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Research to application: the evolution of the CREMA Tool across MULTICLIMACT and MedIREN projects for advancing climate resilience in Europe.

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Climate change poses growing challenges across Europe, demanding innovative, data-driven systems to translate complex data into practical strategies for resilience planning. This paper showcases the evolution of the Climate REsilience Maturity Assessment (CREMA) tool, developed under MULTICLIMACT project (GA n. 101123538), enhanced with Med-IREN project (GA n. 101157707), to advance the resilience of built environments and infrastructures against climate and natural threats.
The CREMA tool integrates deterministic and probabilistic approaches to assess climate change's risks through a structured process that includes hazard and asset characterization, vulnerability analysis, impact quantification. It considers both the actual (AS-IS) and the future (TO-BE) system state, allowing analysis across multiple timescales, spatial scales, performance dimensions for single or multiple hazards. A key feature is the translation of physical damage and secondary impacts, such as disruption and effects on the population, into estimates of economic loss, enabling cost-benefit evaluations and prioritization of resilience measures. Its purpose is to support decision-makers in understanding vulnerabilities and defining adaptation strategies based on resilience metrics.
In MULTICLIMACT the tool focused on assessing the resilience of the built environment, from buildings, cultural heritage sites, to urban areas, territories, under multiple hazards. Within Med-IREN, its scope expands to climate-proof Critical Infrastructures in the Mediterranean region, a recognized climate hotspot, covering sectors like transport, energy and addresses emerging threats including wildfires, coastal erosion, etc, going beyond traditional risks. This evolution broadens the tool's capabilities through the integration of Nature-based Solutions, data streams (Earth Observation, in-situ), multi-sectoral resilience analytics.
The advancement demonstrates the European context diversity and the CREMA tool's value in terms of scalability and transferability across geographical areas, spatial scales, infrastructural systems, climatic conditions. Through case studies, it progresses from conceptual development to operational deployment, acting as a bridge between research and decision-making to empower stakeholders in developing evidence-based climate resilience strategies.

Keywords: Climate resilience, Multi-hazard assessment, Resilience quantification, Critical infrastructure, Built environment, Decision-support tool, Cost-benefit evaluation.

1. Introduction

Climate change is increasingly intensifying climate-related and natural hazards across Europe, posing growing risks to people, ecosystems, infrastructure, and economies, and highlighting the urgency for data-driven resilience planning. Recent reports indicate that Europe is warming faster than the global average and that 2024 was the warmest year on record. Extreme heat, floods, and wildfires are causing widespread impacts, including economic damages amounting to tens of billions of euros and hundreds of thousands of people affected (EEA, 2025). Total weather- and climate-related losses have already exceeded hundreds of billions of euros in recent decades, and without effective adaptation strategies, future costs could reach tens of billions annually (EEA, 2025). In this context, tools capable of integrating heterogeneous data sources and translating complex risk information into actionable decision-support are critical. This paper presents the evolution of the Climate REsilience Maturity

Assessment (CREMA) tool as a research-to-application framework supporting resilience assessment, adaptation planning, and investment prioritisation. Originally developed within the MULTICLIMACT project to assess the resilience of the built environment, CREMA has been enhanced through the Med-IREN project to address the climate-proofing of critical infrastructures in the Mediterranean region, a recognised climate hotspot. The tool combines deterministic and probabilistic risk assessment, considers both current (AS-IS) and future (TO-BE) system conditions over the asset life cycle, and translates physical impacts and service disruptions into economic loss metrics to support cost-benefit analysis and prioritisation of interventions. By integrating multi-source data—including Earth Observation, in-situ measurements, and socio-economic indicators—CREMA provides a flexible and scalable framework for resilience assessment across diverse European contexts.

