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The Risk-Informed Asset-Centric (RIACT) Urban Resilience Enhancement Process: An Outline and Pilot-Case Demonstrator for Earthquake Risk Mitigation in Portuguese Municipalities

Seyed M. H. S. Rezvani [1,*], Maria João Falcão Silva [2] and Nuno Marques de Almeida [1,*]

1 Civil Engineering Research and Innovation for Sustainability (CERIS), Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal
2 Laboratório Nacional de Engenharia Civil, Av. do Brasil 101, 1700-075 Lisboa, Portugal; mjoaofalcao@lnec.pt
* Correspondence: seyedi.rezvani@tecnico.ulisboa.pt (S.M.H.S.R.); nunomarquesalmeida@tecnico.ulisboa.pt (N.M.d.A.)

Featured Application: The application of the Risk-Informed Asset-Centric (RIACT) decision-making process in this study provides a pivotal advancement in urban resilience strategies, particularly for earthquake-prone areas like Portuguese municipalities. This study offers a practical framework for city planners, policymakers, and disaster management authorities to assess and enhance urban earthquake resilience comprehensively. Its potential application extends to improving critical infrastructure resilience across various urban settings, enabling the development of tailored mitigation and adaptation strategies. Moreover, the RIACT process aids in effective resource allocation and the creation of community-based resilience programs, integrating both physical and social aspects of urban resilience. This approach not only contributes to academic understanding but also has significant real-world implications, offering a pathway to creating safer, more resilient urban environments, especially in regions susceptible to seismic activities.

Abstract: This study introduces the Risk-Informed Asset-Centric (RIACT) process, a novel approach aimed at enhancing the safety and resilience of urban infrastructures against natural and man-made disasters. The RIACT method stands out for its comprehensive analysis of potential disruptions to urban areas, encompassing their susceptibility to disasters, vulnerability factors, and recovery capabilities. This study's primary focus is on Portugal's 308 municipalities, assessing their preparedness and ability to recover from earthquake events. Methodologically, the study involved employing geographic information system (GIS) mapping to evaluate earthquake risks, combining data on regional risk areas, demographic and economic profiles, and resilience capacities. This approach provides a detailed understanding of each municipality's strengths and areas in need of improvement, encouraging a collaborative framework for sharing and implementing best practices. The results reveal significant variations in earthquake resilience across different regions, highlighting the need for tailored resilience strategies. Conclusively, the RIACT method not only enhances the resilience of individual municipalities but also contributes to a broader national strategy for urban resilience, offering valuable insights for effective disaster risk management and recovery planning.

Keywords: urban resilience; risk management; asset management; GIS mapping; earthquake preparedness; disaster risk reduction

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1. Introduction

Asset management and risk management are two areas that work together to ensure the long-term sustainability and resilience of cities and urban communities [1]. Asset management is the strategic planning, procurement, and upkeep of a city's financial and physical assets, whereas risk management means identifying, assessing, and mitigating potential risks and hazards that may affect a city and its inhabitants [2].

Effective asset management is critical for preserving and increasing urban quality of life. Cities are complex systems with a diverse collection of assets, such as infrastructure, public services, and natural resources, that must be managed and maintained in order to offer the essential support to city dwellers [3–5]. Cities can ensure that these assets stay in excellent shape and continue to offer people with the required services and facilities by properly planning and maintaining them.

Risk management is also a key component of guaranteeing cities' long-term sustainability and resilience [6,7]. Natural catastrophes, economic downturns, and public health crises are all potential threats to cities. Cities may take actions to limit the effect of these risks and decrease the likelihood of negative outcomes by identifying and evaluating them. This might include putting in place emergency response plans, investing in disaster-resistant infrastructure, or putting in place policies to diversify the city's economy and lessen its vulnerability to hazards [8–10].

The interconnectedness between asset management, risk management, and Urban Resilience (UR) is evident [11–14]. Effective asset management is required for the development of a strong and resilient city, but it is also vital to manage the risks that may affect those assets and impair the city's resilience. Cities may guarantee that they are well positioned to resist and recover from shocks and pressures while continuing to offer a high quality of life for their citizens by carefully balancing the requirement for asset management with the need for risk management [1].

Comprehending how asset management, risk management, and urban resilience interrelate is crucial in the field of civil engineering, particularly with the ongoing concerns of climate change and the pursuit of sustainable infrastructure [15–17]. Civil engineers are actively engaged in devising strategies to shield communities from the consequences of climate change, such as rising sea levels and severe weather patterns [18]. Their role includes the creation of infrastructure that meets environmental, economic, and social sustainability criteria, incorporating the use of renewable resources and advanced technologies [19,20]. Implementing these sustainable practices is fundamental to developing infrastructure that not only withstands climate-related hazards but also maintains sustainability throughout its operational lifespan. This practice is intertwined with the larger concepts of asset management and urban resilience, underscoring the pivotal function of civil engineers in confronting climate change through the development of sustainable infrastructure solutions [21].

This paper is structured to comprehensively explore the relationship between Risk-Informed Asset-Centric decision-making processes and urban resilience, particularly in the context of earthquake hazard assessment in Portugal. The initial sections focus on providing essential background knowledge on disaster risks, risk management principles, asset management strategies, and the concepts of urban resilience and sustainability. These sections aim to establish a foundational understanding of the interconnected elements that are very important in managing risks associated with seismic events and enhancing the resilience of urban areas.

Following this, the paper explores the proposed Risk-Informed Asset-Centric (RIACT) decision-making process. It outlines the inputs derived from optimized asset management and risk management frameworks, detailing the design, development, and outline of the RIACT process. The subsequent sections discuss our case study on earthquake hazard assessment in Portugal, including our methodology, data collection, analysis, and detailed findings. This analysis encompasses identifying disaster risk hotspots, exposure areas, vulnerable regions, and resilient communities. Additionally, it highlights comprehensive treatment plans for enhancing earthquake resilience, emphasizing monitoring, risk review, communication, and consultation strategies. The paper concludes with a discussion of our study's findings, future implications, limitations, and the potential future applications that could be derived from the study.

The following diagram (Figure 1) encapsulates the comprehensive research framework developed in our study. This visual representation delineates the interconnected phases and core components of the Risk-Informed Asset-Centric (RIACT) process when applied to urban resilience enhancement against earthquake risks. At the heart of the diagram lies the RIACT process, surrounded by the primary stages that contribute to its operationalization, including scope definition, risk identification, analysis, evaluation, and treatment. This framework also integrates stakeholder engagement and strategic reporting, ensuring that the process is grounded in practical implementation and knowledge dissemination. Our case study of earthquake hazard assessment in Portugal, as well as the employment of the entropy weighting algorithm, serve as pivotal examples of this framework's application in a real-world context.

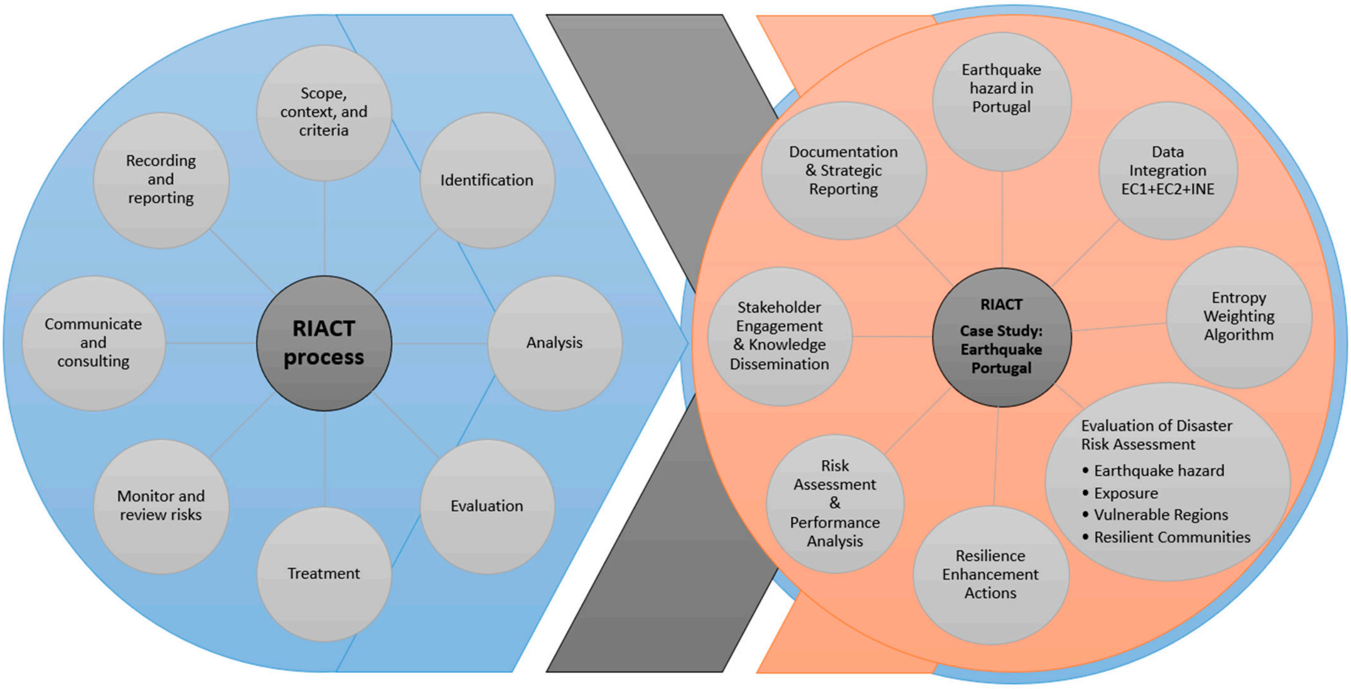

Figure 1. Research framework diagram: A visual guide to the RIACT process for earthquake resilience in urban settings.

The research framework diagram presented above serves as a blueprint for methodically advancing urban resilience. It systematically bridges theoretical concepts with empirical research, highlighting the nature of the RIACT process, which incorporates continuous monitoring and review, alongside effective communication and strategic adaptation. The diagram reflects the synthesis of data collection and integration, risk assessment, and the evaluation of disaster risk assessment across various dimensions. It underscores the necessity of robust treatment strategies and actions to enhance resilience within communities, positioning the framework as a strategic tool for urban planners, policymakers, and researchers dedicated to mitigating the impact of seismic events and fostering resilient urban environments.

2. Background Knowledge

Disaster risk reduction is vital for protecting critical infrastructures like buildings, transportation networks, and power grids. Key strategies include activities and measures aimed at mitigating the impacts of natural disasters [22–24].

Identifying potential hazards and risks is very important in this context [25]. Tools such as hazard maps and risk assessments are instrumental in pinpointing areas vulnerable to natural disasters, including floodplains and earthquake zones [26–29], and coastal areas [30]. Disaster risk reduction also involves planning and coordination across various organizations and agencies [31,32]. Effective planning includes creating emergency procedures and training personnel [33–36]. Building strong partnerships and collaborations is another facet of disaster risk mitigation, involving both public and private sectors [37]. Measures to enhance infrastructure resilience include reinforcing buildings for earthquake resistance and implementing early warning systems for evacuations [38–40]. Additionally, backup power systems and redundant communication networks support critical infrastructure during disasters [41,42]. Investments in disaster risk mitigation yield significant economic and societal benefits. For instance, the World Bank highlights that every dollar spent on disaster risk reduction can prevent up to 7 USD in post-disaster recovery expenses [43]. However, challenges remain, especially in developing nations, due to resource constraints [44].

