supporting both local disk and cloud-based solutions such as **Amazon S3**. Local disk storage is suitable for deployments with modest storage needs or where regulatory requirements dictate data residency. For larger-scale or distributed deployments, cloud storage offers virtually unlimited capacity, built-in redundancy, and geographic flexibility. This dual approach empowers organizations to tailor their storage strategy to specific business needs, balancing cost, performance, and compliance.

In summary, a successful CREMA deployment rests on the thoughtful orchestration of its underlying infrastructure:

- Web Server: Nginx or Apache with PHP 8.3+ for robust, high-performance request handling.
- App Server: Laravel powered by PHP-FPM, ensuring efficient execution and clear application logic.
- Queue Worker: Redis or database-driven background job processing, enabling scalable asynchronous workflows.
- Database: Self-hosted MySQL 8.x, providing secure, high-performance data management.
- Session & Cache: Redis preferred for optimal performance, with fallback to file or database solutions.
- OAuth Provider: Integration with external providers (e.g., RINA) for secure authentication and access control.
- Frontend Assets: Built with Vite and dynamically rendered via Livewire for a modern, responsive UI.
- Storage: Local or cloud-based file and media storage, accommodating both regulatory and operational requirements.

By meticulously aligning each layer of the deployment environment with CREMA's architectural vision, organizations can ensure a platform that is not only performant and scalable but also secure and adaptable to evolving business needs. This attention to infrastructure detail underpins the ongoing success of CREMA, providing a reliable foundation for innovation and growth.

5.4. SECURITY & BEST PRACTICES

In the rapidly evolving landscape of web applications, security and operational discipline are not mere afterthoughts, they are foundational pillars upon which trust, reliability, and long-term success are built. Within the CREMA architecture, these priorities are deeply embedded at every layer of the stack and operational process, ensuring that the platform consistently meets both technical and regulatory demands.

- **Comprehensive CSRF protection**

Cross-Site Request Forgery (CSRF) is a well-known web vulnerability that can compromise user data and system integrity by tricking users into executing unwanted actions on a trusted site. CREMA leverages Laravel's robust built-in mechanisms to mitigate this threat. Every form submission and state-altering request within the application is automatically assigned a CSRF token, which Laravel validates before processing the request. This systematic tokenization, seamlessly integrated into session management, ensures that only legitimate, user-initiated actions are executed, safeguarding against unauthorized or malicious commands.

- **Systematic output escaping**

Another critical layer of defence is systematic output escaping. The CREMA platform adheres to a principle of "escape by default," leveraging Laravel's templating engine (Blade) to automatically escape user-generated content before rendering it in the browser. This approach prevents Cross-Site Scripting (XSS) attacks, which could otherwise enable attackers to inject malicious scripts into web pages viewed by other users. By sanitizing every piece of dynamic content, CREMA tool maintains a strict boundary between trusted and untrusted data, significantly reducing the risk of client-side exploits.

- **Rate limiting on authentication routes**

Authentication endpoints are frequent targets for brute-force attacks and credential stuffing attempts. To mitigate these threats, CREMA implements rate limiting on all authentication-related routes. By restricting the number of login attempts per user or IP address within a defined timeframe, the system effectively deters automated attacks while maintaining usability for legitimate users. Laravel's built-in rate limiting middleware provides both flexibility and reliability, allowing dynamic adjustment of thresholds in response to observed traffic patterns or emerging threats. Rate limits are logged and monitored, with automatic alerts for suspicious activity, enabling rapid incident response and continuous improvement.

- **Granular access control with OAuth scopes (optional)**

Access control is a fundamental aspect of secure, multi-tenant platforms. While CREMA supports a range of external OAuth providers for streamlined authentication and authorization, it also offers optional OAuth scopes to further restrict access to sensitive APIs or functionalities. Scopes provide fine-grained control, allowing administrators to specify exactly which permissions a third-party application or user may exercise. For example, a scope might allow read-only access to user profiles, or restrict write operations to a specific dataset. This approach minimizes the blast radius of compromised credentials and supports compliance with data minimization best practices. The OAuth implementation is reviewed regularly against industry standards (such as OAuth 2.0 and OpenID Connect), and scope management is integrated with the broader policy enforcement framework.

- **HTTPS enforcement across all endpoints**

The security of data in transit is non-negotiable. CREMA enforces HTTPS across all endpoints, leveraging modern TLS configurations to ensure the confidentiality and integrity of every request and response. By redirecting all HTTP traffic to secure HTTPS connections and employing strong ciphers, the platform protects against eavesdropping, man-in-the-middle attacks, and session hijacking. SSL/TLS certificates are managed via automated renewal processes, and regular audits are conducted to identify and remediate any potential weaknesses in transport-layer security.

- **Rigorous input validation with FormRequest classes**

User input is a common vector for attacks ranging from SQL injection to business logic abuse. CREMA addresses this challenge through the disciplined use of Laravel's FormRequest validation classes. Every incoming request that accepts user input is validated against clearly defined rules, ensuring that only well-formed and authorized data is processed by the application logic. Custom validation rules are created for complex scenarios, and error responses are standardized to provide clarity without leaking sensitive information. This layer of defence not only prevents malicious payloads but also improves overall data quality and robustness of the system.

- **Comprehensive policy enforcement – Filament and API routes**

Authorization is enforced consistently across both user interfaces (such as those built with Filament) and API routes. Laravel's policy classes define the business logic governing access to all resources—whether it's viewing a dashboard, editing a record, or invoking an administrative API. These policies are tested extensively and updated in tandem with evolving business requirements. By unifying policy enforcement across all entry points, CREMA ensures that privilege escalation and unauthorized actions are systematically prevented. Audit trails and access logs are maintained for all sensitive operations, providing accountability and traceability for compliance audits.

Through these layered security controls and operational best practices, CREMA provides a resilient, compliant, and user-centric platform. Clients and end users can trust that their data, workflows, and innovations are protected by industry-leading safeguards, while development teams are empowered to deliver new features quickly and securely. This holistic approach to security not only supports regulatory compliance but also underpins the agility and reputation of organizations building on CREMA's foundation.

6. OUTPUTS FOR OTHER WPS

This deliverable, and particularly the CREMA tool, has significant implications across multiple tasks and work packages within the MULTICLIMACT project.

There is a close collaboration and continuous dialogue with Task 7.3 to ensure that the tool remains user-friendly and aligned with practical requirements. This collaborative approach facilitates ongoing feedback and iterative improvements, resulting in a solution tailored to user needs.

Within WP11, the tool will be tested in a variety of contexts and scales:

- T11.1 (Camerino): The primary focus is on building-scale testing, while also considering potential applications at broader spatial scales.
- T11.2 (Barcelona): Urban-scale testing is conducted to verify the tool's applicability and robustness in metropolitan environments.
- T11.3 (The Hague): The tool undergoes territorial-scale assessment, ensuring its adaptability to regional contexts and diverse urban fabrics.
- T11.4: Testing returns to both building and urban scales, with particular attention to the tool's potential for cultural heritage conservation and management.

Additionally, there are strong connections with WP14, specifically Tasks 14.1 and 14.2. These tasks will focus on thoroughly reviewing and refining the tool following the completion of the various testing phases, ensuring its reliability, usability, and effectiveness for all end-users.

This interdependency between tasks and work packages not only reinforces the tool's robustness but also promotes a holistic, user-centred approach to its ongoing development and deployment.

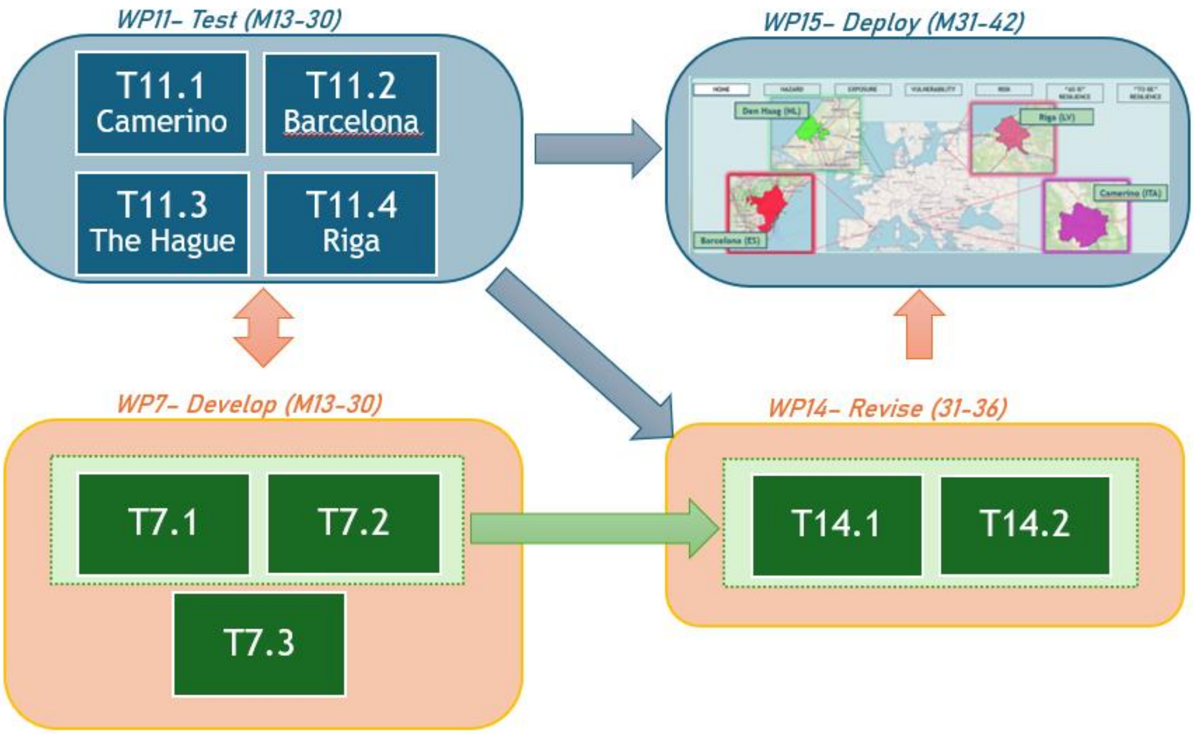

Figure 6-A. CREMA tool development process – next step

7. CONCLUSION

As the project advances through its latest phases, it is essential to reflect on the progress achieved and the insights gained throughout the development of the CREMA tool.

Methodological enhancements have already been integrated into the CREMA tool's development and will continue to play a crucial role during the upcoming test phase. As the tool undergoes real-world trials across various scales and contexts, further opportunities will arise to refine and strengthen the methodology. For instance, by integrating dynamic feedback loops between the outcomes of risk assessments and subsequent tool improvements, we can rapidly adapt to emerging vulnerabilities and address the specific needs of stakeholders for their individual case studies. Scenario-based modelling, introduced during testing, will enable users to visualise how different strategies may affect resilience over time, aiding in informed decision-making. By continually linking risk assessment outputs with resilience metrics throughout the testing phase, the CREMA tool can evolve to address both current hazards and future challenges, ensuring it remains a responsive and sustainable solution. By incorporating elements from the ARCH framework and emphasizing co-creation, the CREMA tool can evolve into a more robust and inclusive resilience-building instrument. Early findings from the first three workshops reinforce the value of iterative development and stakeholder engagement.

