Document Version
Final published version

Citation (APA)
Matteoni, M., Ciurlanti, J., Bianchi, S., Overend, M., & Pampanin, S. (2025). A resilience-based framework for assessing socioeconomic indirect losses from natural hazards. In M. Papadrakakis, & M. Fragiadakis (Eds.), *COMPDYN 2025 - 10th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering* (pp. 2175-2188). (COMPDYN Proceedings). National Technical University of Athens.
https://doi.org/10.7712/120125.12559.25356

Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2025) 2175-2188

ECCOMAS
Proceedia

COMPDYN 2025
10th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15-18 June 2025

A RESILIENCE-BASED FRAMEWORK FOR ASSESSING SOCIO-ECONOMIC INDIRECT LOSSES FROM NATURAL HAZARDS

Michele Matteoni[1], Jonathan Ciurlanti[2], Simona Bianchi[3], Mauro Overend[3], and Stefano Pampanin[1]

[1] Department of Structural and Geotechnical Engineering, Sapienza University of Rome
Via Eudossiana 18, 00184, Rome, Italy
{michele.matteoni, stefano.pampanin}@uniroma1.it

[2] Arup Netherlands
Naritaweg 118, 1043CA, Amsterdam, The Netherlands
jonathan.ciurlanti@arup.com

[3] Department of Architectural Engineering and Technology, Delft University of Technology
Julianalaan 134, 2628BZ, Delft, The Netherlands
{s.bianchi, m.overend}@tudelft.nl

Abstract

The built environment is increasingly exposed to more frequent and intense climate-related extreme events. Although numerous frameworks exist to assess the impacts of extreme events - usually measured in terms of deaths, dollars and downtime - several authors have shown that indirect losses, often driven by the recovery phase rather than the response one, can represent most of community losses. Delays in initiating repairs significantly increase indirect losses but are often overlooked in frameworks focused only on immediate response. While recent resilience-based approaches aim to include both response and recovery, their indices often lack clear links to measurable physical outcomes. The definition of a clear, relatable, scalar index could better inform stakeholders and decision-makers about potential risks and guide them in planning mitigation strategies.

This paper proposes a novel framework for quantifying socio-economic (direct and indirect) losses by considering both the response and recovery phases of extreme events. Building on resilience principles and functionality-time curves, this framework offers a comprehensive yet practical method for quantifying indirect losses. The approach is validated through a multi-story building subject to earthquake and flood hazards, by employing a component-based probabilistic loss modelling approach. The framework was able to provide an estimation of indirect losses due to business interruption showing how indirect losses can match or even exceed the direct economic losses due to damage repairs.

Keywords: Resilience, Multi-Hazard, Risk Assessment, Indirect Losses, Low-Damage.

ISSN:2623-3347 © 2025 The Authors. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of COMPDYN 2025.
doi: 10.7712/120125.12559.25356

1 INTRODUCTION

The increasing intensity and frequency of climate-induced and natural disasters are placing significant pressure on urban communities to enhance the resilience of the built environment. From 2000 to 2019, natural disaster accounted for nearly $3 Trillion USD in direct economic losses alone, alongside more than one million casualties [1]. Despite earthquake accounting for 58% of the casualties, other hazards, such as flood and windstorms, account for 69% of economic losses combined. In 2023, floods accounted for 81% of economic losses due to climate-related causes in Europe, affecting approximately 1.6 million people [2]. Italy, in particular, experienced significant impacts, with unprecedented rainfall causing widespread flooding in the Emilia Romagna region [3]. The frequency of such climate-related events is further compounded by Italy's seismic vulnerability, with the country having sustained €150 million EUR in damages over the past 50 years due to earthquakes [4].

Beyond human casualties and direct economic losses from property damage, disasters can also lead to severe indirect losses. Indirect losses resulting from business interruption have been proven to significantly impact economic losses, as demonstrated by Rodrigues et al. [5]. In many cases, indirect economic losses surpass direct losses due to building damage, like in the case of the Ecuador earthquake in 1987 where indirect losses recorded were 7 times greater than direct losses [6]. Similarly in Italy, indirect losses due to business interruption - combined with interest of public debt that compounds over the years - re estimated to have exceeded direct losses by a factor of 3 to 10 [4]. To address the issue of understanding indirect losses in the Italian peninsula, Di Ludovico et al. [7] performed an in-depth study of the correlation between damage and indirect economic losses analyzing the data from the 2009 L'Aquila earthquake. Indirect losses are not only influenced by the extent of building damage but also by external factors related to response and recovery efforts. Key contributors include the costs of post-disaster population assistance [8] and disruptions to economic activities, such as services and industrial production [9]. Therefore, the usage class of a building plays a crucial role in determining the extent of these indirect losses [10].