Urban resilience (UR) is becoming increasingly recognized as cities face challenges like climate change and natural disasters [45–47]. Effective UR requires a multifaceted strategy, considering the city's unique characteristics and involving various stakeholders [48–50]. Key aspects of UR include institutional capacity, governance, and a systems-based approach [51,52]. UR steps involve identifying hazards and vulnerabilities, assessing current resilience, identifying gaps, developing strategies, and evaluating intervention effectiveness [52]. These steps should be continuously monitored and improved for maximum impact [12,47,53]. UR and sustainability are intertwined, addressing challenges like climate change, resource conservation, and social equity [54]. Cities must adopt strategies that reduce emissions, promote sustainable land use and transportation, conserve water, manage waste, and build green infrastructure. These efforts enhance UR across pre-disaster, disaster, and post-disaster phases [47,55,56]. UR measurement uses classification systems based on physical, social, economic, and environmental indicators [57,58]. These indicators track a city's infrastructure condition, social cohesion, economic stability, and environmental health, helping cities identify resilience strengths and weaknesses. Regular data collection on these indicators informs UR strategies, addressing the city's hazard, exposure, and vulnerability aspects [59].

Risk management within UR involves identifying, analysing, and mitigating risks to the city's assets [60]. Effective risk management supports UR by enabling cities to anticipate and prepare for future risks [52]. Strategies include hazard assessments, emergency response plans, and early warning systems [7,61]. Risk management also involves making infrastructure more resilient against natural disasters [62]. Post-disaster recovery is also a very important aspect, with measures aimed at quickly restoring normalcy [63]. Building rules and standards that promote the development of structures that can resist natural disasters, as well as programs that stimulate the retrofitting of existing buildings to make them more resilient, are examples of such initiatives [64]. Cities can decrease the impact of disasters on key infrastructure and services such as hospitals, schools, and transportation networks by making the built environment more resilient [7,61,65]. However, challenges like cost and complexity, especially in resource-limited settings, can impede effective risk management [33].

Asset management (AM) involves maximizing the value and performance of tangible and intangible assets [66]. It plays a significant role in UR by helping cities identify and prioritize very important assets. Regular maintenance and the upgrading of assets contribute to a city's financial sustainability and resilience [67]. However, challenges include inconsistent data on asset conditions and the high cost of implementing asset management systems, particularly in cities with limited resources [68]. Asset management objectives, integral to UR, must align with overall organizational goals and comply with financial, technical, legal, and regulatory requirements [4,69,70]. These objectives form the strategic asset management plan (SAMP), guiding decisions on managing assets effectively for UR. The regular monitoring, updating, and communication of these objectives are vital for transparency and accountability [71,72]. AM enhances UR by prioritizing the repairing, upgrading, replacement, or maintenance of assets based on their condition and role in resilience. Decision making involves evaluating cost, risk, and performance, considering factors like asset lifespan and functionality [73]. The choice between actions like repairing, upgrading, or replacing depends on the specific needs of the city and its resilience goals.

The contemporary landscape of urban resilience literature presents a multifaceted view of community preparedness, particularly in the face of multihazard scenarios. De Fino et al. (2023) explored innovative methods to enhance urban community resilience, particularly through the use of virtual reality and serious game training prototypes [74]. Their work emphasizes the need for dynamic and interactive training methods in preparing communities for heatwaves and earthquake responses. The integration of technology in disaster preparedness not only aids in efficient response mechanisms but also ensures that community members are actively engaged in resilience-building practices. Similarly, Joo and Sinha (2023) delved into the optimization of built infrastructure resilience through performance-based pathways [75]. Their research underscores the importance of selecting strategic and effective pathways, thereby contributing to the sustainability and durability of urban infrastructure in the face of adverse events.

Complementing the technological and strategic approaches to resilience, Deelstra and Bristow (2023) contributed to the dialogue with their assessment of modelling approaches and tools aimed at refining regional disaster recovery estimates [76]. Their emphasis on modelling serves as a critical tool for emergency planning and preparedness, providing a quantitative basis for decision-making processes in disaster management. This analytical perspective is crucial for the creation of robust emergency plans, ensuring that communities are equipped with the knowledge and tools necessary for effective recovery post-disaster. In the realm of built heritage, Kamal Chapagain (2023) provided reflections on the role of heritage in urban resilience [77]. His insights into the scope and limitations of heritage-based resilience in Nepal offer a unique perspective on the cultural dimensions of resilience, highlighting the importance of preserving historical integrity while fostering community strength.

Furthering the discussion on infrastructure resilience, Lin and Lee (2022) proposed an adaptive evaluation framework to assess the importance and performance of community-based earthquake disaster management [78]. Their framework is aimed at improving the adaptability and efficacy of earthquake disaster management by prioritizing community-based approaches. This focus on adaptability is critical for ensuring that disaster management strategies remain relevant and effective in the ever-evolving urban landscape.

In examining the impact of extreme events on critical infrastructures, Urlainis et al. (2021) investigated the assessment of loss and damage [79]. Their work is pivotal for understanding the vulnerabilities of critical infrastructures and the potential scale of damage from such extreme events. This understanding is essential for planning and implementing mitigation strategies that protect the backbone of urban services.

Lastly, Wei et al. (2016) takes a lifecycle approach to evaluating the sustainability costs and benefits of seismic mitigation designs for buildings [80]. By assessing the entire lifecycle, from construction to post-disaster recovery, their research provides a comprehensive understanding of the long-term implications of seismic mitigation efforts, promoting designs that not only ensure safety but also contribute to the sustainability of urban environments.

Together, these pieces of literature construct a complex, yet coherent narrative on urban resilience, emphasizing the integration of community involvement, technological advancements, and strategic frameworks to build resilience against natural and man-made disasters. Despite the growing body of literature on urban resilience, particularly in the domain of disaster risk reduction and asset management, a research gap still persists in the development and application of an integrated, dynamic, and data-driven decision-making process that encapsulates the multifaceted nature of urban resilience. While existing studies have provided substantial insights into individual aspects of disaster risk management, such as hazard identification, emergency planning, and infrastructure reinforcement, there remains a paucity in the literature regarding a holistic framework that aligns with the continuous evolution of urban risks and the complexity of multidimensional resilience strategies.

Moreover, the literature has yet to fully explore the interplay between socio-economic factors and physical infrastructure in the context of urban resilience, particularly through the lens of a rigorous, quantitative validation of resilience measures. The proposed Risk-Informed Asset-Centric (RIACT) decision-making process aims to bridge this gap by integrating a range of indicators, including socio-economic and infrastructure metrics, through an entropy weighting algorithm. This approach not only refines the assessment of urban resilience by reducing subjective bias but also substantiates the decision-making process with a transparent and replicable methodology.

The iterative nature of the RIACT process, accommodating regular updates based on the latest data and stakeholder feedback, further distinguishes this study from existing studies. It ensures that urban resilience strategies are not static but are instead responsive and adaptive to the dynamic urban environment. This research gap, therefore, is addressed by introducing a comprehensive RIACT framework that provides a scientifically rigorous, evidence-based approach for urban planning and policy making, capable of guiding municipalities in Portugal and potentially other regions in the development of nuanced and locale-specific resilience strategies.

3. The Design and Development of the RIACT Process

This section overviews how optimized risk management and asset management principles inform the RIACT process to help enhance urban resilience (UR). Effective risk management, integral to UR, aligns with ISO 31000 principles including integration, structure, customization, inclusivity, dynamism, using the best available information, considering human and cultural factors, and continual improvement [7,81]. These principles ensure a comprehensive, adaptable approach to managing risks in urban settings. Integrating risk management into city operations necessitates strong leadership, a thorough understanding of the city's context, and a proactive approach to building UR (Table 1).

Table 1. Urban resilience principles: ISO integration and implementation analysis.

Principle Name	Definition in ISO	How to Implement It in UR
Integration	Risk management should be integrated into all aspects of the organization's operations rather than being treated as a separate function.	Urban resilience (UR) planning should be integrated into all aspects of the city's operations, including land use planning, infrastructure development, emergency management, and community engagement.
Structure and comprehensiveness	The organization should have a clear and systematic approach to risk management which takes into account all relevant factors and risks.	The city should develop a structured and comprehensive approach to UR planning which considers all relevant risks and vulnerabilities, as well as the city's specific goals and objectives.
Customization	The risk management process should be tailored to the specific needs and circumstances of the organization, taking into account its external and internal context.	The UR plan should be customized to the specific needs and circumstances of the city, taking into account its unique external and internal context.
Inclusivity	All relevant stakeholders should be involved in the risk management process in order to ensure that their knowledge, views, and perceptions are taken into account.	The UR planning process should involve all relevant stakeholders, including community members, government agencies, private sector organizations, and non-profit groups.
Dynamism	Risk management should be able to anticipate, detect, acknowledge, and respond to changes and events in a timely and appropriate manner.	The UR plan should be designed to anticipate, detect, acknowledge, and respond to changes and events in a timely and appropriate manner.
Best available information	Risk management should be based on the best available information while taking into consideration any constraints and uncertainties.	The UR strategy should be based on the best available information, taking into consideration any constraints and uncertainties.
Human and cultural factors	Risk management should take into account the role that human behaviour and culture play in shaping risk management practices.	UR planning should take into account the role that human behaviour and culture play in shaping the city's resilience.
Continual improvement	Risk management should be a continuous process with an emphasis on learning and improvement over time.	The UR plan should be a continuous process with an emphasis on learning and improvement over time. This can be achieved through continuously monitoring and evaluating the plan's effectiveness, as well as through regular updates, to address new risks and vulnerabilities.

Integrating risk management into an organization requires leadership and commitment. This involves ensuring that risk management is incorporated into all organizational activities, allocating resources, and assigning appropriate levels of authority, responsibility, and accountability. It is very important to customize the risk management framework to fit the organization's needs and culture while understanding its internal and external context [82]. Risk management should be integrated into all aspects of the organization, including its purpose, governance, leadership, strategy, objectives, and operations [7,81,83]. The Sendai Framework for Disaster Risk Reduction (2015) and SSG 32 Contingency Planning [84] & Resilience guidelines also inform this process, emphasizing understanding and reducing disaster risk, enhancing preparedness, and investing in resilience measures [85].

Asset Management (AM), in the RIACT process, involves three decision-making approaches: reactive, collective, and optimized decision making. Reactive decision-making addresses immediate issues without long-term consideration and refers to the practice of responding to immediate issues or problems as they arise without taking into consideration the long-term impacts or consequences. This approach is often associated with a "firefighting" mentality, where the primary focus is on addressing immediate issues instead of proactively managing assets. While it may solve immediate problems, this approach may not optimize performance, risk, or cost over the long term. Collective decision-making leverages diverse expertise for top-down decisions and involves bringing together a group of individuals with different perspectives and expertise to make decisions in a top-down manner. Optimized decision making, preferred in RIACT, uses data and analytics for decisions aimed at optimizing asset performance, risk, and cost. Transitioning from reactive to optimized decision making involves building data and analytics capabilities and instilling a data-driven culture [86]. Although this approach can leverage the knowledge and experience of different team members, it may be slower and less agile than other approaches. Collective decision making assesses the cost, risk, and performance of asset management and identifies potential cost reductions, risk mitigation, and performance enhancements through collaboration and communication. Optimized decision making utilizes data and analytics to make informed and data-driven decisions that optimize asset performance, risk, and cost over the long term. This approach typically involves a bottom-up approach where decisions are made at the asset level and then aggregated to the organizational level. While optimized decision making can be highly effective, it may require significant investments in data and analytics infrastructure and capabilities.

Organizations seeking to shift from reactive to optimized decision making may need to take a step-by-step approach by gradually building up the necessary data and analytics infrastructure and capabilities over time. This may involve implementing asset management systems and processes, training staff in data analysis and asset management best practices, and establishing a culture that values data-driven decision making. By taking this approach, organizations can transition from reactive decision making to optimized decision making, optimizing asset performance, risk, and cost over the long-term regarding UR (Table 2). Since optimized decision making is the most accurate one when using a data-driven approach, the RIACT process tends to use it more mostly because it can enable the decision maker to select the most efficient alternative. Additionally, the approach to data-driven optimized decisions makes it more appropriate to track and find the earlier non-optimized decisions.