The CREMA tool has been shaped by a rigorous development process, guided by flexibility, user-centric design, and technical robustness. Early development stages centred on designing algorithms capable of handling data from a wide spectrum of applications, ensuring that the tool would be adaptable to various spatial and thematic contexts. Iterative prototyping and consultations with end-users, ensured capturing input from T7.3, allowed the project team to refine the user interface, optimize workflows, and improve data integration. Emphasis was placed on creating a platform that could support both granular and wide-reaching analyses, enabling users to navigate seamlessly between building-scale assessments and broader territorial evaluations. Users can create various "AS IS" (current state) scenarios, each tailored to a specific significant hazard. For every scenario, they can then associate a list of adaptation actions. This capability allows users to test and evaluate different strategies aimed at improving resilience and reducing overall risk.

Throughout development, feedback from stakeholders and domain specialists informed enhancements to the tool's architecture. This collaborative approach helped identify practical needs and emerging challenges, enabling the development team to embed features that promote usability and responsiveness. The result is a multifunctional tool, capable of supporting cultural heritage management, urban resilience planning, and disaster risk assessment. By integrating new technologies and maintaining an open channel with the user community, the CREMA tool stands as a robust, adaptable, and future-ready solution for diverse operational environments.

The next project phase, will focus on real-world testing (WP11) across multiple scales and contexts, validating both the methodology and the tool's performance. These trials, designed to mirror the diverse environments in which the tool will be deployed, offer invaluable insights into how the system responds to practical challenges and user demands. The feedback generated throughout this process is critical for WP14, where all lessons learned will be used to revise and refine the tool, ensuring it meets evolving user needs and technical standards.

8. LITERATURE /REFERENCES

ARCH Project. *Report on Co-Creating the ARCH HUB and ARCH RAD (ARCH Deliverable D3.6)*. 2021, https://savingculturalheritage.eu/resources/deliverables#c1058.

ARCH Project. *ARCH Disaster Risk Management Framework (Deliverable 7.3)*. 2020, https://savingculturalheritage.eu/resources/deliverables#c1058.

Australian Institute for Disaster Resilience, 2020. "National Emergency Risk Assessment Guidelines (NERAG)". Australian Institute for Disaster Resilience. https://www.aidr.org.au/media/7600/aidr_handbookcollection_nerag_2020-02-05_v10.pdf

Bai, L., Woodward, A., Cirendunzhu, Liu, Q., 2016. "County-level heat vulnerability of urban and rural residents in Tibet", China. Environmental Health, 15(3). https://doi.org/10.1186/s12940-015-0081-0

Bakhsh, K., Rauf, S., Zulfiqar, F., 2018. "Adaptation strategies for minimizing heat wave induced morbidity and its determinants". Sustainable cities and society, 41, 95-103. https://doi.org/10.1016/j.scs.2018.05.021

Bao, J., Li, X., & Yu, C., 2015. "The construction and validation of the heat vulnerability index, a review". International Journal of Environmental Research and Public Health, 12(7), 7220-7234. https://doi.org/10.3390/ijerph120707220

Barriopedro, D., García-Herrera, R., Ordóñez, C., Miralles, D.G.,Salcedo-Sanz, S,. 2023. “Heat waves: Physical understanding and scientific challenges. Reviews of Geophysics”. 61.e2022RG000780. https://doi.org/10.1029/2022RG000780.

Blauhut, V., Stahl, K., Stagge, J. H., Tallaksen, L. M., De Stefano, L., Vogt, J., 2016. "Estimating drought risk across Europe from reported drought impacts, drought indices, and vulnerability factors". Hydrology and Earth System Sciences, 20(7), 2779-2800. https://doi.org/10.5194/hess-20-2779-20161

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O’Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., von Winterfeldt, D., 2003. "2A framework to quantitatively assess and enhance the seismic resilience of communities". Earthquake Spectra, 19(4), 733-752. https://doi.org/10.1193/1.16234971.

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, Paper No. 472, Vol. 43, No. 3, September 2006, pp. 75-104.

Carrão, H., Naumann, G., Barbosa, P., 2016. "Mapping global patterns of drought risk: An empirical framework based on sub-national estimates of hazard, exposure and vulnerability". Global Environmental Change, 39, 108-124 https://doi.org/10.1016/j.gloenvcha.2016.04.012

Christoforou, R., Lange, S., Schweiker, M., 2024. “Individual differences in the definitions of health and well-being and the underlying promotional effect of the built environment”. Journal of Building Engineering, 84, 108560.

Cimellaro G. P., Kammouh O., Gardoni P., 2019. “Resilience assessment of dynamic engineering systems”. MATEC Web Conferences 281, 01008.

Cimellaro, G. P., Reinhorn, A. M., Bruneau, M., 2010. "Framework for analytical quantification of disaster resilience". Engineering Structures, 32(11), 3639-3649. https://doi.org/10.1016/j.engstruct.2010.08.008

Collins S.E., Malone D.K., Clifasefi S.L., 2013. "Housing retention in single-site housing first for chronically homeless individuals with severe alcohol problems". Am J Public Health. 2013 Dec;103 Suppl 2(Suppl 2):S269-74. doi: 10.2105/AJPH.2013.301312. Epub 2013 Oct 22. PMID: 24148063; PMCID: PMC3969126.

Cornell C.A., Jalayer F., 2003. "A technical framework for probability-based demand and Capacity Factor Design (DCFD) Seismic Formats". PEER 2003/08.

Cornell, C.A., Krawinkler, H., 2000. "Progress and challenges in seismic performance assessment", PEER Center News, Spring 2000.

D'Ayala, D., Meslem, A., Vamvatsikos, D., Porter, K., & Rossetto, T., 2014. "Guidelines for Analytical Vulnerability Assessment of Low/Mid-Rise Buildings". GEM Technical Report 2014-12. Global Earthquake Model Foundation, Pavia, Italy. DOI: 10.13117/GEM.VULN-MOD.TR2014.12

Federal Emergency Management Agency, 2013a. Hazus-MH2.1, Multihazard Loss Estimation Methodology, Earthquake Model Technical Manual, Federal Emergency Management Agency

Federal Emergency Management Agency, 2020. Hazus Earthquake Model Technical Manual (Version 4.2). https://www.fema.gov/sites/default/files/2020-10/fema_hazus_earthquake_technical_manual_4-2.pdf

Fekete, A., Damm, M., Birkmann, J., 2010. "Scales as a challenge for vulnerability assessment". Natural Hazards. 55. 729–747. 10.1007/s11069-009-9445-5.

Fisher R.E., Bassett G. W., Buehring W. A., Collins M. J., Dickinson D.C., Eaton L.K., Millier D.J., 2010. "Constructing a resilience index for the enhanced critical infrastructure protection program". Argonne Decision and Information Sciences.

Fuggini C., Basso A., Basso P., 2019. "Critical Infrastructure Resilience and Protection Study – Risk Assessment and Criticality Identification Methodology".

Galasso, C., Pregnolato, M., Parisi, F., 2021. "A model taxonomy for flood fragility and vulnerability assessment of buildings". International Journal of Disaster Risk Reduction Volume 53 (2021) 101985. https://doi.org/10.1016/j.ijdrr.2020.101985

Gibson, C. C., Ostrom, E., Ahn, T. K., 2000. "The concept of scale and the human dimensions of global change: a survey". Ecological Economics 32:217-239. https://doi.org/10.1016/S0921-8009(99)00092-0

Global Water Partnership Central and Easter Europe, 2015. "Guidelines for the preparation of Drought Management Plans. Development and implementation in the context of the EU Water Framework Directive, Global Water Partnership Central and Eastern Europe".

Golparvar-Fard, M., Balali, V., and de la Garza, J., 2012. "Segmentation and Recognition of Highway Assets Using Image-Based 3D Point Clouds and Semantic Texton Forests." Journal of Computing in Civil Engineering

Grünthal, G., 1998. “European Macroseismic Scale 1998.”

Guttman, N.B., 1999. “Accepting the standardized precipitation index: a calculation algorithm. Jawra Journal of the American Water Resources Association” 35: 311-322. https://doi.org/10.1111/j.1752-1688.1999.tb03592.x.

Hagenlocher, M., Naumann, G., Meza, I., Blauhut, V., Cotti, D., Döll, P.,Ehlert, K., Gaupp, F., Van Loon, A.F., Marengo, J.A., Rossi, L., Sabino Siemons, A.S., Siebert, S., Tsehayu, A.T., Toreti, A., Tsegati, D., Vera, C., Vogt, J., Wens, M., 2023. "Tackling growing drought risks—The need for a systemic perspective". Earth's Future, 11, e2023EF003857. https://doi.org/10.1029/2023EF003857

Häring, I., Sansavini, G., Bellini, E., Martyn, N., Kovalenko, T., Kitsak, M., Vogelbacher, G., Ross, K., Bergerhausen, U., Barker, K., Linkov, I.,2017. "Towards a generic resilience management, quantification and development process: General definitions, requirements, methods, techniques and measures, and case studies". In I. Linkov & J. M. Palma-Oliveira (Eds.), Resilience and Risk (pp. 21-80). Springer. https://doi.org/10.1007/978-94-024-1123-2_2

He, C., Ma, L., Zhou, L., Kan, H., Zhang, Y., Ma, W., Chen, B., 2019. "Exploring the mechanisms of heat wave vulnerability at the urban scale based on the application of big data and artificial societies". Environment International, 127, 573-583. https://doi.org/10.1016/j.envint.2019.01.057

Heaton, M.J., Sain, S.R., Greasby, T.A., Uejio, C.K., Hayden, M.H., Monaghan, A.J., Boehnert, J., Sampson, K., Banerjee, D., Nepal, V., Wilhelmi, O.V., 2014. “Characterizing urban vulnerability to heat stress using a spatially varying coefficient model”. Spatial and Spatio-temporal Epidemiology. Volume 8, April 2014, Pages 23-33. ISSN 1877-5845, https://doi.org/10.1016/j.sste.2014.01.002.

Hill, M., Rossetto, T., 2008. "Comparison of building damage scales and damage descriptions for use in earthquake loss modelling in Europe". Bulletin of Earthquake Engineering, 6, 335-365.

Huizinga, J., de Moel, H., Szewczyk, W., 2017. "Global flood depth-damage functions: Methodology and the database with guidelines". Publications Office of the European Union. https://doi.org/10.2760/16510

Iervolino, I. (2022). Estimation uncertainty for some common seismic fragility curve fitting methods. Soil Dynamics and Earthquake Engineering, 152, 107068. *https://doi.org/10.1016/j.soildyn.2021.107068*IPCC, 2021, “Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change” [Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

IPCC, 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" [Pörtner, H.-O., Roberts, D.C. , Tignor,M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf,S., Löschke, S., Möller, V., Okem, A., Rama, B. (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.