Given that indirect losses are heavily influenced by the response and recovery to extreme events, resilience can be leveraged as a critical metric for assessing these impacts. The concept of resilience has been adapted to the built environment to quantify the impact of multiple hazards, each with its own domain-specific characteristics. In general, resilience is used to describe the performance of a system affected by an adverse event [11-15]. The concept of resilience for the built environment and buildings was introduced by Bruneau et al. [16] in relation to seismic events. The resilience concept encompasses four major metrics: Robustness, Redundancy, Rapidity, and Resourcefulness, with the last two referring to post-disaster response and recovery phases

To assess and enhance the resilience of buildings, the REDi guidelines [17] were introduced specifically for seismic hazard. These guidelines establish resilience objectives and assist designers in integrating multiple resilience aspects beyond life safety, including downtime reduction, repairability, and loss mitigation. Over time, the REDi framework has been expanded to address other hazards, such as flooding and windstorms [18-19].

Most indirect losses assessment frameworks rely solely on damage scenario due to the event, neglecting different possible recovery paths, which can greatly influence the downtime. From a stakeholder's perspective, understanding the actions needed to prepare for an adverse event can significantly reduce the long-term impact of extreme events over the built environment.

This paper presents a novel framework to assess the resilience of a building by integrating direct and indirect losses and leveraging resilience (functionality-time) curves. The framework is designed to be applicable to multiple hazards, enabling to assess the resilience of a building over the whole life cycle when subject to multiple extreme events.

The proposed framework is applied to a case study building: a new multi-story precast concrete structure featuring rocking-dissipative structural connections (PREcast Seismic Structural System - PRESSS [20-24]). Seismic and flood hazard events, conditioned to a probability of occurrence, are considered and a component-based loss modelling approach is used to assess their impacts.

The paper is structured as follows. Section 2 presents the proposed methodology for assessing the indirect losses by means of resilience curves, including the specific methodologies employed for Seismic and Flood risk assessment. Section 3 presents the case study, along with the hazard description and related modelling approach. In Section 4, results are discussed, and Conclusions are presented in Section 5.

2 METHODOLOGY

This section describes the methodology used to estimate the combined post-disaster direct and indirect losses. The approach follows a component-based loss assessment framework to first estimate direct losses and expected downtime (business interruption). These results are then used to construct a resilience curve for the building, which serves as the basis for estimating indirect losses.

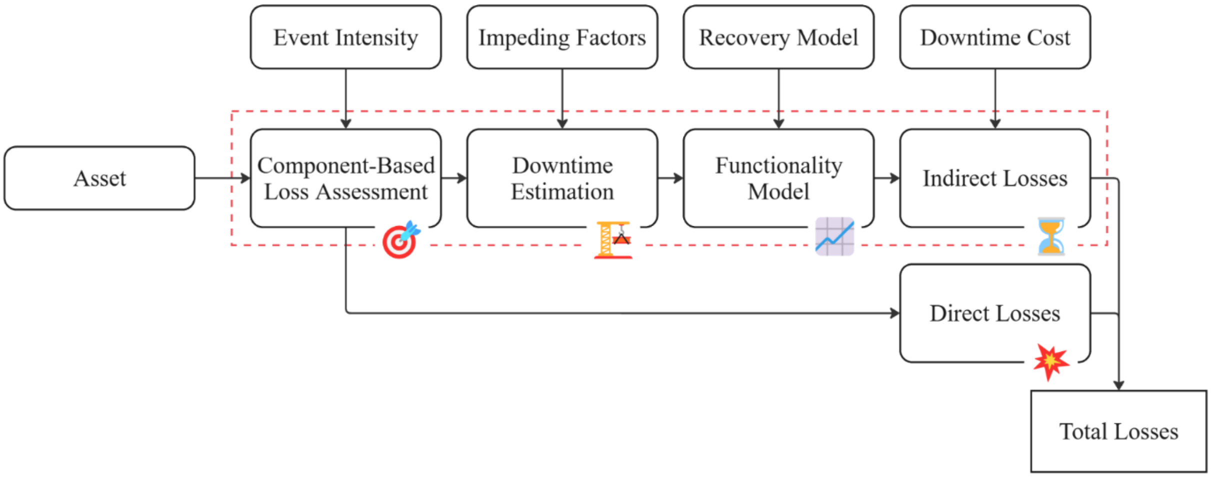

Figure 1: Overview of the proposed framework to estimate direct and indirect losses.