AM requires a shift from reactive decision making to proactive, data-driven decision making to optimize asset performance and minimize risk in the context of UR. By using both collective and optimized decision making, organizations can effectively manage their assets and achieve their long-term goals. In summary, RIACT utilizes optimized asset management and comprehensive risk management principles to enhance UR, requiring a systematic approach, stakeholder involvement, and continual adaptation to changing risks (Table 3).

Table 2. Reactive decision making, collective decision making, and optimized decision making in asset management (IAM—The Big Picture [86]) in conjunction with risk management.

Processes	Reactive Decision Making	Collective Decision Making	Optimized Decision Making
Scope, context, and criteria	Immediate concerns or problems	Long-term impacts or implications	Long-term performance, risks, and costs
Identification	Addressing immediate problems	Proactively managing assets	Data-driven decisions
Analysis	Firefighting mentality	Leveraging different perspectives and expertise	Using data and analytics
Evaluation	Not optimized for long-term performance, risks, or costs	Slower and less agile than other approaches	Highly effective but requires significant investments in data and analytics infrastructure
Treatment	Addressing current issues	Cost reductions, risk mitigation, and performance enhancement	Optimizing asset performance, risks, and costs over the long term
Monitoring and reviewing risks	Not considered	Assessed throughout	Data-driven decisions
Communicating and consulting	Not considered	Collaboration and communication	Data-driven decisions
Reviews and updates	Not considered	Not considered	Data-driven decisions and infrastructure

Table 3. Correspondence of design inputs with the elements of the RIACT process.

RIACT Process Element	Design Inputs								
	ISO 31000	ISO 55000	IAM—The Big Picture	ISO 37123	SSG 32	Sendai Framework	IIMM	URES	ARCDM
Scope, context, and criteria	x	x	x					x	
Identification	x	x	x	x		x	x	x	
Analysis	x			x					x
Evaluation	x		x		x				x
Treatment	x	x	x		x	x			
Monitoring and reviewing risks	x						x		x
Communicating and consulting	x					x			
Recording and Reporting	x						x		

Urban resilience (UR) has gained prominence as cities increasingly face threats from climate change and disasters [87]. To address these challenges, a structured approach to risk management is essential. ISO 31000 offers guidelines for such an approach, enabling decision makers to systematically identify, analyse, evaluate, and manage risks. The Urban Resilience Evaluation System (URES), a comprehensive framework, complements ISO 31000 by providing detailed guidance for assessing and enhancing UR [52]. URES consists of dimensions (such as environmental, social, and economic factors), indicators (specific metrics for measuring each dimension), and parameters (values or thresholds determining resilience levels for each indicator). The objective is to develop strategies that minimize the impact of hazards, thereby improving the overall resilience and stability of urban areas.

This study contributes to a deeper understanding of urban resilience factors and equips decision makers with tools for informed decision making, ultimately leading to more resilient and sustainable cities. This system aids in making informed decisions about resource allocation for enhancing a city's resilience. URES and ISO 31000, together, facilitate a holistic risk management approach for UR. This includes selecting context-based indicators and applying a weighting system for decision making. Decisions regarding capital and operational expenditures are informed by these indicators, and their long-term and short-term impacts are evaluated.

The evaluation categorizes decisions into four strategies, namely avoidance, endurance, recovery, or adaptation, ensuring a structured, systematic, and consistent approach to risk management. This methodical process is very important for understanding and enhancing the resilience of urban areas against natural and human-made hazards. It involves a thorough process of selecting scope, context, and criteria, followed by the identification, analysis, and evaluation of risks [88].

The RIACT process proposes a comprehensive approach to enhancing urban resilience. It involves narrowing down the scope, context, and criteria; identifying potential risks and vulnerabilities; analysing hazards and their potential impact; selecting appropriate indicators for evaluation; prioritizing initiatives for treating, monitoring, and reviewing risks; communicating and consulting with relevant stakeholders; and recording and reporting progress. This process enables cities to allocate resources efficiently, prioritize efforts to enhance resilience, and build the capacity to withstand potential disruptions. The sources used to prove the concept of the RIACT process are international frameworks and guidelines such as ISO 31000, ISO 37123:2019, the Sendai Framework for Disaster Risk Reduction, the City Resilience Index (CRI) [27], the Resilience Action Planning Guide for Cities and Regions, and the United Nations Development Programme (UNDP). The Sendai Framework's emphasis on understanding disaster risk, strengthening disaster risk governance, and investing in disaster risk reduction aligns with the risk identification, analysis, and evaluation stages of the RIACT process [84].

It contributes by encouraging the assessment of disaster exposure, vulnerability, and hazard characteristics of urban areas, thereby guiding the development of strategies tailored towards mitigating these risks. ISO 31000 complements this by offering a structured approach to managing risks, which is very important for the systematic implementation of resilience-enhancing measures [89]. It provides the RIACT process with a set of best practices for risk management, including the establishment of a risk management policy, ensuring the process is integrated into all levels of urban planning, and promoting a culture of continual improvement. Together, these frameworks aid city planners and decision makers in not only formulating comprehensive resilience plans but also in instilling a proactive culture of preparedness and adaptability within urban communities. This combined approach ensures that the RIACT process is both strategic and actionable, leading to sustainable and resilient urban development.

4. Proposed RIACT Process

The different components of the proposed RIACT's processes are summarized in Figure 2 and can be described as follows.

At the highest level, the first step is to reduce the **scope** by choosing the level of analysis to be carried out. Continent-level analysis can range from country-level to city-level and city-level to municipality-level analyses, depending on the needs and goals of the assessment. This step is essential for choosing the right assessment focus and confirming that it corresponds with the desired outcomes. Selecting the analysis' **context** comes after the scope has been established. Two important factors, risk and assets, are used to establish the context of the analysis. The threats and dangers that the system or entity under evaluation might encounter are referred to as risks. Contrarily, assets are the essential parts of the system that must be protected and resilient in the face of these dangers. The next step is to focus the **criteria** that will be used to evaluate the risk and assets of the system after choosing the analysis' context. The "amount and type of risk that it may or may not take relative to objectives" is how ISO 31000 defines criteria. To put it another way, the criteria are the precise parameters that will be used to assess the risk and resources of the system, and they must be customized to the set objectives and context of the assessment. It is important to remember that RIACT processes are not fixed and must be regularly reviewed and updated to stay effective against evolving risks and challenges. By monitoring and evaluating the system's performance against established criteria, we can identify areas that need improvement or adjustment. In addition, RIACT processes are not limited to a specific type of system or entity, and they can be applied to a range of scenarios, such as natural disasters, cyberattacks, terrorism, and other threats. The processes are flexible and adaptable to suit the specific needs and circumstances of the system or entity under evaluation. RIACT processes provide a comprehensive and structured approach to risk assessment and critical asset protection. By following the proposed processes and selecting the appropriate scope, context, and criteria, entities can enhance their resilience and preparedness in the face of potential threats and hazards. Regular monitoring and evaluation can help ensure the continued effectiveness of RIACT processes in addressing the evolving risks and challenges facing the system.

The three main steps taken in this process, which are based on ISO 31000, comprise **identification**, **analysis**, and **evaluation**, and next is the treatment of risk is below of the inner box and then communication and consulting, monitor and review, and recording and reporting are the supportive steps around the main body of the process. The identification of urban resilience consists of two separate boxes, one for disaster risk hazard and the other for asset system exposure. These two boxes work together to provide a comprehensive view of the city's resilience, with each box having three phases: identification, analysis, and evaluation. The **identification** and **analysis** urban resilience phases are the most important aspects for ensuring the longevity and stability of cities. The general form of the process includes scope, context, and criteria located at the centre, with communication and consulting and monitoring and reviewing located on the sides. The **analysis** phase uses the selected context-based indicators as inputs and is used to make long-term and short-term decisions for capital expenditure and operating expenditure. The indicators will work in an automated, rational, and consistent decision-making scenario using a weighting system, providing the best decisions for the scope, context, and criteria of the city. The proposed processes incorporate disaster risk hazards and asset system exposure from the evaluation system's scope context and criteria, as well as effective communication and consultation, assisting in choosing the right indicators and then weighting them using automated rational and consistent decision making. The inquiry will then focus on this solution box based on the indication in which CAPEX and OPEX, on long-term and short-term solutions, as well as their performance costs and risks, are to be evaluated. This will happen after calculating the scores for avoidance, endurance, recovery, and adaptability. Before being entered into the register of lessons learned and being used again in communication and consultation, the output of the solutions that have been chosen to be implemented will first be checked, monitored, and reviewed. The **evaluation** phase of urban resilience will score the probable decisions and determine where to implement them in the categories of avoidance, endurance, recovery, or adaptability.

The treatment list will be subjected to communication and control, monitoring, and review, and **recording and reporting**. By following these steps and utilizing the guidelines provided by ISO 31000, decision makers can make informed and optimized decisions about the city's resilience, expanding the public and private budget to areas that need the most attention. The output of these phases will then be used as an input for the indicator selection phase using the URES. This system has its own parts, including dimensions, indicators, and parameters that can be adjusted for the specific context and system being analysed. The proper indicators will then be selected, and a relational table will be created to show the cascading effect that the indicators have on each other.

The following sub-sections present how the different steps of the risk management process outlined in ISO 31000 could be reconceptualized in the context of UR.

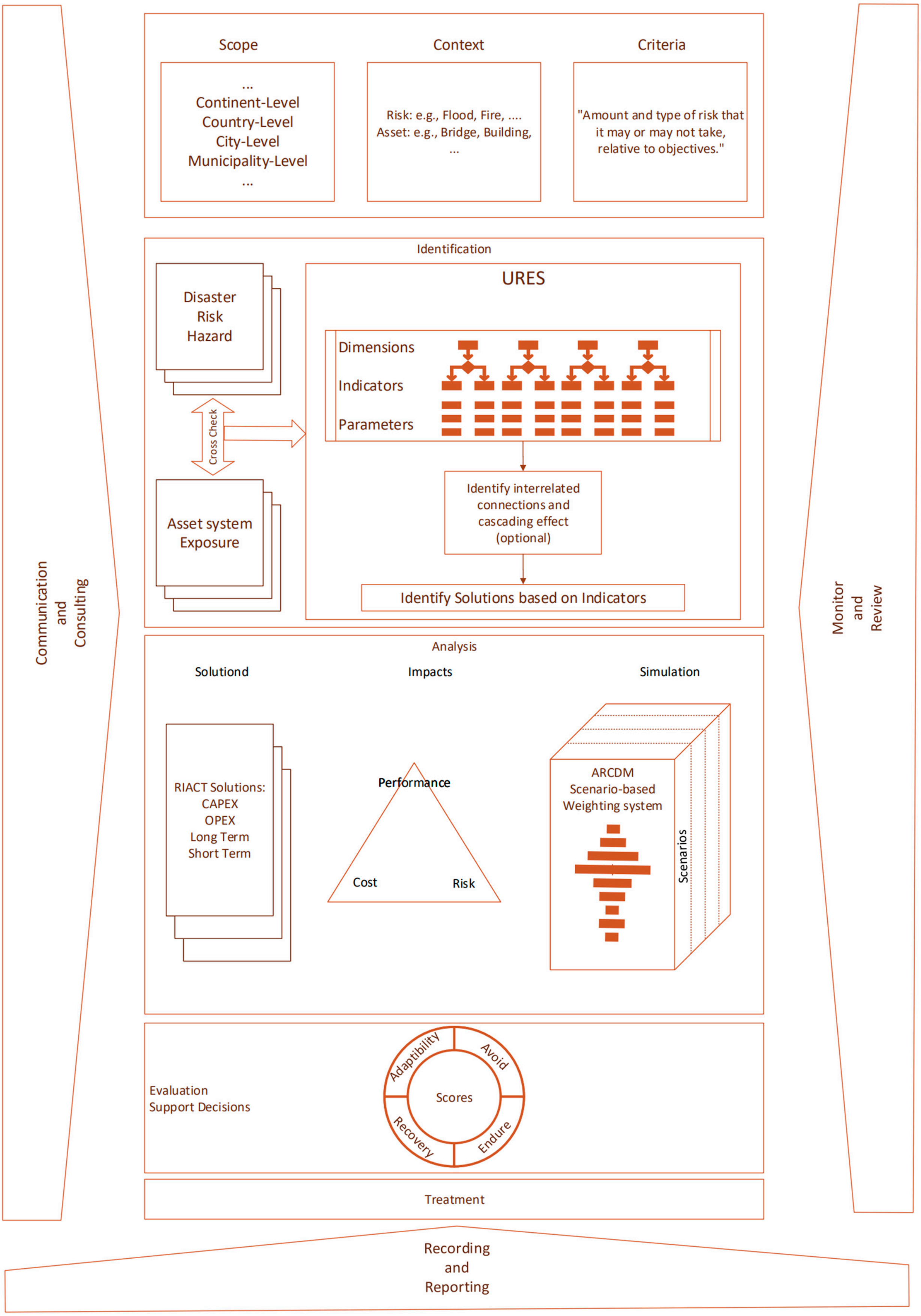

Figure 2. RIACT processes for urban resilience.