ISO 55000 series (2014); ISO 55000 Asset management — Overview, principles and terminology; ISO 55001 Asset management — Management systems — Requirements; ISO 55002 Asset management — Management systems — Guidelines for the application of ISO 55001.

Jain, V. K., Pandey, R. P., Jain, M. K., 2015. "Spatio-temporal assessment of vulnerability to drought". Natural Hazards, 76(1), 443-469. https://doi.org/10.1007/s11069-014-1502-z

Jenerette, D., Wu, J., 2000. "On the Definitions of Scale". Bulletin of the Ecological Society of America. DOI:10.2307/20168403.

JRC Guidelines to Risk and Resilience Assessment of Critical Infrastructures ; 2015.

Kasperson, J., Kasperson, R., 2001. "Global Environmental Risk". Environmental Science, Sociology, Philosophy. DOI:10.4324/9781849776196.

Marston, S.A., 2000. "The social construction of scale". SAGE Journals. Volume 24, Issue 2. https://doi.org/10.1191/0309132006740862

Mazdiyasni, O., AghaKouchak, A., Davis, S. J., Madadgar, S., Mehran, A., Ragno, E., Sadegh, M., Sengupta, A., Ghosh, S., Dhanya, C. T., & Niknejad, M., 2017. "Increasing probability of mortality during Indian heat waves". Science Advances, 3(6), e1700066. https://doi.org/10.1126/sciadv.1700066

McKee, T. B., Doesken, N. J., Kleist, J., 1993. "The relationship of drought frequency and duration of time scales". Eighth Conference on Applied Climatology, American Meteorological Society, Jan17-23, 1993, Anaheim CA, pp.179-186.

McKee, T. B., Doesken, N. J., Kleist, J., 1995. "Drought monitoring with multiple time scales". Ninth Conference on Applied Climatology, American Meteorological Society, Jan15-20, 1995, Dallas TX, pp.233-236.

Meletti C., Montaldo V., 2007. Stime di pericolosità sismica per diverse probabilità di superamento in 50 anni: valori di ag. Progetto DPC-INGV S1, Deliverable D2, http://esse1.mi.ingv.it/d2.html

Merz, B., Hall, J., Disse, M., Schumann, A., 2010. "Fluvial flood risk management in a changing world". Natural Hazards and Earth System Sciences, 10(3), 509-527. https://doi.org/10.5194/nhess-10-509-2010

Mishra, V., Ganguly, A.R., Nijssen, B., Lettenmaier, D.P., 2015. "Changes in observed climate extremes in global urban areas". Environmental Research Letters, Volume 10, Number 2. DOI 10.1088/1748-9326/10/2/024005.

MIT (Italian Ministry of Infrastructures and Transports),2020. "Linee guida per la classificazione e gestione del rischio, la valutazione della sicurezza ed il monitoraggio dei ponti esistenti; Italy.

National Research Council. 2015. "Tying flood insurance to flood risk for low-lying structures in the floodplain". National Academies Press.

Nofal, O. M., van de Lindt, J. W. (2020). "High-resolution approach to quantify the impact of building-level flood risk mitigation and adaptation measures on flood losses at the community-level". International Journal of Disaster Risk Reduction, 51, 101903. https://doi.org/10.1016/j.ijdrr.2020.101903

Nofal, O. M., van de Lindt, J. W., Do, T. Q., 2020. "Multi-variate and single-variable flood fragility and loss approaches for buildings". Reliability Engineering & System Safety, 202, 106971. https://doi.org/10.1016/j.ress.2020.106971

O'Reilly, G. J., & Shahnazaryan, D. (2023). Fitting improved hazard models for SAC/FEMA-compatible seismic analysis. In 14th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP14). Scuola Universitaria Superiore IUSS.

Ogunrinde, A.T., Oguntunde, P.G., Olasehinde, D.A., Fasinmirin, J.T., Akinwumiju, A.S.,2020. "Drought spatiotemporal characterization using self-calibrating Palmer. Drought Severity Index in the northern region of Nigeria". Results in Engineering 5 (2020) 10008. DOI:10.1016/j.rineng.2019.100088

Ouellet Dallaire C., Lehner B., Sayre R., Thieme M., 2018. "A multidisciplinary framework to derive global river reach classifications at high spatial resolution". Environmental Research Letters. doi: 10.1088/1748-9326/aad8e9 (open access).

Ozarisoy, B., Elsharkawy, H., 2019. "Assessing overheating risk and thermal comfort in state-of-the-art prototype houses that combat exacerbated climate change in UK". Environmental Science, Engineering. DOI:10.1016/J.ENBUILD.2019.01.030

Pandey, R. P., Pandey, A., Galkate, R. V., Byun, H.-R., Mal, B. C., 2010. "Integrating hydro-meteorological and physiographic factors for assessment of vulnerability to drought". Water Resources Management, 24(13), 4199-4217. https://doi.org/10.1007/s11269-010-9653-5

PEER (2006), OpenSEES ; Opens System for Earthquake Simulation ; Pacific Earthquake Engineering Research Center, University of California, USA.

Pitilakis, K., 2015. "Earthquake Risk Assessment: Certitudes, Fallacies, Uncertainties and the Quest for Soundness. Geotechnical, Geological and Earthquake Engineering." 39. 59-95. 10.1007/978-3-319-16964-4_3.

Poljanšek, K., Casajus Valles, A., Marin Ferrer, M., De Jager, A., Dottori, F., Galbusera, L., Garcia Puerta, B., Giannopoulos, G., Girgin, S., Hernandez Ceballos, M., Iurlaro, G., Karlos, V., Krausmann, E., Larcher, M., Lequarre, A., Theocharidou, M., Montero Prieto, M., Naumann, G., Necci, A., Salamon, P., Sangiorgi, M., Sousa, M. L, Trueba Alonso, C., Tsionis, G., Vogt, J., and Wood, M., 2019. "Recommendations for National Risk Assessment for Disaster Risk Management in EU ", EUR 29557 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-79-98366-5 (online), doi:10.2760/084707 (online), JRC114650

Reid, C.E., Mann, J.K, Alfasso, R., English, P.B., King, G.C., Lincoln, R.A., Margolis, H.G., Rubado, D.J., Sabato, J.E., West, N.L., Woods, B., Navarro, K.M., Balmes, J.R., 2009. "Evaluation of a Heat Vulnerability Index on Abnormally Hot Days: An Environmental Public Health Tracking Study". Environmental Health Perspectives, Volume 120, Issue 5, Pages 715 – 720. https://doi.org/10.1289/ehp.110376

Rød, B., Lange, D., Theoharidou, M., Pursiainen, C., 2020. "From Risk Management to Resilience Management in Critical Infrastructure". Journal of Management in Engineering. 36. Doi10.1061/(ASCE)ME.1943-5479.0000795.

Rohat, G., Wilhelmi, O., Flacke, J., Monaghan, A., Gao, J., Dao, H., van Maarseveen, M., 2019. "Characterizing the role of socioeconomic pathways in shaping future urban heat-related challenges". Science of The Total Environment, 695, 133941. https://doi.org/10.1016/j.scitotenv.2019.133941

Rossi, L., Wens, M., De Moel, H., Cotti, D., Sabino Siemons, A., Toreti, A., Maetens, W., Masante, D., Van Loon, A., Hagenlocher, M., Rudari, R., Naumann, G., Meroni, M., Avanzi, F., Isabellon, M., Barbosa, P., 2023. "European Drought Risk Atlas". Publications Office of the European Union. DOI: 10.2760/608737.

Rossi, L., Wens, M., De Moel, H., Cotti, D., Sabino Siemons, A.S., Toreti, A., Maetens,W., Masante, D., Van Loon, A., Hagenlocher, M., Rudari, R., Meroni, M., Isabellon, M., Avanzi, F., Naumann, G., Barbosa P. "European Drought Risk Atlas, Publications Office of the European Union". Luxembourg, 2023, doi:10.2760/608737, JRC135215.

Rosvold, E., Buhaug, H., 2021. "Geocoded Disasters (GDIS) Dataset. Palisades, New York: NASA Socioeconomic Data and Applications Center (SEDAC)". https://doi.org/10.7927/zz3b-8y61.

Schneider, D.P., Deser, C., Fasullo J., Trenberth, K. E., 2013. "Climate Data Guide Spurs Discovery and Understanding. Eos Trans" AGU, 94, 121–122, https://doi.org/10.1002/2013eo130001.

Schwarz, J., Maiwald, H., 2007. "Berücksichtigung struktureller Schäden unter Hochwassereinwirkung", Bautechnik 84:7, 450 – 46.

Schweiker, M.,2022. "Rethinking resilient thermal comfort within the context of human-building resilience. Routledge Handbook of Resilient Thermal Comfort", 23-38.

Sewell R.T., Toro G.R., McGuire R.K., 1999. "Impact of ground motion characterization on conservatism and variability in seismic risk estimates". NUREG/CR-6467. Nuclear Regulatory Commission Washington. USA.

Sousa,M.L., Tsionis, G., 2019. "Recommendation for a National Risk Assessment for Disaster Risk Management in EU - Approaches for identifying, analysing and evaluating risk". JRC Science for policy report. Version 0. Cap.9, 56-67.

Tefera, Y., Hailu, Y., & Siraj, Z., 2019. "Potential of agroforestry for climate change mitigation through carbon sequestration". Agricultural Research Technology Open Access Journal, 22, 556196.

Tigkas, D., Vangelis, H., & Tsakiris, G., 2015. "DrinC: a software for drought analysis based on drought indices". Earth Science Informatics, 8, 697-709. doi:10.1007/s12145-014-0178-y1.

Tigkas, D., Vangelis, H., Tsakiris, G., 2012. "Drought and climatic change impact on streamflow in small watersheds". Science of the Total Environment, 440: 33-41

Tigkas, D., Vangelis, H., Tsakiris, G., 2017. "An Enhanced Effective Reconnaissance Drought Index for the Characterisation of Agricultural Drought". Environ. Process. 4 (Suppl 1), 137–148 (2017). https://doi.org/10.1007/s40710-017-0219-x

Tigkas, D., Vangelis, H., Tsakiris, G.,2019. "Drought characterisation based on an agriculture-oriented standardised precipitation index". Theor Appl Climatol 135(3-4):1435-1447. https://doi.org/10.1007/s00704-018-2451-3

Tingting, W., Fubao, S., "Integrated drought vulnerability and risk assessment for future scenarios: An indicator based analysis, Science of The Total Environment" Volume 900, 2023, 165591, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2023.165591.

United Nations Department of Economic and Social Affairs, and United Nations Institute for Training and Research. 2020. “Stakeholder Engagement and the 2030 Agenda: A Practical Guide”. UNDESA & UNITAR.

United Nations Development Programme. 2021. “Methodology for Assessment, Modelling, and Mapping for Georgia”. UNDP.