The framework (Figure 1) begins by defining the asset (building) and its location. Once the asset is characterized, different hazard scenarios and their associated intensity measures are considered. For each hazard and intensity level, defined by the return period, a component-level loss assessment is conducted to quantify damage to building components and estimate direct economic losses. This is achieved using probabilistic methodologies such as FEMA P-58 [25] for seismic hazards, which employs a Monte Carlo simulation to model uncertainty in damage realizations and their corresponding consequences.

Based on the damage scenario, repair times can be estimated based on the number of damaged components and their damage state. Impeding factors, delaying the start of the repair phase, are incorporated based on the specific hazard. These factors may include inspection delays, permitting requirements, resource availability, contractor mobilization, and material procurement. Once these factors are accounted for, the total downtime for the building is computed. The sequence of repairs and the restoration of different functional states (e.g., Immediate Occupancy, Functional Recovery, and Full Recovery) are modeled using approaches such as REDi [17], which refines downtime estimation by considering repair scheduling constraints.

By combining the result for direct losses and downtime, the resilience curve of the building is constructed. The resilience curve represents how the building's functionality evolves over time following the hazard event. From this curve, the loss of resilience [16] is computed, which quantifies the loss of functionality over time and serves as a key metric for assessing indirect losses. The indirect losses are then estimated by linking downtime impacts (e.g., business interruption, temporary displacement costs, and/or operational losses) to the resilience curve. Finally, total losses are computed by summing direct and indirect losses for each hazard scenario.

It is important to note that while the methodology for loss assessment varies across different hazards, once a resilience curve is established, the same procedure can be applied uniformly across multiple hazards to estimate indirect losses.

2.1 Direct loss assessment

A component-based probabilistic framework is employed to estimate direct losses. While this research specifically focuses on seismic and flood hazard, a similar methodology can be extended to other hazards such as windstorms [28-30].

For seismic hazard, the FEMA P-58 [25] methodology is used to model damage at the component level, employing fragility curves which represent the probability of achieving or exceeding a certain damage state. FEMA P-58 [25] was developed within the framework of Performance-Based Earthquake Engineering (PBEE) and provides a probabilistic approach for estimating losses. The methodology employs Monte Carlo simulations to capture the uncertainty in damage states, repair costs, and repair durations. The output includes both the damage realizations, which identify the specific components affected in each sample, as well as the associated consequences that are summed to define the building direct losses.

For flood hazard, a similar approach is used to estimate damage to building components during a flood event. This study follows the methodology proposed by Nofal et al. [26] and modified by Ciurlanti et al. [27], which applies a probabilistic damage function to each component based on the internal flood depth. In this study, flood duration and flow velocity are not explicitly modeled. The framework is extended to account for uncertainties in flood exposure, damage functions, and repair requirements. A more detailed overview of the methodology employed for the flood component-based assessment is presented in Ciurlanti et al. [27].

2.2 Downtime assessment

Once direct losses and damaged components are identified, the next step is to estimate building downtime, which represents the time for repairs before the building can regain full functionality.

FEMA P-58 [25] includes a downtime estimation methodology, but it primarily focuses on component-level repair times and does not fully consider impeding factors—delays that occur before repairs can begin. These impeding factors are critical because they represent real-world constraints that are strictly related to the immediate response after an event. Some of these impeding factors are shared among different hazard types, such as engineering mobilization, contractor mobilization, and financing of the repairs. Other more specific impeding factors can include the post-earthquake inspections for seismic events, as well as restoration and cleaning after flood events. REDi guidelines for flood [18] and earthquake [17] provide a detailed description of the value of the impeding factors and the sequences of actions needed before the repairs can commence.

Moreover, REDi [17] improves downtime estimation by introducing a repair scheduling model that accounts for workforce availability and repair sequencing across different building components, floors, and functional systems. This approach provides a more realistic estimate of how repairs progress over time by considering multiple functional recovery targets (Immediate Occupancy, Functional recovery, and Full Recovery), as well as considering the repair sequences over different components and multiple floors under the constraint of the availability of workers and the ability of the workers to perform repairs concurrently.

By incorporating impeding factors and repair scheduling constraints, REDi [17] provides a more comprehensive estimate of downtime, which is crucial for assessing the recovery path to derive a resilience curve.

2.3 Resilience Curve definition

The final step in the framework is the construction of the resilience curve, which represents how the building's functionality evolves over time following a hazard event. This curve is essential for estimating indirect losses and understanding how long a building remains non-operational.