2. State of the Art on Climate Resilience

2.1. *Existing tools for the built environment climate resilience assessment*

Over the past decade, numerous assessment tools and frameworks have emerged to support the evaluation of climate resilience in built environments. Notable examples include the City Resilience Profiling Tool (CRPT) (UN-Habitat, 2018) and the City Resilience Index (Rockefeller Foundation, 2014), which offer robust diagnostics for cities facing multifaceted risks. These instruments commonly integrate hazard exposure mapping, vulnerability analyses, and adaptation strategies, providing structured methodologies for local governments and asset managers. Despite their utility, many existing tools exhibit limitations in terms of sectoral coverage, integration of multi-hazard scenarios, and flexibility for application in diverse geographic and climatic contexts, and a predominant reliance on qualitative rather than quantitative methods. Most are tailored to specific hazards or asset types, limiting their applicability. Furthermore, there is often a gap in translating technical risk assessments into actionable, economically justified adaptation strategies (Helgeson, Al Kajbaf, & Fung, 2025).

2.2. Multi-hazard assessment approaches

The growing awareness of multiple, interacting hazards in built environments has driven the creation of multi-hazard assessment methodologies. These approaches address compound and cascading hazards, such as urban heat islands amplifying drought or coastal storms compounding sea-level rise. They integrate hazard interdependencies, temporal dynamics, and cross-sectoral effects for more comprehensive risk evaluation (White, et al., 2025). However, operationalising multi-hazard assessments remains a challenge due to the complexity of modelling interactions, data limitations, and the need for interdisciplinary expertise (Reeves, O'grady, & Aldridge, 2018). Growing recognition highlights the need for tools that fully integrate diverse hazard types, properly handle uncertainties, and support scenario-based planning to guide effective adaptation strategies (White, et al., 2025).

2.3. Resilience quantification and decision-support frameworks

Quantifying resilience in tangible, decision-relevant terms is a persistent challenge in climate adaptation practice. A range of resilience metrics have been proposed to span various dimensions (such as physical, social, economic, environmental and governance) for built environments. Decision-support frameworks, such as cost-benefit analysis (CBA), multi-criteria decision analysis (MCDA), and robust decision-making (RDM), are increasingly employed to prioritise adaptation options. These frameworks facilitate the comparison of interventions under uncertainty, enabling stakeholders to weigh trade-offs and select strategies aligned with local priorities and resource constraints (Watkiss & Hunt, 2013). Nevertheless, the integration of resilience metrics with decision-support outputs is still evolving, with a need for transparent, user-friendly tools that bridge technical analysis and policy action.

2.4. Identified gaps addressed by CREMA tool

The CREMA tool distinguishes itself through its modular architecture, scalability, and adaptability to a wide spectrum of asset types and geographical contexts. This flexibility empowers users to customise hazard, vulnerability, and impact assessments according to specific needs, thereby enabling the effective implementation of resilience strategies at building, urban, and broader scales (Attanasio, et al., 2025). Although CREMA incorporates the assessment of multiple hazards, the framework developed within the MULTICLIMACT does not yet fully encompass the complex interdependencies and cascading effects among different hazards. The integration of multi-hazard interconnections remains an area for further development during Med-IREN project. Despite this, CREMA bridges the gap between technical risk and vulnerability assessments and their practical application by embedding quantitative methodologies within cost-benefit and multi-criteria decision-support modules. Through this approach, a wide range of stakeholders are provided with comprehensive tools to support informed and actionable climate adaptation planning.

3. The CREMA Tool: Conceptual Framework and Methodology

3.1. *Methodological Framework*

The CREMA tool was developed through interdisciplinary collaboration. Its architecture is modular, supporting customisation for different asset types, hazard profiles, and user requirements. The development process incorporated feedback from potential stakeholders, ensuring practical relevance and robustness. The tool employs a structured, stepwise framework for assessing risk and resilience in built environments facing multiple hazards. This methodology guides decision-makers through the identification of vulnerabilities, quantification of risks, and evaluation of the effectiveness of resilience measures. The approach is designed to be evidence-based, transparent, and adaptable to different contexts. The process includes: characterising the system and assets; identifying hazards and their characteristics; assessing vulnerability; estimating damage probabilities; aggregating impacts; calculating risk and evaluating resilience for current and improved states (Attanasio, De Maio, Osmani, & Fuggini, 2024).