United Nations Office for Disaster Risk Reduction (UNDRR), 2015. “Global Assessment Report on Disaster Risk Reduction (GAR)”. ISBN/ISSN/DOI 9789211320428

United Nations Office for Disaster Risk Reduction (UNDRR), 2016. “UNISDR annual report”. United Nations

United Nations Office for Disaster Risk Reduction. 2021. "GAR Special Report on Drought 2021". Geneva, Switzerland: UNDRR.

University of Oxford, Environmental Change Institute. (2024). “Climate Data 111+ : Synthesis of Hazard Data Sources (Version 1*)*”. https://www.eci.ox.ac.uk/research/tools-and-datasets

Vangelis, H., Tigkas, D., & Tsakiris, G., 2013. "The effect of PET method on Reconnaissance Drought Index (RDI) calculation". Journal of Arid Environments, 88, 130-140.

Verkade, J. S., & Werner, M. G. F., 2011. Estimating the benefits of single value and probability forecasting for flood warning. Hydrology and Earth System Sciences, 15, 3751-3765. *https://doi.org/10.5194/hess-15-3751-2011*

Wang, T., Sun, F., 2023. "Integrated drought vulnerability and risk assessment for future scenarios: An indicator based analysis"". Science of The Total Environment. Volume 900, 20 November 2023, 165591. https://doi.org/10.1016/j.scitotenv.2023.165591"

World Meteorological Organization. 1992. "International Meteorological Vocabulary". 2nd ed. Secretariat of the World Meteorological Organization.

Yihdego, Y., Vaheddoost, B., Al-Weshah, R. A., 2019. "Drought indices and indicators revisited". Arabian Journal of Geosciences, 12(69). https://doi.org/10.1007/s12517-019-4237-z

Zarei, A.R., Moghimi, M.M., 2019. "Modified version for SPEI to evaluate and modeling the agricultural drought severity". Int J Biometeorol 63, 911–925 (2019). https://doi.org/10.1007/s00484-019-01704-2

Zebisch, M., Renner, K., Pittore, M., Fritsch, U., Fruchter, S. R., Kienberger, S., Schinko, T., Sparkes, E., Hagenlocher, M., Schneiderbauer, S., Delvis., J.L., 2023. “Climate Risk Sourcebook. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH”. Bonn.

9. ANNEX

9.1. RESILIENCE SCORE QUESTIONS

Building on the methodology outlined in paragraph 3.2.1, Table 9 serves as a practical guide to understanding how each resilience factor—spanning the categories of Preparation, Internal Resourcefulness, and External Resourcefulness—is systematically anchored to targeted scorecard items. This table provides a detailed overview of the alignment between the resilience factors used in the MULTICLIMACT project and the specific questions from the Resilience Scorecard that underpin them.

INDICATIVE MEASUREMENT SCALE			
0 - WORST	1	2	3 - BEST

Legend of measurement colour scale

REF. NO.	QUESTION	ANSWER					
P1: Existence and status of emergency plans							
9.2.1	Is there a detailed and up-to-date plan for the building/city/ territory for dealing with disasters - processes, procedures, responsibilities and roles, equipment, communication channels and contents, etc?	**No plans.**	Plans exist but may be outdated or incomplete. May be outdated or incomplete/have **significant deficiencies**, in terms of coverage, fitness for purpose, detail/specificity and obsolescence.	Plans exist but may **not cover all necessary aspects** or be fully up-to-date.	Plans exist with efforts to establish processes, procedures, responsibilities and roles, equipment, communication channels and contents, etc., although there may be **some gaps or areas for improvement.**	Plans which are **fairly detailed and up-to-date**, covering a range of processes, procedures, responsibilities and roles, equipment, communication channels and contents, etc. exist, although **may not be reviewed annually.**	**Fully detailed and up to date plans** exist that address all impacts and are critically reviewed at least annually, and it includes a potential historic areas emergency plan.
P2: Frequency of training course/exercise							
6.1.5	Is resilience training offered and regularly updated to the administration or to the building management?	**No resilience training** is offered to the administration or building management.	Resilience training courses are currently **under development.**	**Some resilience training** is offered, but it is **not consistently updated.**	Resilience training is **occasionally** offered and updated, providing **basic knowledge and skills** to the administration or building management.	Resilience training is **regularly offered** but it is **updated at very long intervals.**	**Comprehensive and regularly updated** resilience training is **systematically offered** to the administration or building management.

6.1.6	How often are trainings repeated?	Trainings are **never repeated.**	Trainings are repeated **very rarely**, with **long intervals** between sessions.	Trainings are repeated **occasionally**, with **inconsistent intervals** between sessions.	Trainings are **repeated periodically**, with **some regularity** in scheduling.	Trainings are **repeated regularly**, with **consistent intervals** between sessions.	Trainings are **repeated frequently and consistently**, ensuring continuous learning and reinforcement of knowledge and skills.
9.5.1	Do regular drills exist for first responders and are they effective?	**No drills** in the last two years.	**Ad hoc partial exercises** - not all scenarios tested, most relevant entities not included, or not realistic.	**Drills do not happen annually** and may not be complete or realistic (scenarios, relevant entities). Performance is not reported.	**Regular** tests and drills but they **may not include a number of relevant entities.** Performance is not reported.	**Regular (at least annual)** drills take place to generally test all emergency response and test interoperability with at least **some relevant entities.** Performance may not be assessed and reported.	**Regular (at least annual)** drills take place to fully test all emergency response plans and skills, and test interoperability with **all other relevant entities.** Performance is assessed and reported. All professional and public participants in drills show strong evidence of having absorbed training.
9.5.2	Do regular drills for disasters for the public exist and include all vulnerable groups and are information about these drills freely accessible?	**No drills** in the last two years.	**Ad hoc partial exercises** - not all scenarios tested, only a small part of the public is involved.	**Drills do not happen regularly** and may not be complete or realistic (scenarios, relevant entities) and only a part of the public is involved.	**Regular** tests and drills but they may **not include a large part of the public.**	**Regular** drills take place to generally test all emergency response aspects and is accessible to **almost the whole public.**	**Regular** drills take place to fully test all relevant emergency response plans and skills and test interoperability with **all other relevant entities.** The public including **all vulnerable groups** is included and information about the drills can be easily accessed.

P3: Insurance cover							
3.2.2	To what extent are damages to the building/city/territory covered by insurance? (Personal or life coverage is not assessed)	There is **no insurance** coverage for damages.	Coverage for damages is **minimal or insufficient**.	**Some damages** are covered by insurance, but coverage may be **limited or inadequate** for comprehensive protection.	Damages are **moderately covered (<80%)** by insurance, providing some protection but with **potential gaps**.	The **majority of damages (80-100%)** are covered by insurance, offering significant financial protection in case of disasters or accidents **with minimal gaps**.	Insurance coverage is **extensive and comprehensive**, ensuring that nearly all potential damages to the building/city/territory are covered, providing robust financial protection.
P4: Existence of backup systems							
8.2.3	Do the building/urban area/territory have a backup system in case of water supply failure?	**No backup** in case of water supply failure exist.	Only a **partial backup** system exists and it is significantly exposed to the disaster for which it may be required.	A backup system exists only to support **critical functions** and for **24 hours.** The backup elements may not be located entirely securely.	A backup system exists only to support **critical functions** and for **72 hours.** The backup elements may not be located entirely securely.	A backup system exists to support **all functions** for at least **24 hours.** The backup elements are located safely.	A backup system exists to support **all functions** for at least **72 hours.** The backup elements are located safely.
8.3.3	Do the building/urban area/territory have a redundant power supply feed and or backup power?	**No backup** power supply.	**Partial backup** power via secondary supply or renewable sources for some functions; this is significantly exposed to the disaster for which it may be required.	Reliable backup power supply for **critical functions** only, for **24 hours** and is also exposed in its own right.	Reliable backup power supply for **critical functions** only, for **72 hours**; it may not be entirely safely located.	A backup power supply to support **all functions** for at least **24 hours** exists. The supply is itself located safely.	A backup power supply to support **all functions** for at least **72 hours** exists. The backup supply is itself located safely.

8.4.3	Do the building/urban area/territory have a redundant backup system in case of gas supply failure?	**No backup** power supply.	**Partial backup** power via secondary supply or renewable sources for some functions; this is significantly exposed to the disaster for which it may be required.	Reliable backup power supply for **critical functions** only, for **24 hours** and is also exposed in its own right.	Reliable backup power supply for **critical functions** only, for **72 hours**; it may not be entirely safely located.	A backup power supply to support **all functions** for at least **24 hours** exists. The supply is itself located safely.	A backup power supply to support **all functions** for at least **72 hours** exists. The backup supply is itself located safely.
8.5.3	Do the building/urban area/territory have an alternative system in case of waste management failure?	**No alternative systems** in place to serve as backups	There are **minimal alternative systems** in place as backups, but they are insufficient to fully mitigate waste management failures.	**Some alternative systems** are in place to serve as backups in case of waste management failures, but they may not cover all necessary functions adequately.	Alternative systems are **moderately implemented** as backups, providing reasonable redundancy to address waste management failures.	**A significant array** of alternative systems is in place as backups, offering robust redundancy to effectively manage waste management failures.	Alternative systems are **extensively implemented** as backups, ensuring comprehensive redundancy and continuity of waste management functions.
8.7.2	Are there alternative systems in place to serve as backups in the event of communication system failures?	**No alternative systems** in place to serve as backups.	There are **minimal** alternative systems in place as backups, but they are insufficient to fully mitigate communication system failures.	**Some alternative systems** are in place to serve as backups in case of communication system failures, but they may not cover all necessary functions adequately.	Alternative systems are **moderately implemented** as backups, providing reasonable redundancy to address communication system failures.	**A significant array** of alternative systems is in place as backups, offering robust redundancy to effectively manage communication system failures.	Alternative systems are **extensively implemented** as backups, ensuring comprehensive redundancy and continuity of communication functions in the event of system failures.