4.1. Scope, Context, and Criteria

To effectively evaluate UR, a detailed process is essential, beginning with the definition of the analysis scope at various levels, from continent to municipality, as guided by ISO 31000. This approach aligns with the European legislation Council Directive 2008/114/EC, which mandates member states to identify and safeguard critical infrastructure by assessing risks. The process involves setting clear objectives, identifying risks and hazards in urban areas, and selecting relevant constructed assets for evaluation, ensuring compliance with the Directive [90]. Gathering accurate information about risks, vulnerabilities, and critical assets from various stakeholders, including city authorities, community leaders, and emergency response professionals, is a critical component of this process. To enhance the evaluation process' effectiveness and adherence to standards, various frameworks and systems are integrated. These include IAM—The Big Picture [86] and ISO 55000 [70], which offer a comprehensive view of asset management across the entire lifecycle of assets. Additionally, the Urban Resilience Evaluation System (URES), outlined in [52], is utilized to assess urban resilience specifically in relation to the risks and hazards faced by urban areas, as discussed in Tarpani & Azapagic, 2023 [21].

4.2. Identification

Evaluating UR involves identifying risks and hazards to city assets, requiring communication with stakeholders for comprehensive risk understanding. This process is guided by ISO 31000 and ISO 55000, which offer frameworks for risk and asset management [91]. Selecting indicators for resilience, as outlined in ISO 37123:2019, helps cities develop strategies for shock resilience and facilitates resilience performance comparison among cities [92] (Figure 3).

Figure 3. A general view of the topics highlighted in ISO 37123:019.

The International Infrastructure Management Manual (IIMM) [69] and the Urban Resilience Evaluation System (URES) [52,93] provide further guidance and tools for this evaluation. Additionally, the Sendai Framework for Disaster Risk Reduction 2015–2030 emphasizes the integration of disaster risk reduction in urban planning [84]. Professionals should use a holistic approach, incorporating various frameworks and tools like ISO 31000, ISO 55000, IAM—The Big Picture, ISO 37123, IIMM, and URES for effective urban resilience evaluation [83–86,92].

4.3. Analysis

The adoption of globally recognized standards such as ISO 37123 can assist cities in assessing risks to their urban resilience from constructed assets. ISO 37123 provides a framework for evaluating and monitoring a city's sustainability and resilience, including the assessment of potential hazards and their impacts. By adopting a standardized approach, cities can ensure the consistency, reliability, and comparability of their risk assessments across regions and cities. This can also facilitate knowledge sharing and collaboration, allowing cities to learn from each other's experiences and best practices in enhancing resilience. Automated Rational and Consistent Decision Making (ARCDM) is another useful tool in the risk assessment process. ARCDM applies a weighting system to prioritize potential hazards and their impacts on critical infrastructure, enabling cities to make informed and optimized decisions based on objective and comprehensive data analysis. The use of ARCDM can assist cities in identifying and prioritizing the most effective strategies for reducing risks and enhancing resilience, ensuring the efficient use of resources, and maximizing the benefits of risk reduction measures. In addition to evaluating the likelihood and impact of hazards, considering the exposure of city assets to potential hazards is also essential. Integrating disaster risk hazard and asset system exposure into the risk assessment process can provide a more comprehensive view of a city's resilience. By identifying and analysing the exposure of critical infrastructure to potential hazards, cities can develop targeted strategies and measures to reduce risks and increase resilience. This can include retrofitting or upgrading critical infrastructure, developing emergency response plans, and establishing early warning systems.

Making sure that resilience measures are regularly monitored and reviewed is very important to ensuring that cities are continuously adapting and improving their resilience strategies. Standardized approaches like ISO 37123 and ARCDM, through providing benchmarks for cities to measure their resilience against other cities, enable cities to identify gaps and areas for improvement and develop targeted strategies and measures to reduce risks and increase resilience. Adopting these globally recognized standards and tools can provide a reliable and consistent framework for assessing and enhancing urban resilience, ensuring sustainability and well-being in the face of potential hazards. It is important to assess the probability and potential impact of the risks posed by constructed assets to a city's urban resilience. This analysis is important for prioritizing efforts to enhance resilience and determining effective strategies to mitigate identified risks. Natural and man-made disasters, as well as the exposure of city assets to these hazards, must be considered in risk assessments [91]. It is important to evaluate the likelihood of a hazard arising and the potential repercussions if it does occur.

In terms of funding, capital expenditure (CAPEX) and operational expenditure (OPEX) play very important roles in enabling cities and communities to prepare for and recover from natural disasters, environmental crises, and other disruptions. CAPEX refers to the money spent by an organization to acquire or improve physical assets such as buildings, machinery, or equipment [94]. This spending is generally viewed as a long-term investment, as it aims to benefit the organization over time [95]. Conversely, OPEX refers to the money spent on day-to-day business operations such as employment, utilities, and other ongoing costs. OPEX typically encapsulates short-term expenses, as it is incurred regularly and is necessary for the continued functioning of the business. Investing in both CAPEX and OPEX is essential to increase urban resilience and better equip cities to deal with disruptions. CAPEX can be used to construct or upgrade infrastructure, while OPEX can support ongoing emergency preparedness and response programs. Regular communication and consultation with stakeholders is also necessary to ensure the process remains effective over time.

4.4. Evaluation

The process of assessing and improving urban resilience involves various tools and frameworks, including [86], SSG 32 Contingency Planning & Resilience (a UK government standard), and Automated Rational and Consistent Decision Making (ARCDM). Risk is evaluated through a weighting system that considers different variables related to avoidance, endurance, recovery, and adaptation. Based on the resulting ratings, plans and activities are developed to enhance urban resilience. The process also includes implementing, monitoring, and reviewing solutions, and making necessary improvements to ensure their effectiveness [48–50,96]. The documentation of the implementation process is essential to inform future resilience efforts.

4.5. Treatment

The implementation of risk treatment measures is a critical step in enhancing urban resilience. To guide this process, various tools and frameworks are available, including ISO 55000, IAM [86], SSG 32 Contingency Planning & Resilience (a UK government standard), and the Sendai Framework. These frameworks provide a comprehensive approach to risk management, including identifying and assessing risks, developing risk treatment measures, and monitoring their effectiveness. To address the risks and vulnerabilities identified in a city, customized risk treatment measures are necessary, taking into consideration factors such as feasibility, effectiveness, and cost. It is very important to involve and obtain support from stakeholders, as their participation and feedback can significantly contribute to the success of these measures.

For instance, in cities that are prone to hurricanes, emergency response plans must be created to include evacuation procedures, infrastructure protection, and post-storm emergency services. To reduce the probability and impact of flooding, redundant infrastructure can be implemented. Moreover, incorporating natural and green infrastructure can help mitigate the effects of heat waves and droughts [97,98].

The effective implementation of the goals of risk treatment measures centre around reducing the likelihood or impact of identified risks, or providing methods for recovering from them when they occur. Risk treatment measures are based on the specific risks and vulnerabilities identified for the city, taking into account the feasibility, effectiveness, and cost of the different options. Stakeholder views and concerns must also be considered, as their support and participation is essential for the success of risk treatment measures.

These measures require collaboration among various stakeholders, including city authorities, community leaders, emergency response professionals, and subject matter experts. Thorough risk assessments and cost–benefit analyses ensure that the best solutions are implemented to reduce risk and enhance urban resilience.

4.6. Monitoring and Reviewing Risks

To ensure the sustainability and effectiveness of urban resilience plans, it is very important to continuously monitor and review risk treatment measures. This involves collecting and analysing data on their performance and gathering feedback from stakeholders, which may include city officials, emergency response personnel, and community members. Revisiting urban resilience plans must involve continuously monitoring and reviewing the effectiveness of risk treatment measures to ensure that they remain efficient and identify areas for improvement. Data on their performance must be collected and analysed, as well as feedback from key stakeholders. Regularly reviewing and adjusting the risk treatment measures will help maintain the city's urban resilience over time. It may also be necessary to periodically revisit the risk identification and analysis process to prepare for emerging risks or changes in the existing risks. The use of standardized approaches such as ISO 31000 and the International Infrastructure Management Manual (IIMM) as well as the use of

Automated Rational and Consistent Decision Making (ARCDM) tools, can facilitate the monitoring and review process.

4.7. Communicating and Consulting

Communication with stakeholders is vital for the effective evaluation and enhancement of urban resilience (UR) processes. These stakeholders include city officials, emergency response personnel, community leaders, field experts, and the general public. In order to obtain a comprehensive evaluation that incorporates diverse perspectives and expertise, it is very important to establish communication channels and ensure that stakeholders have access to accurate and timely information. By engaging in open and transparent communication with stakeholders, trust and support for UR measures can be fostered, leading to more effective implementation and increased community involvement.

We have referred to ISO 31000, a risk management standard, to emphasize the importance of effective communication in risk management and UR implementation. We have also cited the Sendai Framework, a United Nations agreement on disaster risk reduction, which highlights the significance of stakeholder engagement in disaster risk reduction strategies. Prioritizing communication and consultation with stakeholders can enable UR efforts to benefit from the collective knowledge and resources of the community.

To ensure that stakeholders are informed and involved in UR efforts, it is necessary to establish communication channels, provide accurate and timely information, and engage in open and transparent communication. Effective communication and consultation with stakeholders are critical components of UR evaluation processes.

4.8. Recording and Reporting

The process of evaluating UR is an ongoing cycle that involves identifying, assessing, and responding to risks. To ensure its effectiveness and relevance over time, it is essential to periodically review and update the analysis and evaluation process. This requires collecting and analysing data on the performance of risk treatment measures and the evaluation process, as well as gathering feedback from stakeholders. Based on the data and feedback collected, adjustments may need to be made to the risk treatment measures or the overall evaluation process.

Recording and reporting are very important steps in this process as they provide a comprehensive record of the evaluation process and its outcomes, which can inform future decision making. ISO 31000 and the International Infrastructure Management Manual (IIMM) provide guidance on how to document and report on the evaluation process and its outcomes effectively. This information can be used to track progress and identify areas for improvement, as well as to demonstrate the effectiveness of the UR evaluation process to stakeholders and the wider community.