3.2.*AS-IS vs TO-BE System Analysis*

A distinctive feature of the CREMA is the explicit comparison between 'AS-IS' (current state) and 'TO-BE' (improved, adapted state) system conditions. This enables stakeholders to visualise the benefits of proposed adaptation measures.

3.2.1. *System characterization: asset, hazard, and context*

CREMA begins with the characterisation of the system under study, including asset inventory, criticality assessment, and contextual factors such as demographic, environmental, and socio-economic conditions. It integrates hazard data from historical records, climate projections, and local monitoring to ensure comprehensive risk profiling.

3.2.2. *Vulnerability analysis, impact quantification and resilience assessment*

The tool employs quantitative techniques to assess vulnerabilities at asset and system levels. Impact quantification leverages scenario analysis, enabling users to estimate potential losses under different hazard events and adaptation pathways. Resilience is evaluated using indices that reflect preparation, internal and external resourcefulness, as well as key performance indicators measuring the robustness, rapidity, resourcefulness, and redundancy of strategies employed (Ricciardi, et al., 2025).

3.2.3. *Economic loss estimation and cost-benefit evaluation for decision-support outputs*

The Expected Annual Loss (EAL) calculation serves as a key metric for assessing the economic consequences of climate change. It quantifies the average yearly financial losses attributed to climate-related impacts, encompassing both direct cost, such as physical damage to assets, and indirect costs, including disruptions to economic activities, public inconveniences, and loss of life (De Maio, et al., 2025).

4. Evolution of the CREMA Tool framework: From MULTICLIMACT to Med-IREN

4.1. *MULTICLIMACT Applications*

The initial implementation of CREMA took place as part of the MULTICLIMACT project, which addressed both climate and non-climate resilience within the built environment. The system was applied in conducting vulnerability and risk assessments for buildings, urban areas, and territorial contexts throughout Europe. These applications spanned diverse climatic zones in Spain, Italy, the Netherlands, and Latvia, focusing primarily on hazards such as floods, heatwaves, and earthquakes.

4.2 *Med-IREN Expansion*

Building on the achievements of the MULTICLIMACT project, the CREMA tool is undergoing significant advancement as part of the ongoing Med-IREN project, with particular emphasis on safeguarding critical infrastructures within the Mediterranean climate hotspot. This region is characterised by heightened vulnerability to a spectrum of climate-induced hazards. The compounded nature of these threats, often cascading from one hazard to another, poses severe risks to vital systems such as energy grids, water supply networks, and transport corridors, making robust risk assessment and resilience planning indispensable. In response to these emerging threats, the CREMA tool is expanding its analytical capacity to address not only traditional hazards such as heatwaves and floods, but also complex, interconnected events like extreme precipitation leading to landslides, wildfire outbreaks with multi-factor triggers (e.g., drought, heatwave, wind), and coastal erosion exacerbated by rising sea levels. The Med-IREN phase is introducing substantial methodological enhancements. Among these, the integration of Nature-based Solutions (NbS) stands out, leveraging the buffering capacity of natural systems to mitigate climate impacts and enhance resilience. Additionally, the CREMA tool incorporates advanced Earth Observation (EO) techniques and in-situ data streams, providing hazard detection, refined exposure mapping, and improved impact assessment.

5. Applications: an example of flood risk assessment

This section presents how the CREMA methodology is applied to flood risk assessment in these projects: one demonstrates its scalability and flexibility across different scales, while the other shows its customization for specific infrastructure needs. These examples highlight CREMA's versatility in varied risk scenarios.