8.8.2	In case of a disaster, to what extent can care be maintained for those who are already sick or dependent?	Care of existing patients **would fail completely** or almost completely.	There are **some efforts** to maintain care for those who are already sick or dependent during a disaster, but **resources and support are insufficient**.	Measures are in place to **partially maintain** care for those who are already sick or dependent in the event of a disaster, but gaps exist in preparedness and response.	Care for those who are already sick or dependent is **moderately maintained** during a disaster.	Efforts are made to ensure **substantial care** for those who are already sick or dependent in the event of a disaster.	Care for those who are already sick or dependent is **fully ensured** during a disaster, with comprehensive and robust plans, resources, and protocols in place to provide uninterrupted support and meet their needs comprehensively.
8.8.3	In case of a disaster, to what extent can the continuity of educational schools be ensured?	The continuity of educational schools is **minimally ensured** in the event of a disaster, with little to no contingency plans or preparations in place.	There are **some efforts** to ensure the continuity of educational schools during a disaster, but they are insufficient to guarantee uninterrupted operations.	Measures are in place to **partially ensure** the continuity of educational schools in the event of a disaster, but gaps exist in preparedness and response.	The continuity of educational schools is **moderately ensured** during a disaster, with adequate contingency plans and preparations to maintain essential functions.	Efforts are made to ensure the **substantial continuity** of educational schools in the event of a disaster, with comprehensive plans and resources to maintain operations.	The continuity of educational schools is **fully ensured** during a disaster, with comprehensive and robust plans, resources, and protocols in place to guarantee uninterrupted operations and support the well-being of students and staff.
P5: Community experienced a significative hazardous event							
6.1.1	Are skills, experience and knowledge in disaster risk management and climate change adaptation (including cultural heritage management) present in the management/ administration?	There are **no skills, experience, or knowledge** in disaster risk management or climate change adaptation.	**Minimal** skills, experience, or knowledge exist in disaster risk management or climate change adaptation, but they are **inadequate** for effective action.	**Some skills**, experience, and knowledge in disaster risk management and climate change adaptation are present, but they are limited and require	There is a **moderate level** of skills, experience, and knowledge in disaster risk management and climate change adaptation, contributing to **some degree of effectiveness**.	Skills, experience, and knowledge in disaster risk management and climate change adaptation are present at a **sufficient level**.	The management/ administration possesses **extensive skills**, experience, and knowledge in disaster risk management and climate change adaptation, including cultural heritage management, ensuring robust capabilities in addressing related challenges.

				further development.			
6.1.2	Are available skills, experience and knowledge in disaster risk management and climate change adaptation regularly inventoried?	Key skills, experience and knowledge are **not inventoried.**	Key skills, experience and knowledge are **not inventoried**, but corresponding **plans are being developed** to do so.	**Some key skills**, experience and knowledge are inventoried, but **not updated regularly**.	**Most key skills**, experience and knowledge are inventoried, but **not updated regularly.**	**Most key skills,** experience and knowledge are inventoried and **updated regularly.**	**All available key skills**, experience and knowledge are inventoried and regularly updated.
P6: Warning time before the hazardous event							
9.1.2	How sufficient is the warning time and how reliable are warnings - do they allow practical actions to be taken?	The **warning time is insufficient**, providing little to no opportunity for practical actions to be taken.	There is **minimal warning time** provided, and warnings are **unreliable**, thus likely to be ignored.	Warning time is **shorter than required (<1h)** and there may also be some **false positives** making it challenging to take practical actions.	There is **moderate warning time (<12h)** provided, and warnings are **generally reliable**, allowing for some practical actions to be taken, although there may be **occasional shortcomings.**	The warning time is **fairly sufficient (<24h)**, and warnings are **mostly reliable**, enabling practical actions to be taken in a timely manner, although there may be **minor issues**.	There is **ample warning time** provided **(≥24h)** , and warnings are **highly reliable**, allowing for practical actions to be taken effectively and ensuring preparedness for potential hazards.
P7: Specific countermeasures							
4.4.1	Is sustainable procurement considered at a building/city/territory level?	Sustainable procurement is **not considered.**	Consideration of sustainable procurement is **minimal or sporadic.**	There are **some efforts** to consider sustainable procurement, but they are **not comprehensive or consistent.**	Sustainable procurement is **moderately considered**, with some initiatives and efforts underway, although **improvements are needed.**	Sustainable procurement is **fairly considered**, with **significant initiatives** and efforts contributing to sustainable practices.	Sustainable procurement is **comprehensively considered** with robust initiatives and support at all levels of procurement practices.

8.1.1	Do protective structural measures for climate-related and non-climate related hazards exist and are regularly maintained?	There are **no protective structural** measures in place.	**Very few** protective structural measures exist, but they are **limited in scope and effectiveness**, and there are **hardly ever maintained.**	**Some** protective structural measures are in place, but **maintenance is inconsistent.**	Protective structural measures are **moderately present and maintained,** though there may be **occasional lapses or deficiencies.**	There is a **significant and regularly maintained array** of protective structural measures, with **minor maintenance issues** being addressed promptly.	Protective structural measures are **extensive and comprehensive** for both climate-related and non-climate-related hazards, with **robust maintenance protocols** in place to ensure continual effectiveness and resilience.
8.1.4	Are digital solutions implemented to enhance climatic and non-climatic resilience?	**No digital solution** implemented.	Digital solutions are **minimally implemented** to enhance resilience, with very limited application and effectiveness.	Some digital solutions are implemented, but their **deployment may be inconsistent or incomplete.**	Digital solutions are **moderately implemented** to enhance resilience.	A **significant array** of digital solutions is implemented to enhance resilience.	Digital solutions are **extensively implemented** to enhance resilience comprehensively, providing innovative and adaptive approaches to address both climatic and non-climatic resilience needs.
Int1: Early warning system							
9.1.1	Do warning systems exists? Are they for single hazards or multi-hazards?	**No warning system** exists.	**There are plans** to include warning systems but they still don't exist.	Warning systems **exist for just one hazard.**	Warning systems **exist for few hazards.**	Warning systems exists and are in function **for all the hazards** hitting the territory.	Warning systems exists, are in function for **all the hazard** hitting the territory and they **regularly monitored** for the function.

Int2: Available material to offset the loss							
9.3.3	Are equipment and supply needs identified, available and regularly reviewed?	**No equipment and supply needs identified**, or no review within last 3 years.	Needs definition is only **nominal or guesswork**. Rudimentary efforts to review equipment needs and availability.	Equipment and supply **needs definition**, availability and revisions have **gaps and shortcomings**.	Some needs defined but with **some gaps** for specific professions or geographic areas. Some significant gaps in review and availability and/or interval is longer than once per year.	Equipment and supply needs are **defined. Most equipment** is reviewed at least once per year.	**Needs defined** either based on actual historic events or from practice drills, also taking into account the role of volunteers. **All safety and emergency equipment** reviewed at least once per year.
9.4.1	How large is the "shelter gap", i.e. the number of persons potentially in need of shelter minus the number of shelter places available within 24 hours?	Estimated shelter gap is **disastrous.**	Estimated shelter gap is **significant.**	Estimated shelter gap is **moderate.**	Estimated shelter gap is **minor.**	Available shelter places are **at least equal** to estimated needs.	Available shelter places **exceed** estimated needs.
9.4.2	Are depots available and able to withstand disaster events and remain safe and usable?	**All depots** are assessed as unlikely to withstand the event.	**A large number of depots** is assessed as unlikely to withstand the event.	**A medium number of depots** is assessed as unlikely to withstand the event.	**A small number of depots** is assessed as unlikely to withstand the event.	**Only a very limited number of depots** is assessed as unlikely to withstand the event.	**All depots are assessed as likely to withstand the event.**

Ext1: Mutual agreements and exercises with relevant institutions and organizations							
6.3.1	Are learning and cross-fertilization activities actively pursued with other cities, territories, and organizations to foster knowledge exchange and innovation?	**No learning or cross-fertilization activities** are pursued with other entities.	There are **minimal efforts** towards learning or cross-fertilization activities, which are **sporadic and largely ineffective**.	**Some learning** and cross-fertilization activities exist, but they **lack consistency and depth**, resulting in limited knowledge exchange and innovation.	Learning and cross-fertilization activities are **moderately pursued**, with periodic exchanges and collaborations, but there are some **major shortcomings**.	Learning and cross-fertilization activities are **fairly regular and comprehensive**, with few **minor shortcomings**, fostering considerable knowledge exchange and innovation.	Learning and cross-fertilization activities are **highly effective**, with comprehensive strategies, ongoing collaborations, and regular exchanges ensuring significant knowledge exchange and innovation, thereby enhancing overall development.
6.3.2	Is the administration/ management actively engaging with relevant working groups, communities of practice, practitioners, and local administration networks to collaborate on shared challenges and advance collective goals?	**No engagement** is happening.	**Networking is limited**, resulting in constrained collaboration potential.	There are **occasional exchanges**, more ad hoc in nature, with diffuse impact and benefits that are harder to identify.	Reliance is mainly on **individual practitioners networking** with their peers in other organizations, with frequent exchanges and some attempt to capture and implement learnings.	**Regular exchanges** occur, often within other meetings, leading to sharing of best practices as a side-effect. Outcomes are captured, and some impact is identified on disaster preparedness.	**Annual exchanges** with other cities and regions specifically to share resilience best practices, responses, and learnings. Changes made in the city as a result are evident. Additionally, regular peer-to-peer contacts with practitioners in other organizations supplement these efforts.

Ext2: Coordination with public units and local government institution							
9.3.1	Does an emergency operations centre exist, with participation from all relevant agencies/ entities? Does it have automated standard operating procedures?	**No emergency operations center** is established.	An emergency operations center is designated but has **significant general shortcomings**, and **minimal participation** from different agencies/ entities.	An emergency operations center exists, but its **standard operating procedure is unproven**, and **few agencies participate**.	Emergency operations centre exists with established standard operating procedures, but **only some agencies** participate.	An emergency operations center exists with **established standard operating procedures**, with **most relevant agencies/ entities** participating.	An emergency operations center exists with **established standard operating procedures**, and **all relevant agencies/ entities** participate.
Ext3: Coordination with hospitals with special treatment units							
8.8.1	In case of a disaster, to what extent are hospitals and emergency care centers able to manage a sudden influx of patients?	**No surge capacity identified.**	Surge capacity is **theoretically available** but has never been assessed or tested.	Surge capacity exists but is known to have **significant shortcomings** in geographical coverage or type of service available, and can only be activated **within 12 hours or longer.**	Surge capacity exists with **identified shortcomings** in geographical coverage or type of service available, and can be activated within **6-12 hours.**	Surge capacity exists with **minor shortcomings** in geographical coverage or type of service available, and can be activated within **3-6 hours.**	Surge capacity exists to **deal with additional health needs** and is tested either via actual events or practice drills - can be activated **within 0-3 hours,** ensuring rapid response to patient influx.
8.8.2	In case of a disaster, to what extent can care be maintained for those who are already sick or dependent?	Care of existing patients **would fail completely** or almost completely.	There are **some efforts** to maintain care for those who are already sick or dependent during a disaster, but **resources and support are insufficient.**	Existing measures provide **partial** continuity of care during disasters, but preparedness and response remain insufficient.	Care for those who are already sick or dependent is **moderately maintained** during a disaster.	Efforts are made to ensure **substantial care** for those who are already sick or dependent in the event of a disaster.	Care for those who are already sick or dependent is **fully ensured** during a disaster, with comprehensive and robust plans, resources, and protocols in place to provide uninterrupted support and meet their needs comprehensively.

Table 9. Resilience interview

9.2. SELECTION OF KPIS FOR EACH PILOT

In the following pages, a comprehensive overview of all potential KPIs relevant to the assessment of resilience is presented for each pilot. This synthesis has been developed according to the assessment framework outlined in T1.2 (Ricciardi, 2024).