The RIACT solution register is a standardized format used to streamline the process of analysing and evaluating potential solutions. It contains both capital expenditure (CAPEX) and operational expenditure (OPEX) information for the identified solutions, as well as the short-term and long-term effects of each option. It also assesses the cost risk and performance of each solution, helping decision makers make informed decisions and mitigating any potential risks associated with the chosen solution. By utilizing the RIACT solution register, organizations can ensure that they are making informed decisions based on comprehensive data and analysis, resulting in effective and impactful solutions.

5. Case Study and Results: An Assessment of Earthquake Hazards in Portugal

5.1. Scope, Context, and Criteria

Considering the application of the RIACT process to our case study, the '**scope**' encompasses all municipalities of Portugal, as we set out to compare and analyse their varying degrees of exposure to earthquake risks. This comprehensive scope is most important to understand and illustrate the different levels of earthquake susceptibility across the municipalities, ranging from high to very low. The '**context**' of this study is defined by the 308 municipalities, each with its unique position in relation to seismic threats. This contextual framework is very important as it allows for a detailed examination of how different regions are affected by and respond to earthquake hazards. The '**criteria**' for the study are centred on the socio-economic vulnerability and resilience of these municipalities. This focus is key to addressing the broader implications of seismic activity. It helps in evaluating not just the physical robustness of infrastructure, but also the socio-economic readiness and adaptive capacities of communities. Such a nuanced approach enables a more holistic understanding of urban resilience at a macro scale, offering valuable insights into how different areas might effectively prepare for, withstand, and recover from seismic events. The case study presented in the following sub-sections serves as an exemplar for comprehensively evaluating urban resilience, taking into account the varied degrees of earthquake risk and socio-economic dynamics across a broad geographic area.

5.2. Identification and Data Gathering

The basis of our analytical structure is rooted in a comprehensive data gathering process. Our assessment is supported by a variety of datasets, with a focus on the following:

- Earthquake Information: Central to our study, we gathered information on both near-field (EC2) and far-field (EC1) earthquakes [26,99]. These data provide a detailed look at Portugal's history of seismic events. Additionally, we utilized geospatial data from the Portugal cities border shapefile, obtained from the Global Administrative Areas (GADM) database, to define geographical boundaries that are very important for our analysis;
- Demographic and Socioeconomic Data: We collected detailed demographic and socioeconomic information from the Instituto Nacional de Estatística (INE), Portugal's National Statistics Institute [100]. These data cover all 308 municipalities in Portugal, offering a comprehensive view of the social and economic landscape;
- HASC Naming Convention: To ensure a precise and clear understanding of Portugal's municipalities and cities, we adopted the Hierarchical Administrative Subdivision Codes (HASC) system [101]. This coding, which combines letters and dots, distinctly identifies each municipality within its city. For example, 'PT.AV.AG' signifies the municipality of Águeda in Aveiro. This methodical naming system aids in accurately overlaying earthquake data, demographic, and socioeconomic information across the 308 municipalities, thereby thoroughly encapsulating the intricacies of each area. Utilizing such a structured naming convention enhanced the precision of our analysis and makes our findings more accessible and understandable to stakeholders.

5.3. Analysis Using the Entropy Weighting Algorithm

The weighting method centres around the entropy weighting approach, realized through a specially designed Python 3.11.7 algorithm [102,103]. This algorithm comprises several essential steps:

- Normalization: The initial phase involves normalizing the dataset values to ensure uniformity, scaling them to a range between 0 and 1. The normalization technique differs based on whether the data are positive (suggesting a beneficial outcome) or negative (indicating a detrimental outcome).

$$\text{For positive data}: \ y_{ij} = \frac{x_{ij} - min\ x_j}{max\ x_j - min\ x_j} \tag{1}$$

$$\text{For negative data (inversion of the scaling)}: \ y_{ij} = \frac{x_{ij} - min\ x_j}{max\ x_j - min\ x_j} \tag{2}$$

Here, x_{ij} represents the value for the ith munici ality for the jth variable, and $min\ x_j$ and $max\ x_j$ denote the minimum and maximum values for the jth variable.

- Calculation of P_{ij}: After normalization, the P_{ij} matrix comes into the fold. This matrix represents the proportionate weight of a variable relative to the total weights in its row, which is very important for gauging the importance of each variable.

$$P_{ij} = \frac{y_{ij}}{\sum_{i=1}^{n} y_{ij}(n = 1, 2 \ldots)} \quad (3)$$

- Entropy (E_i) Calculation: We calculate the entropy value for each variable to measure its information content. Entropy, a marker of data randomness, is key in this analysis.

$$E_j = -\frac{I}{ln\ n_i} \sum_{i=1}^{n} P_{ij} ln\ P_{ij} \quad (4)$$

and

$$d_j = 1 - e_j \quad (5)$$

- Weight (W_i) Calculation: Next, we determine the weight (W_i) for each variable by normalizing these entropy values, indicating each variable's significance in the broader context.

$$w_i = d_{ij} / \sum_{j=1}^{m} d_{ij}(m = 1, 2, \ldots) \quad (6)$$

- Final Score of entropy using of W_i: The weights are further normalized for comparability across all variables.

$$U = \sum_{i=1}^{m} y_{ij} w_j \quad (7)$$

The Python script presented below, intricately designed for this analysis, enables the execution of these steps with accuracy and consistency, ensuring the reliability of the entropy weighting process.

```
import pandas as pd
import numpy as np

def calculate_urban_resilience(input_csv):
    """
    Calculate urban resilience from the provided CSV file.

    Args:
    input_csv (str):  Path to the input CSV file.

    Returns:
    None:  Saves the results to output CSV files and prints the file names.
    """
    # Load data from CSV
    df = pd.read_csv(input_csv + ".csv", sep=',', header=0)

    # Normalize data based on positive or negative values
    df_norm = pd.DataFrame()
    for col in df.columns:
        if col != 'HASC_2':  # Exclude non-numeric column
            normalization_type = df[col][0]
            col_data = pd.to_numeric(df[col][1:], errors='coerce').dropna()

            # Normalize based on the type specified in the first row
            if normalization_type == 'pos':
                df_norm[col] = (col_data - col_data.min()) / (col_data.max() -
col_data.min())
            elif normalization_type == 'neg':
                df_norm[col] = (col_data.max() - col_data) / (col_data.max() -
col_data.min())
```

```
    # Save normalized data
    df_norm.to_csv(input_csv + "_norm.csv", index=False)

    # Calculate proportional weight (P_ij)
    df_Pij = (df_norm.T / df_norm.sum(axis=1)).T
    df_Pij['HASC_2'] = df['HASC_2'] # Add HASC_2 column for identification

    # Calculate entropy (E_i) for each variable
    df_Ei = pd.DataFrame({'E_i':  -1 / np.log(len(df_Pij.columns) - 1) *
                          df_Pij.apply(lambda col:  (col * np.log(col)).sum())})

    # Calculate weight (W_i) for each variable
    df_Wi = pd.DataFrame({'W_i':  df_Ei['E_i'] / df_Ei['E_i'].sum()})
    df_Wi['VarNames'] = df_Pij.columns[:-1] # Exclude HASC_2 column

    # Normalize weights and calculate final score
    df_Wi_norm = df_norm.drop(columns=['HASC_2']).mul(df_Wi['W_i']).sum(axis=1)
    df_Wi_norm = pd.DataFrame({input_csv:  df_Wi_norm.round(3), 'HASC_2':  df['HASC_2']})

    # Save results
    df_Wi_norm.to_csv(input_csv + "_output.csv", index=False)
    df_Wi.to_csv(input_csv + "_Wi.csv", index=False)

    print(f'Result saved to {input_csv+"_output.csv"} and {input_csv+"_Wi.csv"}')

# Example usage
calculate_urban_resilience('input_file_name')
```

5.4. *Evaluation of Disaster Risk Assessment in Portuguese Municipalities: A Detailed Justification of Dimensions and Indicators*

The case of the Portuguese municipalities serves as a prime example, employing a robust and methodologically sound framework. This approach integrates distinct dimensions—Disaster Hazard Risk (in the present case is the Earthquake), Exposure Assessment, Vulnerability Assessment, and Resilience Assessment—facilitating a comprehensive assessment, from recognizing potential threats to evaluating a region's adaptability and recovery capacities:

- Disaster Hazard Risk (in the present case-study is the Earthquake): The assessment's foundation lies in recognizing the inherent natural hazards, especially seismic potential, in Portuguese municipalities. Differentiating between far-field (EC1) and near-field (EC2) earthquakes is very important. This differentiation provides insight into varying seismic impacts and is key to pinpointing areas at greater risk.
- Exposure Assessment: This step quantifies the potential impact of seismic events, focusing on geographical areas and populations at risk. The integration of area and population metrics, through entropy weighting, helps gauge the potential scale and severity of seismic impact, thus highlighting the regions most susceptible to seismic events [104,105];
- Vulnerability Assessment: Beyond exposure, this dimension evaluates societal factors that could intensify or mitigate the effects of a disaster. The analysis includes various socio-economic indicators, such as municipal revenue per inhabitant, educational attainment, ageing ratio, housing density, and population density. Each indicator offers insight into how societal characteristics can influence a municipality's vulnerability to seismic events [106];
- Resilience Assessment: The final dimension shifts focus from vulnerabilities to strengths, assessing each area's capacity to withstand, adapt, and recover from seismic activities. Resilience is gauged through various indicators, including municipal revenue, educational levels, ageing population, housing conditions, population density, con-

struction activity, emergency response capabilities, medical facilities, and economic power. These indicators collectively reflect a municipality's resilience, highlighting its ability to effectively respond to and recover from seismic challenges [52,104,107].

Each dimension, along with its associated indicators, is carefully selected based on extensive statistical data specifically relevant to Portuguese municipalities, ensuring a detailed and encompassing perspective of seismic risk. This structured approach is essential for identifying and understanding the multifaceted aspects of disaster risk, setting the stage for effective risk management and resilience enhancement in urban areas. This thorough assessment framework provides an in-depth understanding of seismic risks in Portuguese municipalities, allowing for targeted and effective disaster risk management and resilience building strategies.

Geographic Information Systems (GISs) play a very important role in the evaluation phase of the RIACT process, offering a powerful means to visualize, analyse, and interpret spatial and geographic data. The ability of GISs to graphically represent complex data sets allows for a more intuitive understanding of spatial relationships and patterns, which is essential in identifying trends, anomalies, and correlations that might be less apparent in traditional data formats. This graphical representation enhances the scientific process by improving the reproducibility and transparency of research, thanks to the standardized data presentation platforms of GISs. The integration of diverse data sources in GISs enables comprehensive, cross-disciplinary studies, synthesizing vast amounts of data into clear, actionable insights. This functionality is particularly valuable in academic and scientific contexts, where GISs can significantly improve the quality of research. By enhancing the interpretability and communicability of research findings, GISs make complex data more accessible and understandable to both experts and the public.

In the context of the RIACT process, GISs thus serve as an essential tool in effectively analysing and evaluating urban resilience, transforming raw data into meaningful information that can inform decision making and policy development [108–110]. Our analysis utilizes Python for applying the entropy weighting method and QGIS 3.32 for managing geospatial data, including its extraction, preprocessing, and spatial representation. These technologies work together to enable thorough data analysis and the creation of illustrative outputs.

The following sub-sub-sections will detail the outcomes of our analysis, providing in-depth insights into Portugal's seismic environment and highlighting key areas regarding earthquake hazards, exposure, vulnerability, and resilience. In this segment of the manuscript, we unveil the results of our extensive evaluation of earthquake hazards across Portugal's municipalities. These findings offer a detailed view into areas with high disaster risk, regions with significant exposure, municipalities that are particularly vulnerable, and those demonstrating notable resilience.