5.1. *MULTICLIMACT multi-scale assessment approach*

Within the MULTICLIMACT project, in order to transition from the scale of individual assets to a broader territorial assessment, the study area was subdivided into discrete units, such as grid cells. For each grid cell, detailed information was collected on the relevant hazards, as well as the average characteristics of exposure and vulnerability. This approach enabled a mapping of risk factors, ensuring that localised differences in hazard intensity, asset concentration, and susceptibility were captured across the territory.

5.1.1. *Hazard modelling*

The assessment begins with the collection of hazard data, including flood depths for a range of return periods (RP), typically sourced from international datasets such as those provided by the JRC (Baugh, et al., 2024). Hazard curves are constructed to quantitatively represent the likelihood and severity of flooding throughout the study area. These curves are constructed using intensity measurements for at least four well-distributed return periods, as presented in Table 1. By plotting these intensity values against their respective return periods, a trend line is identified, which forms the basis for the hazard curve illustrated in Figure 1.

To project hazard curves across different time horizons, reference is made to the Aqueduct platform Aqueduct (WRI, 2020), which offers qualitative projections for future climate scenarios. These projections enable the adjustment of current intensity measures to model hazard curves for medium-term (2050) and long-term (2080) futures under RCP 4.5 and 8.5 scenarios. This approach ensures the risk assessment remains relevant as climate conditions evolve, supporting planning for a range of plausible futures.

Table 1. Flood intensity measure at grid cell

RP [years]	Water depth [m]
10	0.78
50	2,10
100	2,61
500	3,82

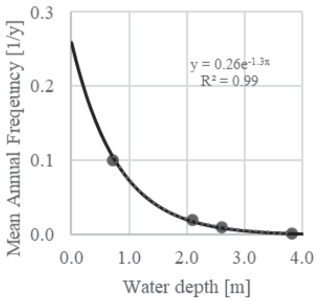

Fig. 1. Illustration of hazard curve for a grid cell unit

5.1.2. *Vulnerability assessment*

Vulnerability was mapped at the territorial level based on the average building characteristic, such as construction material, dimensions and usage, with building height being a key factor in flood susceptibility. Similar to the process used for individual assets, fragility curves from literature are assigned to each territorial unit, linking specific damage states (DS) to corresponding impact levels. The four damage states range from minor cracking (DS1) to total collapse (DS4), indicating increasing levels of structural damage (De Maio, Valsecchi, Osmani, Solari, & Basso, 2023). Figure 2 shows typical fragility curves for multi-storey concrete buildings, based on a lognormal distribution. Table 2 (Suppasri, et al., 2013) provides the mean and standard deviation used to estimate the probability of each damage state.

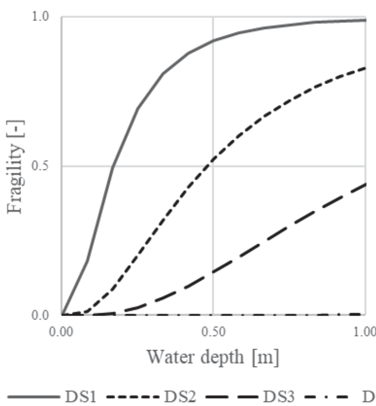

Fig. 2. Example of fragility curve for multi-storey concrete buildings.

Table 2. Flood fragility curve for concrete building with three or more stories (Suppasri, et al., 2013)

Damage State	Mean value	Standard deviation
DS1 - Slight	0.17	0.77
DS2 - Moderate	0.48	0.77
DS3 - Extensive	1.13	0.77
DS4 - Complete	10.6	0.77

5.1.3. *Impact analysis*

Impact analysis is structured around three principal categories: impacts on people (including fatalities and injuries); direct impacts on the physical system (such as structural damages); and indirect impacts on service continuity (including interruptions or downtime). Each element is assessed in economic terms, enabling their combination to produce a unified measure of impact (Basso, Osmani, Scolari, & Valsecchi, 2021). Additionally, the spatial distribution of impact identifies where and how much these effects occur within the study area. This assessment identifies hotspots, quantify the spread of damage, and supports targeted response strategies. By aggregating the results for the area under analysis, it is possible to obtain the total impact corresponding to each state (Figure 3).