KPIs for Resilience Assessment

Resilience qualities
- Robustness
- Redundancy
- Resourcefulness
- Rapidity

Resilience dimensions
- Physical
- Human health
- Environmental
- Organisational
- Digital
- Economic

Location
Camerino, Italy

Scale
Building

Users
- building owners and managers (both public and private)

Climatic and non-climatic hazards
- Extreme precipitations and storms
- Extreme Heat
- Earthquake

Systems
- People
- Building
- Cultural Heritage

Solutions to reduce risks and increase resilience

Materials and Technologies
- Self-sensing EECs for monitoring general structural health and external loads,
- Multifunctional mortar with low environmental impact

Digital solutions
- Multi-purpose tool for environmental and structural behavior monitoring of buildings
- Decision Support System for prevention and damage estimation of natural extreme events consequences at multiple scales

Robustness
- RO1 Seismic Stability Index (SSI)
- RO2 predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD)
- RO3 Flood Resilience Index (FRI)
- RO4 Robustness Index
- RO5 Robustness indicator for buildings
- RO6 Enhanced Structural and Non-structural design
- RO7 Reduction in Peak Site Power Demand Intensity
- RO8 Cool surfaces in proportion to the number of dwellings
- RO9 Drainage system capacity

Redundancy
- RE1 Purchasing generator or PV systems that allows islading
- RE2 Pumping backup systems
- RE3 Redundancy Indicator (RI) for Extreme Heat
- RE4 Conduct peer review
- RE5 MEP Review
- RE6 Temporary shelter availability
- RE7 Redundancy and Structural Robustness of Electric Distribution Systems

Resourcefulness
- RF1 Fundamental access to first aid, emergency supplies, water, food, and communication
- RF2 Available Budget for Building Refurbishment
- RF3 Local resourcefulness

Rapidity
- RA1 Wet-bulb globe temperature (WBGT)
- RA2 Recovery factor
- RA3 Recovery Time
- RA4 Recovery Time Indicator (RTI) for Extreme Heat
- RA5 Downtime assessment
- RA7 Recovery Capacity
- RA8 Time to recovery adequate level of Land Surface Temperature
- RA9 Mean time to repair
- RA10 Psychological distress

Cost-Benefit Analysis
- CBA1 Injuries and casualties
- CBA2 Adaptation Protection Cost Index (APCI)
- CBA3 Avoided injuries and casualties
- CBA4 Damages for building materials
- CBA5 Avoided damage for building materials
- CBA6 Damages for building materials, structures and systems due to extreme precipitations and earthquake
- CBA7 Damages for building systems
- CBA8 Avoided damage for building systems
- CBA9 Damages for building due to natural hazards
- CBA10 Avoided damage for buildings
- CBA11 Adaptation benefits

Operational and Construction cost
- OC1 General Construction Cost Index (GCCI)
- OC2 Maintenance Cost Efficiency Index (MCEI)

Digital for Resilience
- DR1 Hours outside comfort temperature
- DR2 Occurrence probability of a certain consequence
- DR3 Thermal transmittance
- DR4 Seismic resistance
- DR5 Energy demand and consumption of the systems
- DR6 Floodwater Depth
- DR7 Ambient temperature
- DR8 Surface temperature of pavement
- DR9 Global solar radiation
- DR10 Permeability and infiltration rate
- DR11 Operational Continuity
- DR12 Mean Time of Recovery
- DR13 Mean Time for Mitigation
- DR14 Structural redundancy

Capacity of Digital Tech
- DC1 Inventory of Assets covered by the digital solution
- DC2 Probability of Detection (POD)
- DC3 False alarm ratio
- DC4 Probability of false detection (false alarm rate)
- DC5 Success ratio
- DC6 ROC curve
- DC7 Mean lead time

Resilience dimensions

Physical
RO1, RO4, RO5, RO6, RO7, RO8, RO9, RE1, RE2, RE3, RE4, RE5, RE6, RE7, RA4, RA5, RA7, RA8, RA9

Human
RO2, RO3, RA1, RA2, RA3, RA10, CBA1, CBA3

Environment

Organizational
RF1, RF2, RF3

Digital
DR1, DR2, DR3, DR4, DR5, DR6, DR7, DR8, DR9, DR10, DR11, DR12, DR13, DR14, DC1, DC2, DC3, DC4, DC5, DC6, DC7

Economic
CBA2, CBA4, CBA5, CBA6, CBA7, CBA8, CBA9, CBA10, CBA11, OC1, OC2

KPIs for Resilience Assessment

Resilience qualities
Robustness | Redundancy | Resourcefulness | Rapidity

Resilience dimensions
Physical | Human health | Environmental | Organisational | Digital | Economic

Location
Barcelona, Spain

Scale

Users
local administrations (district, city)
infrastructures owners and managers (both public and private)

Climatic and non-climatic hazards
Extreme precipitations and storms
Extreme Heat

Systems
People
Urban
Infrastructure

Solutions to reduce risks and increase resilience

Materials and Technologies
- cool recycled pavement;
- bioswale.

Digital solutions
Data-driven and physics-based characterization of thermal and energy solutions at the district level

Robustness
- RO1 Flood Resilience Index (FRI)
- RO2 Cool surfaces in proportion to the number of dwellings
- RO3 Drainage system capacity
- RO4 The resilience capacity of people
- RO5 Urban drainage stormwater robustness

Redundancy
- RE1 Temporary shelter availability

Resourcefulness
- RF1 Fundamental access to first aid, emergency supplies, water, food, and communication
- RF2 Local resourcefulness
- RF3 Resourcefulness index RFS

Rapidity
- RA1 Recovery Time Indicator (RTI) for Extreme Heat
- RA2 Time to recovery adequate level of Land Surface Temperature
- RA3 Insurance policies covering catastrophic risks, including flood risk
- RA4 Mean time to repair
- RA5 Psychological distress
- RA6 Sweat rate

Cost-Benefit Analysis
- CBA1 Injuries and casualties
- CBA2 Adaptation Protection Cost Index (APCI)
- CBA3 Avoided injuries and casualties
- CBA4 Damages for building materials
- CBA5 Avoided damage for building materials
- CBA6 Damages for building materials, due to extreme precipitations
- CBA7 Adaptation benefits
- CBA8 Potential loss of lives

Operational and Construction cost
- OC1 General Construction Cost Index (GCCI)
- OC2 Maintenance Cost Efficiency Index (MCEI)

Digital for Resilience
- DR1 Occurrence probability of a certain consequence
- DR2 Floodwater Depth
- DR3 Ambient temperature
- DR4 Surface temperature of pavement
- DR5 Global solar radiation
- DR6 Permeability and infiltration rate
- DR7 Hours outside comfort temperature
- DR8 Mean Time of Recovery
- DR9 Mean Time for Mitigation

Capacity of Digital Tech
- DC1 Inventory of Assets covered by the digital solution
- DC2 Probability of Detection (POD)
- DC3 False alarm ratio
- DC4 Probability of false detection (false alarm rate)
- DC5 Success ratio
- DC6 ROC curve
- DC7 Mean lead time

Resilience dimensions
- Physical: RO1, RO2, RO3, RO5, RE1, RA1, RA2, RA4
- Human: RO4, RA5, RA6, CBA1, CBA3, CBA8
- Environment: —
- Organizational: RF1, RF2, RF2, RA3
- Digital: DR1, DR2, DR3, DR4, DR5, DR6, DR7, DR8, DR9, DC1, DC2, DC3, DC4, DC5, DC6, DC7
- Economic: CBA2, CBA4, CBA5, CBA6, CBA7, OC1, OC2

KPIs for Resilience Assessment

Resilience qualities: Robustness, Redundancy, Resourcefulness, Rapidity

Resilience dimensions: Physical, Human health, Environmental, Organisational, Digital, Economic

Location
Leidschendam-Voorburg and Roermond, The Netherlands

Scale
Territorial

Users
- local administrations (metropolitan, provincial or regional level)
- infrastructures owners and managers (both public and private)

Climatic and non-climatic hazards
- Extreme precipitations and storms
- Drought

Systems
- Urban
- Territorial

Solutions to reduce risks and increase resilience

Materials and Technologies
- Fiber optics monitoring system for flood and drought barriers and peat dikes

Digital
- Early warning monitoring solutions for flood defense systems during flood and drought episodes

Robustness
- RO1 Shannon Diversity Index
- RO2 Practical Moisture Buffer Value
- RO3 Drainage system capacity
- RO4 Forest Resistance
- RO5 Lines tripped / Hours
- RO6 Relative efficiency ratio of pipeline network
- RO7 Road network resilience
- RO8 The resilience capacity of people
- RO9 Urban drainage stormwater robustness

Resourcefulness
- RF1 Medium and average farm size with insurance coverage
- RF2 Fundamental access to first aid, emergency supplies, water, food, and communication
- RF3 Local resourcefulness
- RF4 Resourcefulness index RFS

Redundancy
- RE1 Road density in the flood plain
- RE2 Conduct peer review
- RE3 Study + design for long term adaptability, diversity + redundancy
- RE4 Temporary shelter availability
- RE5 Functional redundancy for freshwater systems
- RE6 Redundancy and Structural Robustness of Electric Distribution Systems
- RE7 Network redundancy index
- RE8 Redundancy and Structural Robustness of Water Distribution Systems

Rapidity
- RA1 Water pumps per unit cropland area and rural labor loss
- RA2 Downtime assessment
- RA3 Insurance policies covering catastrophic risks, including flood risk
- RA4 Forest recovery
- RA5 Mean time to repair

Cost-Benefit Analysis
- CBA1 Loss of harvested crop yields per hectare
- CBA2 Adaptation Protection Cost Index (APCI)
- CBA3 Avoided loss of harvested crop yields per hectare
- CBA4 Damages for building due to natural hazards
- CBA5 Avoided damage for building
- CBA6 Damages for Electric Distribution Networks due to natural hazards
- CBA7 Adaptation benefits
- CBA8 Damages for Gas Distribution Networks due to natural hazards
- CBA9 Damages for Highways and Railroads due to natural hazards
- CBA10 Potential loss of lives
- CBA11 Avoided injuries and casualties
- CBA12 Damages for Water Distribution Networks due to natural hazards

Operational and Construction cost
- OC1 General Construction Cost Index (GCCI)
- OC2 Maintenance Cost Efficiency Index (MCEI)
- OC3 General measure cost
- OC4 Intervention costs

Digital for Resilience
- DR1 Occurrence probability of a certain consequence
- DR2 Floodwater Depth
- DR3 Operational Continuity
- DR4 Mean Time of Recovery
- DR5 Mean Time for Mitigation
- DR6 Structural redundancy

Capacity of Digital Tech
- DC1 Inventory of Assets covered by the digital solution
- DC2 Probability of Detection (POD)
- DC3 False alarm ratio
- DC4 Probability of false detection (false alarm rate)
- DC5 Success ratio
- DC6 ROC curve
- DC7 Mean lead time