5.4.1. Earthquake Hazard

In our study, the evaluation of earthquake risk considers both near-field and far-field seismic events for each municipality identified by the HASC_2 coding system. The earthquake risk score for each municipality is derived by averaging the values assigned to near-field (EC zoning 1) and far-field (EC zoning 2) earthquakes. This approach ensures a comprehensive assessment of seismic risk that considers the varied impacts of different types of earthquakes on the Portuguese municipalities.

The variation in earthquake risk scores across different regions of Portugal, particularly increasing towards the south and southwest, emphasizes the necessity for tailored preparedness and infrastructure planning suited to the specific seismic activities of each location. In the detailed earthquake risk assessment conducted across Portugal, distinct regional variations become evident (Figure 4). In the Aveiro region, encompassing municipalities from Águeda to Vale de Cambra, the earthquake risk scores are generally uniform at 0.27, although some areas like Arouca and Castelo de Paiva register lower scores at 0.18. In contrast, the Azores region shows significantly higher risk levels, with many municipalities, such as Angra do Heroísmo and Horta, scoring 1.0, indicating heightened risk. Some areas, like Corvo and Lajes das Flores in the Azores, however, have slightly lower scores at 0.73. Moving to Beja, the earthquake risk scores vary between 0.45 and 0.55, with Odemira exhibiting an elevated risk score of 0.64. The Braga region's scores are comparably stable, like Aveiro's, maintaining a score of 0.18.

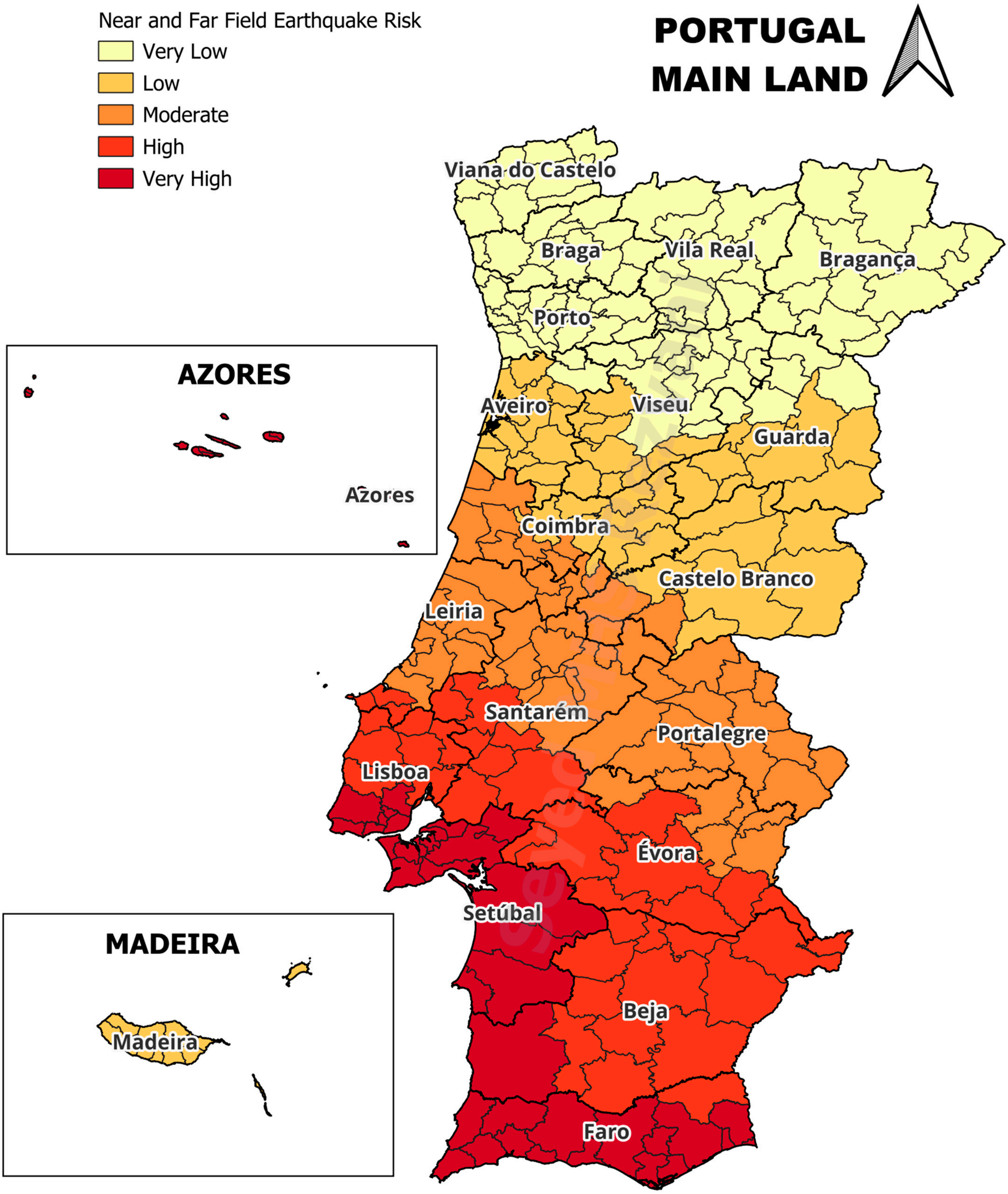

Figure 4. Map depicting Portugal's 308 municipalities and their earthquake hazard status.

5.4.2. Exposure

For the exposure analysis in our study, we assess the potential impact based on two primary factors: the area in square metres and the population of each region, categorized by the HASC_2 coding system. The exposure score is calculated using an entropy weighting method, where 'area sqm' is given a weight of approximately 0.421 and 'population' a weight of approximately 0.579. This weighted approach allows us to account for both the geographical size and the number of people potentially affected by seismic events, providing a balanced measure of exposure for each municipality.

The pattern of diverse exposure levels across various areas indicates the heterogeneity of seismic risk potential in Portugal, offering vital insights for region-specific disaster preparedness and resilience planning (Figure 5). The data analysis highlights the varying degrees of exposure to earthquake hazards across different regions and sub-regions in Portugal, with area (in square metres) and population identified as key indicators. For instance, in the Aveiro region, Santa Maria da Feira stands out, having the highest exposure at 0.236 and contrasting sharply with Murtosa's much lower exposure of 0.022. In the Azores, Ponta Delgada faces a higher exposure level at 0.146, while Corvo is notably less exposed at 0.002. In the Beja region, both Odemira and Mértola register the highest exposure value at 0.324, in stark contrast to Barrancos, which has the lowest exposure at 0.041. Moving to Braga, the city itself shows a significant exposure level of 0.279, compared to Vizela's minimal exposure of 0.036. Similarly, in Bragança, the city of Bragança experiences the highest exposure at 0.331, while Carrazeda de Ansiães has the lowest at 0.074.

5.4.3. Vulnerable Regions

The dataset reveals a detailed picture of vulnerability across various regions and municipalities in Portugal, factoring in several key indicators. These vulnerability assessments consider several factors: (i) Municipal Revenue per Inhabitant: A higher revenue per inhabitant usually means more resources for infrastructure and services, reducing vulnerability. Conversely, lower revenue indicates limited financial capabilities, increasing susceptibility to disaster impacts; (ii) Upper Secondary Education Rate: Municipalities with higher education rates typically have populations that are more aware of and prepared for seismic risks, reducing vulnerability. Lower education rates suggest a less informed populace, increasing the risk during seismic events; (iii) Ageing Ratio: A higher proportion of elderly residents often means increased vulnerability due to the mobility and health challenges inherent in disasters; (iv) Housing Density (House stock per 1000 population): Lower housing density, implying overcrowding, can heighten vulnerabilities in disasters due to resource limitations and emergency response capacities; (v) Population Density: Densely populated areas are more vulnerable in seismic events due to their potential for higher casualties and evacuation complexities.

This comprehensive analysis (Figure 6) enables stakeholders to pinpoint areas needing focused attention or intervention, optimizing resource allocation to effectively address vulnerabilities across Portugal. In Aveiro, vulnerability scores range from 0.634 in Murtosa to 0.678 in Anadia, illustrating diverse risk levels. The Azores show a wider variation, with Corvo at a lower vulnerability of 0.558, and Praia da Vitória at a high of 0.811. In Beja, vulnerability scores vary from 0.504 in Barrancos to 0.635 in Beja, indicating differing degrees of susceptibility. Esposende in Braga shows a notable high vulnerability of 0.767, while Terras de Bouro is relatively lower at 0.628.

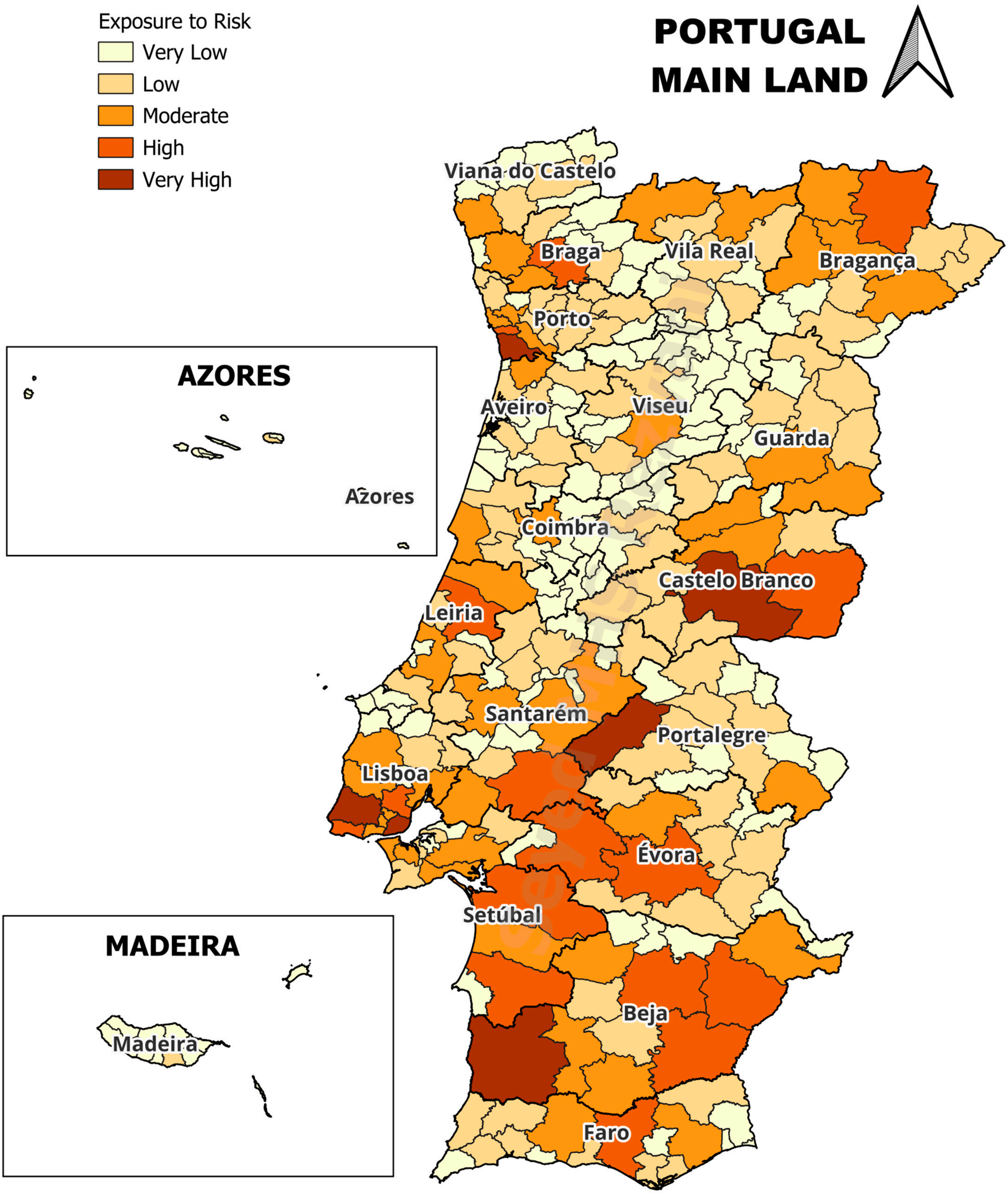

Figure 5. Map depicting Portugal's 308 municipalities and their exposure areas.