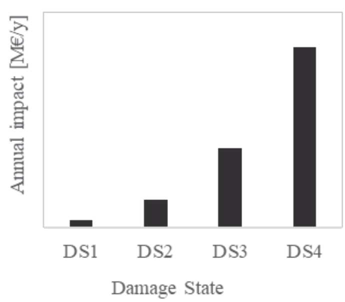

Fig. 3. Total impact for each damage state.

5.1.4. *Resilience capacity*

The initial impact calculations do not account for the system's capacity to withstand and recover from adverse events. To incorporate resilience, a structured questionnaire is used, covering three categories: preparation, internal resources, and external collaboration. Each question yields a coefficient reflecting the system's resilience, which is then used to adjust the calculated impacts. This ensures that the assessment captures

the actual ability of the system to respond and recover.
The questionnaire is administered twice: once to establish the current "AS-IS" condition, and again after adaptation measures to evaluate the improved "TO-BE" scenario. This dual assessment enables clear comparison and quantification of resilience enhancement due to targeted interventions.

5.1.5. *Risk assessment*

A thorough risk assessment requires combining the probabilities of different damage levels, calculated from hazard and fragility data, with their respective estimated impacts, taking into account resilience. By doing so, an Expected Annual Loss (EAL) curve can be developed (refer to Figure 4). The area under this curve quantifies the average annual loss, offering a clear metric for risk assessment. This approach enables comparison between current and improved scenarios, supporting evaluation of adaptation strategies and mitigation effectiveness.

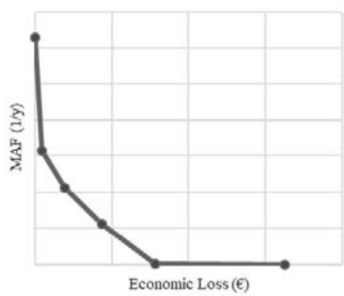

Fig. 4. EAL curve.

5.2. *Med-IREN sectoral approach*

The Med-IREN project concentrates on critical infrastructure in the Mediterranean, focusing particularly on assets highly exposed to climate-related hazards. In the context of flood risk, roads are prioritised because of their vital role in connectivity and their vulnerability to disruption. The CREMA framework is adapted to assess risk and resilience for road networks, starting with the selection of asset-specific fragility curves. This enables estimation of damage likelihood and extent under varying flood intensities. The analysis extends from direct physical damage to broader impacts on network connectivity, recognising that localised failures can have cascading effects on regional accessibility and emergency response.

5.2.1. *Resilience metrics evaluation*

In addition to the previously mentioned methodological advancements, adopting an asset-oriented evaluation approach allows for more detailed customization of resilience assessments. Specifically, the goal will be to develop resilience curves for each asset analyzed. For road infrastructure, a set of asset-specific Key Performance Indicators (KPIs) will be selected to comprehensively assess resilience. Resourcefulness will be measured using questionnaires, which generate indices reflecting how effectively the system can mobilize and allocate resources during and after disruptive events. Recovery will be evaluated based on data from the literature, focusing on the typical time required to restore full functionality after damage, which is closely linked to the network's robustness. Robustness itself will be assessed through various indices and KPIs tailored to different asset types; these indicators measure the system's ability to maintain its function despite sustaining damage. Redundancy will be assessed using indices that consider the presence and effectiveness of alternative routes or components, evaluating the network's ability to maintain service if certain segments become unavailable.

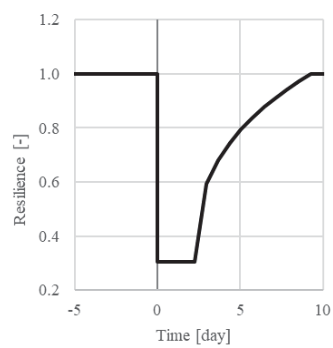

Fig. 5. Resilience curve for road network.