Resilience dimensions

Physical: RO1, RO2, RO3, RO5, RO6, RO7, RO9, RE1, RE4, RE5, RE6, RE7, RE8, RA1, RA2, RA5

Human: RO8, CBA10, CBA11

Environment: RO4, RA4, CBA1

Organizational: RF1, RF2, RF3, RF4, RE2, RE3, RA3

Digital: DR1, DR2, DR3, DR4, DR5, DR6, DC1, DC2, DC3, DC4, DC5, DC6, DC7

Economic: CBA2, CBA3, CBA4, CBA5, CBA6, CBA7, CBA8, CBA9, CBA12, OC1, OC2, OC3, OC4

KPIs for Resilience Assessment

Resilience qualities: Robustness, Redundancy, Resourcefulness, Rapidity

Resilience dimensions: Physical, Human health, Environmental, Organisational, Digital, Economic

Location
Riga, Latvia

Scale
Building

Users

- building owners and managers (both public and private)

Climatic and non-climatic hazards

- Extreme precipitations and storms
- Extreme Heat

Systems

- People
- Building
- Cultural Heritage

Solutions to reduce risks and increase resilience

Materials and Technologies

- Passive Low temperature heating and passive cooling systems for adapting buildings (including cultural heritage) to global warming

Digital solutions

- Climate-proofing energy planning solution

Robustness

- RO1 predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD)
- RO2 Flood Resilience Index (FRI)
- RO3 Robustness Index
- RO4 Robustness indicator for buildings
- RO5 Reduction in Peak Site Power Demand Intensity
- RO6 Cool surfaces in proportion to the number of dwellings
- RO7 Drainage system capacity

Redundancy

- RE1 Purchasing generator or PV systems that allows islading
- RE2 Pumping backup systems
- RE3 Redundancy Indicator (RI) for Extreme Heat
- RE4 Conduct peer review
- RE5 Temporary shelter availability

Resourcefulness

- RF1 Fundamental access to first aid, emergency supplies, water, food, and communication
- RF2 Available Budget for Building Refurbishment
- RF3 Local resourcefulness
- RF4 Insurance policies covering catastrophic risks, including flood risk

Rapidity

- RA1 Wet-bulb globe temperature (WBGT)
- RA2 Recovery factor
- RA3 Recovery Time Indicator (RTI) for Extreme Heat
- RA4 Downtime assessment
- RA5 Recovery Capacity

Cost-Benefit Analysis

- CBA1 Injuries and casualties
- CBA2 Adaptation Protection Cost Index (APCI)
- CBA3 Avoided injuries and casualties
- CBA4 Damages for building materials
- CBA5 Avoided damage for building materials
- CBA6 Damages for building materials, structures and systems due to extreme precipitations
- CBA7 Damages for building systems
- CBA8 Avoided damage for building systems
- CBA9 Damages for building due to natural hazards
- CBA10 Avoided damage for buildings
- CBA11 Adaptation benefits

Operational and Construction cost

- OC1 General Construction Cost Index (GCCI)
- OC2 Maintenance Cost Efficiency Index (MCEI)

Digital for Resilience

- DR1 Hours outside comfort temperature
- DR3 Thermal transmittance
- DR5 Energy demand and consumption of the systems
- DR6 Floodwater Depth

Capacity of Digital Tech

- DC1 Inventory of Assets covered by the digital solution
- DC2 Probability of Detection (POD)
- DC3 False alarm ratio
- DC4 Probability of false detection (false alarm rate)
- DC5 Success ratio
- DC6 ROC curve
- DC7 Mean lead time

Resilience dimensions

- Physical: RO3, RO4, RO5, RO6, RO7, RE1, RE2, RE3, RE4, RE5, RA3, RA4, RA5
- Human: RO1, RO2, RA1, RA2, CBA1, CBA3
- Environment: –
- Organizational: RF1, RF2, RF3, RF4
- Digital: DR1, DR2, DR3, DR5, DR6, DR7, DR8, DR9, DR10, DR11, DR12, DR13, DR14, DC1, DC2, DC3, DC4, DC5, DC6, DC7
- Economic: CBA2, CBA4, CBA5, CBA6, CBA7, CBA8, CBA9, CBA10, CBA11, OC1, OC2

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multiclimact

D7.1 – MULTICLIMACT CREMA TOOL

Technical set-up and development

ANNEX A

SEPTEMBER 2025 | RINA Consulting S.p.A. (RINA-C)

MULTICLIMACT
D7.1 - MULTICLIMACT CREMA TOOL TECHNICAL SET-UP AND DEVELOPMENT - ANNEX A

Project Title	MULTI-faceted CLIMate adaptation ACTions to improve resilience, preparedness and responsiveness of the built environment against multiple hazards at multiple scales
Project Acronym	MULTICLIMACT
Contract Number	101123538
Project Coordinator	Rina Consulting S.p.A.
WP Leader:	National Center for Scientific Research “Demokritos”

Deliverable	D7.1 – MULTICLIMACT CREMA tool technical set- up and development - ANNEX A
DoA	Task 7.1 - CREMA tool development - Assessment of the current resilience of built environment assets Task 7.2 - CREMA tool development - integration of the MULTICLIMACT toolkit of Design, Materials and Technologies, and Digital solutions
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Due date	30.09.2025
Report date	26.09.2025
Version	1.0

Document classification	SEN Sensitive

Co-funded by
the European Union

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1. INTRODUCTION

This document serves as the SEN Annex to Deliverable D7.1 – MULTICLIMACT CREMA Tool Technical Set-up and Development, providing a comprehensive outline of the calculation formulae underpinning the methodology adopted within the project. The MULTICLIMACT CREMA tool has been developed to facilitate multi-hazard climate risk assessment and adaptation planning, supporting stakeholders in making informed decisions based on robust scientific foundations.

Within this annex, each calculation formula is presented with accompanying explanations, clarifying its purpose, variables, and integration into the overall workflow of the CREMA tool.

This annex is intended primarily for technical experts, project partners, and stakeholders involved in climate risk modelling and tool development. However, it is also accessible to policy-makers and other interested parties seeking to understand the scientific basis for the tool's outputs. By providing detailed formulae and methodological notes, the annex supports both the internal validation of the MULTICLIMACT CREMA tool and its broader adoption in climate adaptation strategies.

1.1. RESILIENCE COEFFICIENT ESTIMATION

This section provides an overview of resilience coefficients and the methodology employed for their estimation within the MULTICLIMACT CREMA tool. Resilience coefficients represent quantitative measures used to assess the capacity of a system to withstand and adapt to various climate-related hazards. By means of the resilience coefficient, resilience indicators are incorporated directly into the impact analysis, ensuring that the assessment reflects the system's ability to respond and recover. Table A1, adapted from Table 8 of the deliverable, summarizes the key resilience indicators, the corresponding coefficients, and the related questions from the scorecard.

Resilience indicators			*Resilience coefficient*			*Scorecard questions*
			Peop.	Phys.	Serv.	
Preparation	P1	Existence and status of emergency plans	δ_t			9.2.1
	P2	Frequency of training course/exercise	δ_t			6.1.5 - 6.1.6; 9.5.1- 9.5.2
	P3	Insurance cover				3.2.3
	P4	Existence of backup systems			δ_{rec}	8.2.3; 8.3.3; 8.4.3; 8.5.3; 8.7.2; 8.8.2- 8.8.3
	P5	Community experienced a significative hazardous event	δ_p			6.1.1- 6.1.2
	P6	Warning time before the hazardous event	δ_p			9.1.2
	P7	Specific countermeasures	δ_{S1}	δ_{S2}	δ_{S3}	8.1.1 - 8.1.4
Resourcefulness – *Internal*	Int1	Early warning system			δ_{rec}	9.1.1

		Int2	Available material to offset the loss			δ_{rec}	9.3.3; 9.4.1- 9.4.2
	External	Ext1	Mutual agreements and exercises with relevant institutions and organizations			δ_{E1}	6.3.1-6.3.2
		Ext2	Coordination with public units and local government institutions			δ_{E1}	9.3.1
		Ext3	Coordination with hospitals with special treatment units.	δ_{E2}			8.8.1- 8.8.2

Table A1. Summary of resilience coefficient (Table 8 from D7.1)

1.1.1. Δ_T: PREPAREDNESS - EVACUATION EFFICIENCY INSIDE THE ASSET

The assessment of casualties should consider the ability of individuals within the asset to evacuate effectively. This ability generally relates to two factors:

- the presence of an emergency plan, including an evaluation of its existence and quality;
- the provision of training, which involves not only whether training occurs but also how frequently it is conducted.

According to *Li et al.* (2025), evacuation efficiency is evaluated using two factors:

- k_S represents the effectiveness of the exit in attracting people within the asset;
- k_D pertains to evacuation behaviour and the level of coordination among individuals.

δ_t [%]	worst ← k_D → best					
worst ← k_D → best	14.80	35.26	43.77	56.44	64.94	73.10
	14.80	14.80	14.80	15.99	19.81	23.11
	14.80	14.80	14.80	14.80	14.80	14.80
	14.80	14.80	14.80	14.80	14.80	14.80
	14.80	14.80	14.80	14.80	14.80	14.80
	14.80	14.80	14.80	14.80	14.80	14.80

Table A2. Training efficiency k_D

Thanks to the study of *Li et al.* (Li at al, 2025) the planning and training can be used to build a matrix which describes the preparedness effect on the number of deaths.

δ_t		TRAINING (k_D)		
		Yearly	Yes	No
PLAN (k_S)	No	0.35	0.73	1.00
	Yes	0.15	0.15	0.15
	Detailed	0.15	0.15	0.15

Table A3. δ_t coefficient: preparedness - evacuation efficiency inside the asset

1.1.2. Δ_P: PREPAREDNESS - EVACUATION EFFICIENCY AROUND THE ASSET

The second aspect of preparedness examined is community-level preparedness. The resilience coefficient plays a significant role in reflecting the actual number of individuals affected by a hazardous event. Studies indicate a correlation between warning time and the proportion of people evacuated from a given area.

EVACUATION [%]	TIME [h]	0	1	2	3	4	5	7	9	11	13	15	18	24
	Lower bound	0	0	1	3	6	10	24	40	55	67	76	84	89
	Upper bound	0	1	3	7	14	24	46	66	79	85	88	90	90

Table A4. Evacuation time range

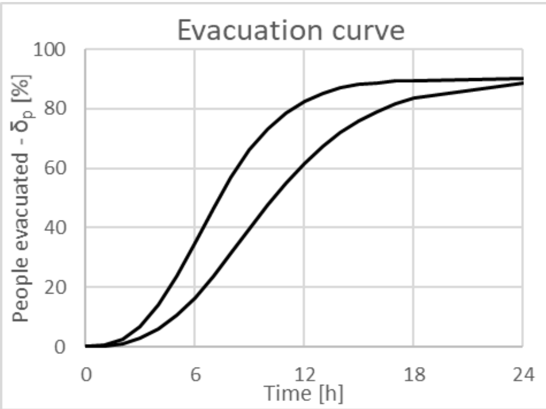

Figure A1. Evacuation curve range (see time range in Table A4)

The variability in evacuation rates is linked to a community's prior experience with hazardous events: communities familiar with certain hazards typically respond more effectively.