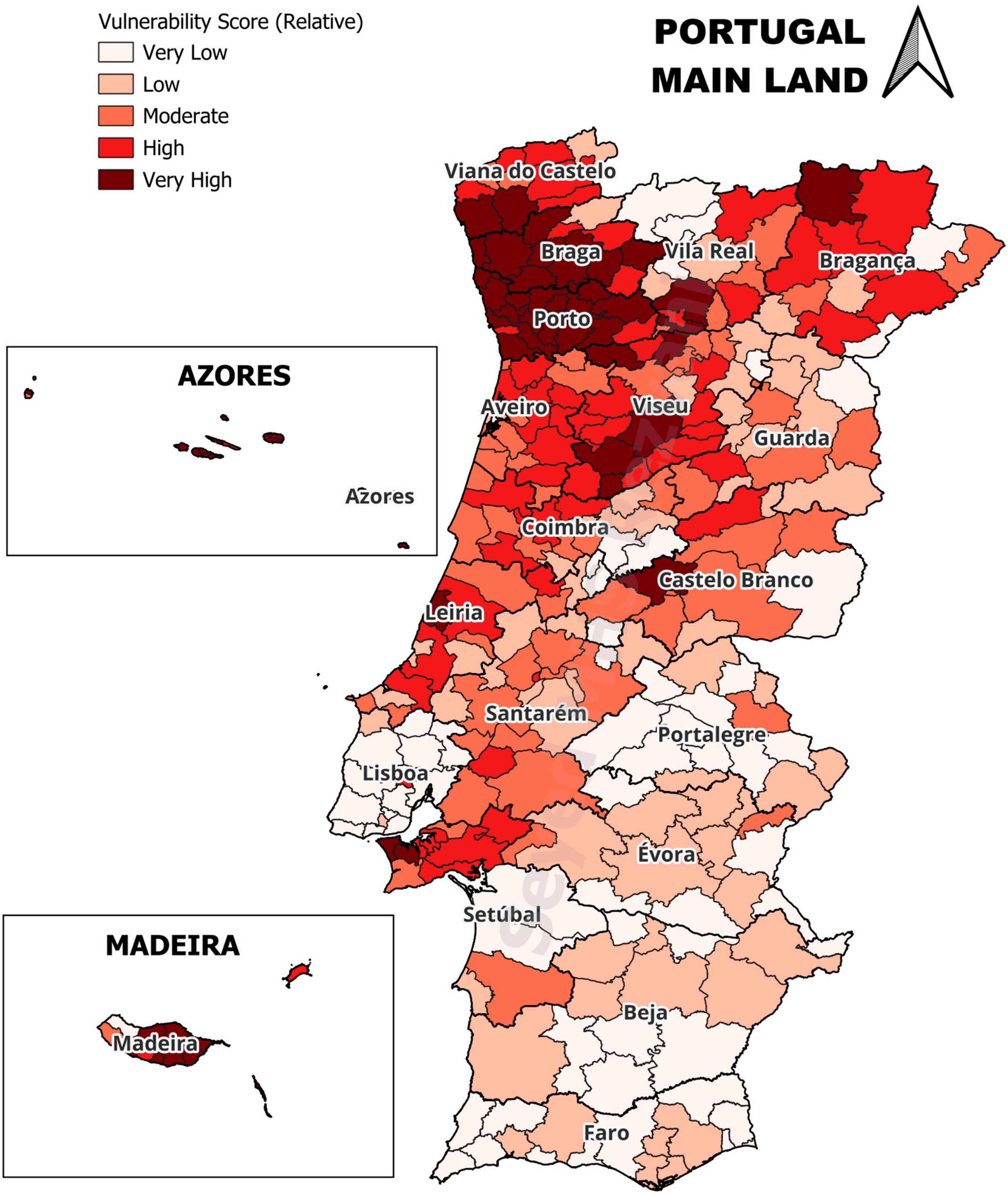

Figure 6. Map depicting Portugal's 308 municipalities and their vulnerability.

5.4.4. Resilient Communities

The resilience assessment, spanning across various Portuguese cities, reveals significant regional differences in their ability to withstand and recover from seismic events (Figure 7). This variation in resilience is influenced by several factors: (i) Revenue per Inhabitant: Municipalities with higher revenue per inhabitant tend to have better resources for post-disaster recovery, contributing to higher resilience; (ii) Upper Secondary Education Rate: Higher education levels in a community correlate with better preparedness and informed responses to disasters, enhancing resilience; (iii) Ageing Ratio: A higher ratio of elderly residents can limit resilience due to potential challenges in recovery and the need for more support services; (iv) Housing Density: A greater number of houses per capita, indicating less overcrowding, suggests better living conditions, which aid in quicker recovery and thus enhance resilience; (v) Population Density: High population density can challenge resilience due to the resource constraints and logistical difficulties inherent in post-disaster scenarios; (vi) Construction Projects: An increase in construction projects, especially those upgrading older structures, can indicate ongoing development and improved resilience against seismic activities; (vii) Fire Personnel: More firemen per capita suggests better emergency response capabilities, enhancing a municipality's resilience; (viii) Hospitals: A higher number of medical facilities per capita indicates stronger medical response capabilities, aiding community recovery and resilience; (ix) Purchasing Power: Higher per capita purchasing power reflects a stronger economic capacity at the individual and community levels, bolstering resilience against seismic threats.

Considering the obtained results, in Aveiro, Murtosa demonstrates strong resilience with a score of 0.548, while São João da Madeira shows a lower resilience at 0.469. In the Azores, Corvo stands out with a high resilience index of 0.625, contrasting with Praia da Vitória's lower score of 0.351. In Beja, Barrancos leads with a resilience score of 0.607, while Serpa shows a moderate level at 0.508. In Braga, Esposende has a notably lower resilience index of 0.403, whereas Amares and Barcelos exhibit similar levels around 0.48–0.49.

These data provide very important insights for guiding regional policy, infrastructure planning, and community development initiatives aimed at enhancing resilience across Portugal.

5.5. Treatment

The base context adapted measures presented that contribute significantly to earthquake resilience within the framework of comprehensive treatment plans, ongoing monitoring, risk review, effective communication, and community consultation [111]. Here is how they align with these aspects:

In what concerns the physical infrastructure, the treatment comprises the following: (i) upgrading stormwater and sewage systems; (ii) improving building insulation; (iii) fire-resistant materials and designs. Upgrading stormwater and sewage systems, as part of a comprehensive treatment plan, involves the continuous monitoring and reviewing of potential earthquake risks to ensure these systems are resilient. Regular communication and consultation with relevant stakeholders are very important to implement necessary upgrades effectively. Improving building insulation, part of treatment plans, should involve the continuous monitoring of structural integrity. Communication about earthquake-resistant designs and consultation with experts help in enhancing insulation methods for better seismic resilience. Fire-resistant materials and designs for homes should be regularly monitored in terms of their effectiveness in earthquake scenarios. Continuous communication about fire safety measures and consultation with local fire departments can ensure their optimal use in earthquake-prone areas [111].

Concerning water management, the protection of groundwater resources, integrated into treatment plans, requires ongoing monitoring to safeguard against earthquake-induced contamination. Regular communication with water authorities and consulting hydrogeologists can ensure effective protection strategies [111].

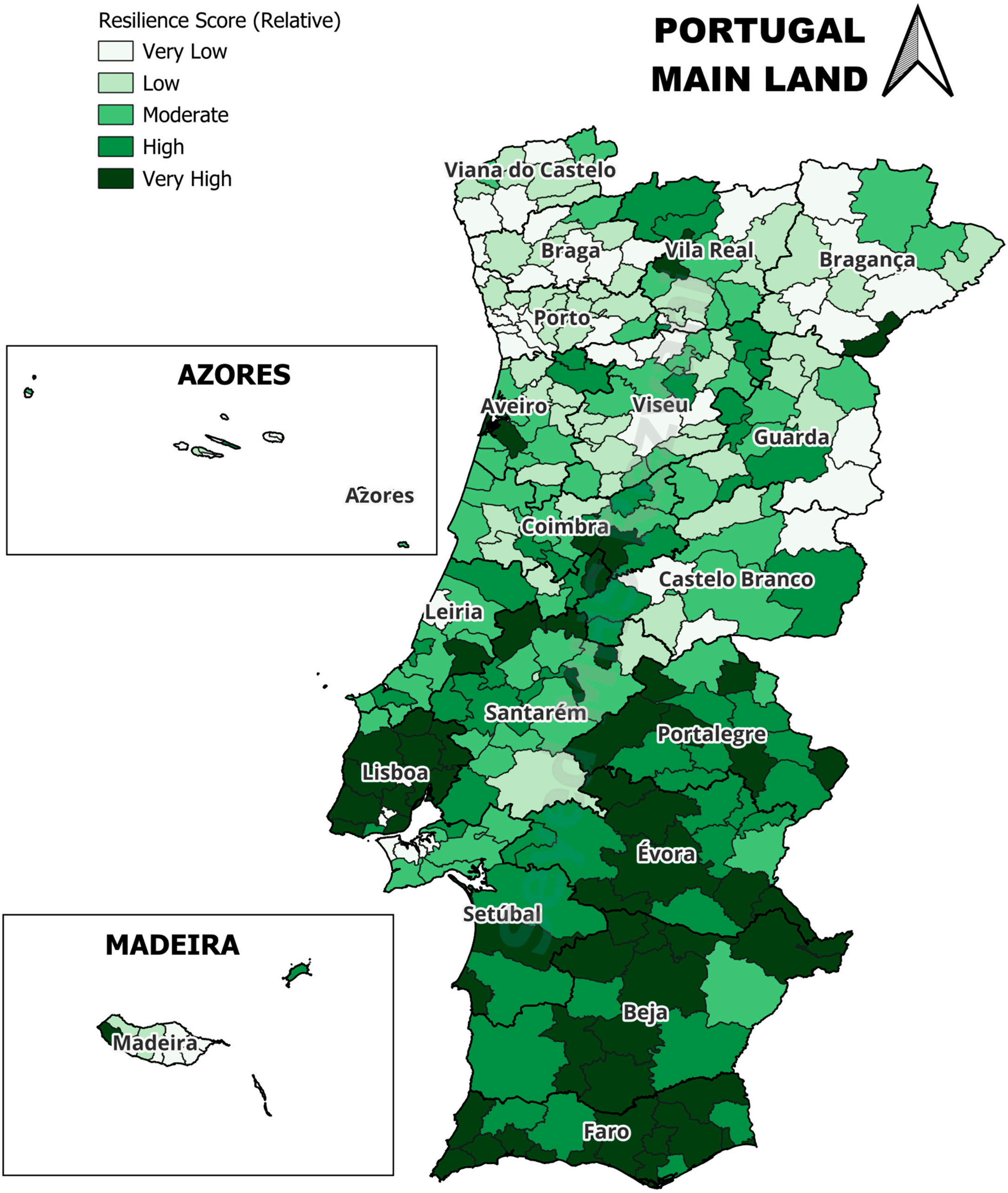

Figure 7. Map depicting Portugal's 308 municipalities and their resilience.