Through these KPIs, resilience curves can be constructed; the area beneath these curves provides an estimate of the overall resilience capacity of the system, quantifying its ability to absorb, withstand, and recover from disruptive events (Figure 5).

6. Discussion: Implications, Scalability and Limitations

The described methodology provides significant benefits for climate adaptation planning. By integrating quantitative risk analysis with resilience metrics, stakeholders are empowered with actionable insights for both immediate and long-term hazard mitigation. The capacity to compare "AS-IS" and "TO-BE" scenarios supports the prioritisation of adaptation investments and interventions.

A key strength of the approach lies in its scalability and adaptability. The modular nature of CREMA's risk and resilience assessment enables its application across varied regions, asset types, and hazard scenarios. This flexibility is crucial as climate risks become increasingly complex and widespread, requiring robust tools for cross-sectoral planning.

Nevertheless, challenges remain. The precision of risk quantification hinges on the availability and quality of hazard, vulnerability, and impact data, which can vary widely between locations. Assumptions in fragility and resilience modelling introduce uncertainty, and stakeholder engagement is essential to validate and refine results. Looking forward, the Med-IREN project offers opportunities to further integrate Nature-Based Solutions (NBS), combining ecological and engineered resilience for more sustainable adaptation. Harnessing NBS alongside technical interventions could open new pathways for robust climate adaptation, enhancing the value and of the CREMA assessment methodology.

7. Conclusions and Future Developments

7.1 Key findings and scientific contributions

This paper presented the methodological and operational evolution of the CREMA tool as a research-to-application framework to assess the climate risk and resilience of the built environment and its infrastructures. The work demonstrates how a scientifically grounded methodology has matured into an operational decision-support system capable of translating complex information into an actionable planning instrument, aiming to effectively protect assets and services against the growing impacts of climate change. The framework integrates deterministic and probabilistic approaches, multi-hazard analysis, and compares AS-IS versus TO-BE scenarios, quantifying resilience through performance-based and economic metrics. It features a modular architecture applicable across scales, from single assets to urban systems and infrastructure networks.

The main scientific contribution lies in bridging risk modelling with decision support. By combining multi-source quantitative data – risk metrics with cost-benefit evaluation and scenario-based analysis – CREMA empowers end-users – such as infrastructure managers, public authorities, investors – to assess the economic effectiveness of resilience investments and justify expenditures aimed at protecting assets, maintaining service continuity and enhancing the capacity to adapt, respond and recover from increasingly frequent and severe climate-related events.

7.2 Future direction

CREMA will further consolidate its role in connecting research innovation and operational deployment. Building on the advancement achieved in MULTICLIMACT and Med-IREN projects, future developments will focus on increasing CREMA's versatility and operational applicability through the expansion of multi-hazard modelling capabilities, broader observation and the introduction of sector-specific modules, ensuring alignment with the rapidly changing climate risk landscape. Beyond traditional hazard assessments, CREMA will progressively integrate emerging relevant hazards, enabling more realistic multi-hazard and multi-risk analyses that capture the complexity, interdependencies and cascading dynamics of compound climate events. In parallel, the framework will extend its asset coverage to additional categories of critical and strategic infrastructure, enabling the identification of systemic vulnerabilities and cross-sector cascading effects. Through these enhancements, CREMA is expected to strengthen the capacity of decision-makers to prioritise interventions, allocate resources efficiently, and guide strategic long-term investments toward climate-proof and adaptive systems.

Overall, CREMA represents a robust, transferable and quantitative decision-support framework for multi-scale resilience assessment, linking risk analysis with investment planning and enabling evidence-based climate adaptation strategies that contribute to safer, more resilient infrastructures and communities in an increasingly climate-stressed environment.

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