Therefore, the percentage of people that can be evacuated within the due time can be set according to the information derived from:

- Time passed since the last hazardous event was experienced by the community;
- The average warning time before the event.

Therefore, the two boundaries found in literature (Jonkman, 2007) can be associated with ones of the community experience, namely less than 10 years and more than 100 years. Successively the other values can be included in the just mentioned two boundaries.

According to Jonkman (2007), boundaries based on community experience are set at less than 10 years and more than 100 years since the last event, with other values falling between these limits.

δ_p		COMMUNITY EXPERIENCE			
		Extensive	Sufficient	Moderate	Minimal
WARNING TIME	< 1 hour	0.003	0.007	0.010	0.007
	< 12 hours	0.615	0.680	0.746	0.824
	< 1 day	0.885	0.891	0.897	0.900
	> 1 day	0.900	0.900	0.900	0.900

Table A5. δ_p coefficient: preparedness – evacuation efficiency around the asset

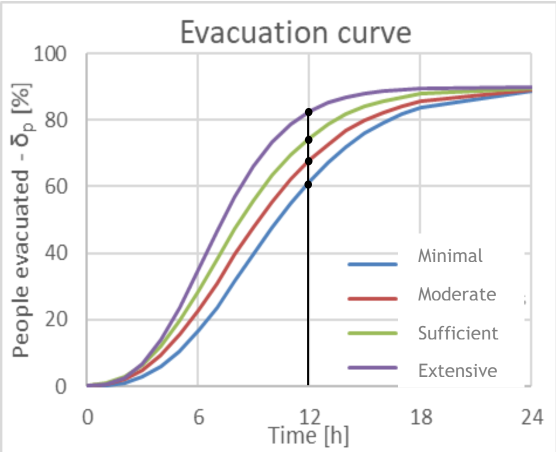

Figure A2. Evacuation curve range with boundaries

1.1.3. Δ_S: PREPAREDNESS – MEASURE SOLUTION

This coefficient takes into account the implemented countermeasures that can affect physical performance, service levels, and the human response. The impact of each solution will be examined in detail according to the specific measure adopted from the MULTICLIMACT Toolkit solutions (see §3.3 of D7.1).

1.1.4. Δ_{REC}: RECOVERY EFFICIENCY

Recovery efficiency plays a crucial role after an event, influencing the recovery process. The recovery coefficient reflects changing performance during this period and depends on the asset's internal resources and preparedness (Cimellaro et al., 2010). Selection should be based on asset datasheet details such as:

- Existence of backup system;
- Available Early Warning System;
- Existence of available material to offset the loss.

These factors help determine the variation in recovery performance, as outlined by Cimellaro et al. The economic loss corresponds to cumulative unmet needs over time, with the coefficient determined as the reciprocal of the area beneath the recovery function, $f_{rec}(t)$.

$$\delta_{rec,i} = \int 1 - f_{rec}(t)\ dt$$

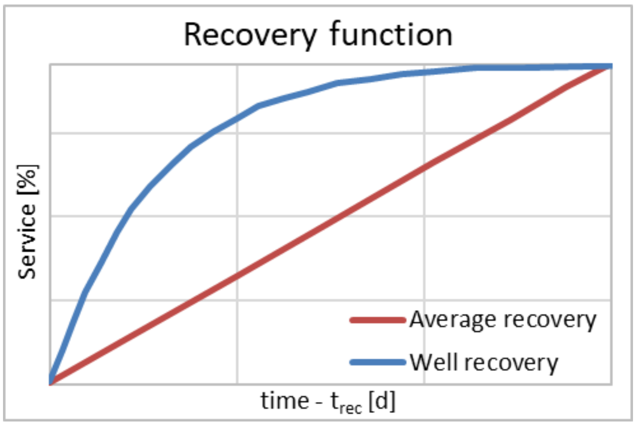

Figure A3. Service recovery function curve

Two $\delta_{rec,i}$ values are set: a lower bound of 0.19 (well) and an upper bound of 0.5 (average and not-well). The coefficient changes linearly between these bounds based on the average score for the relevant question, which ranges from 0 to 3.

$$\delta_{rec} = \delta_{rec,up} - \frac{Avg.Score}{3} \cdot (\delta_{rec,up} - \delta_{rec,down})$$

As shown in the following table an average scoring can be computed.

INTERNAL RESOURCEFULNESS & PREPAREDNESS		MATERIAL TO OFFSET THE LOSS	BACKUP SYSTEM	WARNING SYSTEM
NO		0	0	0
YES	Partly	1	3	3
	Full	3		

Table A6. δ_{rec} coefficient: recovery efficiency

1.1.5. Δ_{E1}: EXTERNAL RESOURCEFULNESS – INSTITUTION EFFICIENCY

One aspect to consider is external resourcefulness, particularly in relation to institutional efficiency. In this context, the coefficient may pertain to accessibility to a mobile healthcare post, which can maintain a level of treatment capacity even if service is reduced due to experienced damage. Accordingly, δ_{E1} may be determined based on information from the following factors:

- Mutual agreements and exercises with relevant institutions and organizations;
- Coordination with public units and local government institution.

δ_{E1}		AGREEMENTS WITH ORGANIZATION/INSTITUTION	
		YES	NO
LOCAL GOVERNMENT COORDINATION	YES	1	0.5
	NO	0.5	0

Table A7. δ_{E1} coefficient: external resourcefulness - institution efficiency

This parameter is initially assigned as a Boolean function: it is set to 1 if both questions yield positive effects, and 0 otherwise. If the two questions receive opposite answers, the value is taken as one half.

1.1.6. Δ_{E2}: EXTERNAL RESOURCEFULNESS – CARE SYSTEM EFFICIENCY

An aspect to consider is external resource coordination, particularly regarding the integration of the selected asset with the health care system. The coefficient corresponds to a hospital's ability to provide immediate care for severely injured individuals during emergencies. Thus, δ_{E2} is determined based on information from the asset datasheet, specifically:

- Coordination with hospitals with specialised treatment units.

This factor is assigned a value of 0 if coordination exists and 1 if it does not. When an agreement is in place, severely injured individuals are regarded as being adequately covered.

δ_{E2}		
COORDINATION WITH HOSPITALS	YES	0
	NO	1

Table A8. δ_{E2} coefficient: external resourcefulness - care system efficiency

2. IMPACT ASSESSMENT

The following section will examine methods for evaluating economic, direct, and indirect impacts resulting from adverse events, focusing on the immediate consequences for structures and services as well as effects on people.

2.1. DIRECT IMPACT

The impact on the physical system (ID_{DSi}) can be defined as the cost associated with direct damage sustained by the asset (Sousa and Tsionis, 2019). The economic loss can be characterized as follows:

$$ID_{DSi} = Damage_{DSi}(\%) \cdot Reconstruction\_Cost$$

In which:

- $Damage_{DSi}(\%)$ represents the damage value for each state, based on literature (Kappos et al., 2006);
- $Reconstruction\_Cost$ is the estimated expense to restore the asset to full operation, including structural and equipment costs. It can be determined either directly, from adjusted construction costs found in the asset datasheet, or indirectly, by multiplying the asset's dimensions by unit costs reported in the literature.

2.2. INDIRECT IMPACT

The impact on service continuity (IR_{DSi}) reflects how service reduction from damage affects the population (Sousa and Tsionis, 2019). Evaluation uses mean recovery time and service reduction for each damage state based on established relationships (Cimellaro et al., 2010).
As can be seen in the following formula the recovery is considered as a linear function:

$$IR_{DSi} = \delta_{E1}\delta_{rec} \cdot t_{r,DSi}(Service_{DSi}(\%) \cdot Size) \cdot Cost$$

Where:

- $Service_{DSi}(\%)$ is the percentage of service reduction per each damage state, that can be derived from literature per each damage state;
- $t_{r,DSi}$ is the recovery time, that can be derived from literature per each damage state;
- $Size$, it must be expressed by the characteristic unit of measure (e.g.,mq), which is derived from the asset datasheet.
- $Cost$, it is the economic losses for service interruption (e.g., alternative space rental value (€/smq))
- δ_{E1} (§1.1.5) is a coefficient that accounts for how easily individuals can access alternative service points when the primary service is disrupted. This value can be determined based on factors such as the presence of temporary replacement facilities, mutual aid agreements with other institutions, or coordination with local agencies to provide substitute services.
- δ_{rec} (§1.1.4) is the coefficient that accounts for how recovery efforts are handled. This value can be set based on factors such as whether backup systems exist, if early warning systems or special countermeasures are available, or if there are materials readily available to help restore services.

2.3. IMPACT ON PEOPLE

The analysis of the impact on the people is based on the evaluation of the number of fatalities and injuries (Sousa and Tsionis, 2019), due to the occurrence of a certain hazard.

The evaluation is conducted following the methodology outlined by Cimellaro et al. (2010). In their study, the percentage of fatalities and injuries is correlated with the damage state, which can subsequently be associated with the corresponding mean intensity measure (IM), as illustrated in the table below.

	U.M.	DS1	DS2	DS3	DS4
$Death_{DSi}$	%	0.000	0.000	0.0015	12.500
$Injury_{DSi}$	%	0.000	0.030	0.1005	22.500

Table A9: Normalized human losses ratios for different damage state (Cimellaro et al., 2010)

The number of deaths can be obtained multiplying the death loss ratio shown in Table A9 with the number of people inside the asset:

$$Death_{DSi} = Death_{DSi}(\%) \cdot \delta_t \cdot People\_in\_asset$$

$$Severe\_injured_{DSi} = Severe\_injured_{DSi}(\%) \cdot \delta_t \cdot People\_in\_asset$$

In which:

- $Death_{DSi}(\%)$ and $Severe\_injured_{DSi}(\%)$ are the percentages derived from Table A9;
- $People\_in\_asset$ is the number of people in the asset;
- δ_t (§1.1.1) is the coefficient of reduction that consider the effect of the asset preparedness on the people evacuation.

Therefore, the number of human life losses can be multiplied by the mean value of human life.

$$IP_{DSi} = (Death_{DSi} + \delta_{E2} \cdot Severe\_injured_{DSi}) \cdot Life\ Value$$

Where:

- The $Life\ Value$ is taken equal to 4,7 M€/person (EUROCONTROL, 2024);
- δ_{E2} (§1.1.6) represents the coordination with hospitals during an emergency.

2.4. TOTAL IMPACT

The total impact ($I_{TOT,DSi}$) is evaluated by summing the different economic losses categories per each damage state, as shown in the following formula:

$$I_{TOT,DSi} = ID_{DSi} + IR_{DSi} + IP_{DSi}$$

In which:

- ID_{DSi} is the Impact on Physical System economic loss;
- IR_{DSi} is the Impact on Service Continuity economic loss;
- IP_{DSi} is the Impact on People economic loss.