Referring to policy and planning, the treatment should incorporate earthquake-exposed, socioeconomically vulnerable locations into urban planning, as a part of treatment plans, which necessitates continuous risk reviews and communication with at-risk communities. Consulting urban planners and community leaders ensures that plans consider their needs and risks effectively. The development and enforcement of building codes related to earthquakes should include the ongoing monitoring of compliance and periodic reviews to enhance effectiveness. Continuous communication and consultation with engineers and architects are vital for updating codes according to the latest seismic research. Insurance policies require continuous monitoring and reviewing to ensure their alignment with evolving earthquake risks. Transparent communication about policy coverage and consulting with risk assessment experts help in optimizing coverage for affected communities. Additionally, zoning laws to prevent building in high-risk areas need regular reviewing, and communication with stakeholders to ensure their alignment with updated seismic risk assessments is also important. Consulting geologists and urban planners' aids in making informed zoning decisions. Tax incentives for earthquake-resilient practices should be periodically reviewed for their effectiveness. Clear communication about these incentives and consulting with construction professionals encourage the adoption of resilient designs. Moreover, the development of adaptation plans should include the continuous monitoring of their implementation progress. Continuous communication and consultation with local authorities ensure that plans remain adaptable to changing earthquake risks. Finally, educational programs about earthquake risks and adaptation strategies must be continuously reviewed for relevance and reach. Consistent communication through various channels and consulting with educators refine these programs for better community preparedness [111].

Finally, health and social measures pertain to the need for enhanced emergency services and the continual monitoring of infrastructures to assess their readiness for earthquake scenarios. Open communication about emergency protocols and consulting with emergency responders enhance preparedness. Early warning systems for earthquakes require regular reviews, and technological updates are also needed, as well as open communication about system reliability and consultation with seismologists ensure timely and accurate warnings. Regarding community-based adaptation initiatives, continuously monitoring and reviewing their effectiveness, communication within the community, and consulting with local leaders aid in tailoring initiatives to specific earthquake risks. Training programs for new skills that are needed due to earthquake risks should be reviewed and updated periodically, and open communication about skill demands and consulting with industry experts to ensure relevant training programs should also be considered.

These measures, through being incorporated within treatment plans, monitoring processes, risk reviews, communication strategies, and consultations, contribute to a comprehensive approach towards earthquake resilience.

5.6. Monitoring and Reviewing Risks

The process of monitoring and reviewing risks in the context of enhancing urban resilience, particularly regarding earthquake hazards in Portugal, is very important. This involves the continuous assessment of implemented measures and their effectiveness. To ensure that urban areas remain resilient against seismic activities, it is important to regularly revisit and update the risk management strategies based on new data, technological advancements, and changing environmental conditions. Regular monitoring can be achieved through various methods, including: (i) data analysis; (ii) technology utilization; (iii) stakeholder feedback; and (iv) performance metrics

Data analysis includes utilizing updated earthquake and demographic data to reassess risk levels in different municipalities. Changes in population density, infrastructure developments, or recorded seismic activities can significantly alter the risk landscape. Technology utilization includes employing advanced technologies such as seismic monitoring systems and GISs to track seismic activities and their impact on urban areas. Stakeholder feedback involves gathering input from local authorities, emergency services, and residents to understand the practical effectiveness of current resilience measures. Finally, performance metrics allow for the establishment of clear performance indicators to measure the effectiveness of the implemented resilience strategies. These metrics should align with the initial goals and objectives of the urban resilience plan.

5.7. Communicating and Consulting

Effective communication and consultation with various stakeholders are essential components for enhancing urban resilience. In the context of assessing earthquake hazards in Portugal, it is necessary to engage with a diverse group of stakeholders, including government bodies, local communities, experts in seismology and urban planning, emergency services, and non-governmental organizations. This engagement should aim to achieve the following: (i) Disseminate Information: Share updated risk assessments and resilience strategies with the relevant stakeholders to ensure transparency and informed decision making; (ii) Gather Input: Obtain feedback from communities and experts to identify any gaps or areas that need further attention in the current resilience plan; (iii) Enhance Awareness: Conduct educational programs and workshops to raise awareness about earthquake risks and preparedness strategies among residents; (iv) Foster Collaboration: Encourage collaborative efforts between different stakeholders to develop more comprehensive and effective resilience strategies.

5.8. Recording and Reporting

Documenting the outcomes of risk assessments and resilience strategies is very important for transparency, accountability, and continuous improvement. In the case of earthquake hazard assessment in Portugal, it is important to maintain detailed records of the following: (i) Risk Assessment Outcomes: Documenting the results of the hazard, exposure, vulnerability, and resilience assessments for each municipality; (ii) Implemented Strategies: Recording the details of implemented resilience measures, including their scope, objectives, and expected outcomes; (iii) Monitoring Results: Keeping track of the monitoring data and how the implemented strategies are performing against the set metrics; (iv) Stakeholder Feedback: Documenting the feedback received from stakeholders and how it has influenced the resilience strategies; (v) Reviews and Updates for Processes: Reporting the processes involved in reviewing and updating the resilience strategies, including the rationale behind any changes.

These practices not only aid in refining current strategies but also provide valuable insights for future urban resilience planning and implementation in Portugal and similar seismic event-prone regions.

6. Discussion

This study's exploration of the Risk-Informed Asset-Centric (RIACT) decision-making process has provided a nuanced understanding of urban resilience, specifically in the context of earthquake preparedness and mitigation in Portugal. By utilizing an entropy weighting algorithm and extensive data gathering, our study has successfully mapped the diverse landscape of earthquake risks, exposure, vulnerabilities, and resilience across Portuguese municipalities. This granular approach has highlighted the complex nature of seismic hazards and the importance of tailored resilience strategies.

One of the most significant findings of this study is the clear demonstration of regional variations in earthquake risk within Portugal. This heterogeneity underscores the need for region-specific resilience planning, moving beyond one-size-fits-all solutions. Such localized approaches enable municipalities to address their unique risk profiles effectively, ensuring that resources are allocated where they are most needed.

The RIACT process, rooted in principles of optimized asset and risk management, emerges as a comprehensive framework for enhancing urban resilience. Its strength lies in its integrative approach, combining robust data analysis, stakeholder engagement, and continuous adaptation. This study illustrates how the RIACT process facilitates a dynamic response to seismic risks, allowing for proactive measures that enhance both the physical infrastructure and the social fabric of communities.

A crucial aspect of this approach is the emphasis on proactive treatment plans. This study has highlighted the importance of infrastructural improvements such as upgrading building standards and enhancing water management systems, which are vital for reducing vulnerability to seismic events. However, equally important are the policy and planning measures, including the development of adaptive building codes, insurance policies, and zoning laws. These policy-level interventions can significantly strengthen the overall resilience framework.

Continuous risk monitoring and revision stand out as key components of the RIACT process. The dynamic nature of seismic risks requires resilience strategies to be adaptive rather than static in response to new data, technological advancements, and changing environmental conditions. This adaptive approach ensures that resilience measures remain relevant and effective over time.

Moreover, this study underscores the critical role of communication and stakeholder engagement in the resilience-building process. Establishing dialogues with local communities, government bodies, and industry experts enhances the understanding of seismic risks and the effectiveness of resilience strategies. It fosters a culture of preparedness wherein community input and expert advice shape more robust and inclusive resilience plans.

In conclusion, this study not only contributes a methodological approach to assessing and enhancing earthquake resilience but also emphasizes the need for an ongoing, collaborative effort in resilience planning. The insights from this study advocate for a dynamic, integrative approach to urban resilience, highlighting the importance of continuous adaptation, stakeholder engagement, and policy development in the face of seismic challenges. As urban areas continue to grapple with the complexities of natural disasters, the RIACT process offers a valuable framework for building more resilient, sustainable communities.

7. Validation

The RIACT process delineates a robust methodology to elevate urban resilience, harnessing risk-informed, asset-centric decision-making. This innovative framework extends across multiple scales, from continental to municipal, anchored by the principles of ISO 31000. The process proactively embeds a stratified risk and asset analysis within its fabric, fostering an adaptive urban milieu resilient to both natural and man-made perturbations. The process' iterative core mandates frequent reassessments, facilitating alignment with the evolving landscape of urban risks.

The efficacy of the RIACT methodology is substantiated through the meticulous assessment of earthquake hazards in Portugal, serving as a testament to its robustness. While the entropy weighting method effectively harmonizes diverse datasets, including earthquake, demographic, and socioeconomic dimensions, the process' versatility allows for alternative techniques such as the random forest classifier to be employed when confronting multifaceted variables of phenomena like flooding. The entropy weighting method, employed in this case study, systematically mitigates subjective biases by anchoring the analysis to a data-driven foundation. This approach ensures that the process' framework and the analytical procedures maintain a transparent, replicable nature, thus bolstering the RIACT process as a scientifically grounded framework that propels evidence-based urban planning and policymaking.

In practical deployment, the RIACT process revealed stark regional disparities in earthquake risk across multiple Portuguese municipalities. The entropy weighting algorithm's precise application to standardized data facilitated the development of nuanced, locale-specific resilience strategies. Vital to this endeavour is stakeholder engagement, which infuses data analysis with localized insights, rendering the resulting urban resilience strategies both relevant and holistic. This iterative loop of ongoing scrutiny, refinement, and adaptation injects a dynamic aspect into the process, ensuring that urban resilience strategies mature congruently with unfolding data and revelations, enhancing their applicability and potency in tangible settings.

8. Conclusions

The application of the Risk-Informed Asset-Centric (RIACT) decision-making process to the context of Portuguese municipalities has yielded significant insights into the multifaceted nature of earthquake resilience. This study not only maps the varied seismic risk landscape across Portugal but also sets a precedent for future studies on urban resilience. The findings advocate for a comprehensive approach that extends beyond traditional risk assessment, encompassing a spectrum of strategies, from infrastructural upgrades to community engagement and policy reform.

A key takeaway from this study is the critical importance of a multidimensional approach in addressing earthquake resilience. The RIACT process, with its emphasis on dynamic and adaptive strategies, has proven effective in integrating diverse measures, ranging from physical infrastructure enhancements to socio-economic initiatives. This holistic approach underscores the necessity of addressing both the tangible and intangible aspects of urban resilience.

This study also highlights the evolving nature of seismic resilience as a field that requires ongoing research and adaptation. The RIACT process, in its essence, is a call for the continuous evolution and re-evaluation of strategies in response to emerging data and changing seismic patterns. This dynamic approach is vital in a world where urban environments and their associated risks are constantly in flux.

Looking ahead, the RIACT framework's application to specific assets such as critical infrastructures—roads, rail networks, water systems, energy grids, and telecommunication networks—presents a promising avenue for future research. This expansion will allow for a more targeted and asset-specific understanding of resilience, crucial for the development of tailored mitigation and preparedness strategies. Additionally, exploring the application of the RIACT process to the healthcare sectors, emergency services, and the education sectors would provide a more comprehensive view of urban resilience.

This study's methodology, particularly the entropy weighting algorithm, offers a robust tool for future applications in diverse urban contexts. Applying these algorithms to various assets will not only enhance the specificity of resilience assessments but also contribute to the development of more effective and efficient resilience-building interventions.

This research marks a significant step in the journey towards understanding and enhancing urban earthquake resilience. The conclusions drawn from our case study on the aforementioned Portuguese municipalities provide a foundation for future studies, encouraging deeper exploration into the resilience of critical infrastructures and key urban sectors. The RIACT process, with its comprehensive and adaptable framework, stands as a pivotal contribution to the ongoing endeavour of building safer, more resilient urban environments in the face of seismic uncertainties.

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