The resilience curve is defined by three key phases. First, the initial drop in functionality is associated with the building damage and related repair costs, described in terms of Probable Maximum Loss (PML), which is typically represented by the 90th percentile of direct cost realizations obtained from Monte Carlo simulations in the loss assessment phase [31]. This phase reflects the immediate impact of the hazard on the building's operability. Following this, there is a delay period during which no repairs occur, determined by the time required for impeding factors. Finally, the gradual recovery phase begins as repairs progress over time, leading to full functional recovery.

For sake of simplicity, the resilience curve is modeled as a trapezoid (Figure 2). The initial sharp drop represents the sudden reduction in functionality immediately after the event. This is followed by a plateau, during which functionality remains unchanged due to delays caused by impeding factors. Once repairs commence, functionality increases linearly until the building reaches functional recovery [17]. Although minor repairs may continue beyond this point, they are considered non-critical and it is assumed they do not significantly affect the building's operational capacity.

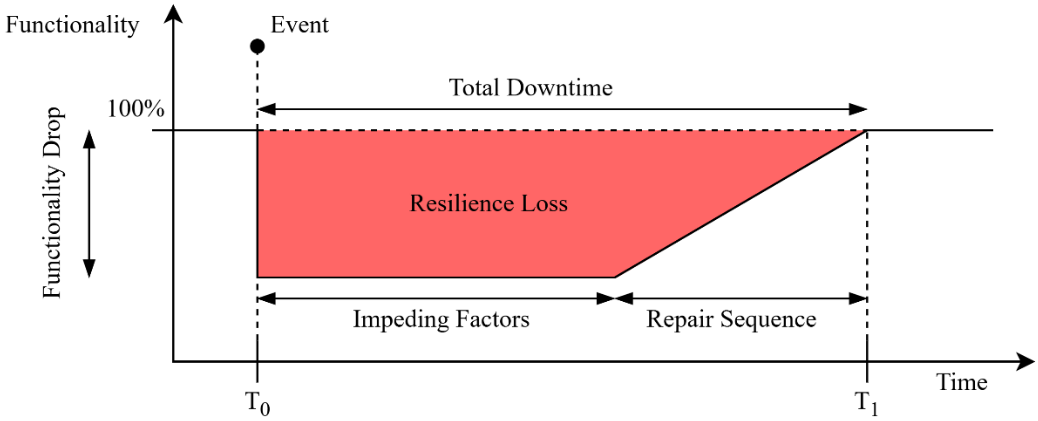

Figure 2: Schematic representation of the resilience curve employed in this study.

It is worth noting that the framework does not enforce a specific methodology for defining the resilience curve itself. The assumptions regarding the shape of the resilience function are here made to showcase the framework. Finally, the framework can be employed together with probabilistic frameworks for the definition of the resilience curves, such as the one proposed by Cao & Feng [32]. Including a probabilistic definition of a resilience curve can propagate uncertainties also in the evaluation of indirect losses.

2.4 Indirect Loss assessment

The concept of using resilience to evaluate economic losses is not new. The resilience deficit index, proposed by Singh et al. [33], extends the concept of loss of resilience to assign a monetary value to the resilience loss itself. However, the framework uses such an index not to compute indirect losses, but to offer a robust metric to compare building performance. On the other end, Cardone et al. [34] integrated the impact of downtime (both impeding factors and repairsequence) in the evaluation of indirect costs for buildings. However, the authors did not consider the evolution of functionality over time of the asset.

The framework proposed in this study is based on the hypothesis that the indirect losses are only dependent on the functionality of the building over time and are directly proportional to the loss of functionality.

$$IL = IC_{daily} \int_{T_0}^{T_1} \big(1 - Q(t)\big) dt \tag{1}$$

Where:

- IL is the total indirect losses related to the functional downtime,
- IC_{daily} is the daily cost of a total loss of functionality of the building,
- $Q(t)$ is the resilience curve for a given hazard and given intensity,
- T_0 is the time at which the event occurs,
- T_1 is the time at which the asset recovers its fully operational status,
- t is the time expressed in days.

It is worth noting that the integral is the resilience loss proposed by Bruneau et al. [16].
Finally, given that multiple realizations are obtained for one hazard intensity as part of the probabilistic approach, Eq.1 needs to be expressed in terms of expected values given an intensity measure (IM):

$$\mathrm{E}[IL|IM] = IC_{daily} \int_{T_0}^{T_1} (1 - E[Q(t)|IM]) dt \tag{2}$$

The direct and indirect losses can be combined into a single metric to compute total losses (Eq. 3):

$$E[IL|IM] = E[DL_{total}|IM] + E[IL_{total}|\mathrm{IM}] \tag{3}$$

It is worth noting that the same framework is applicable to multiple hazards, as long as a resilience curve is defined for the hazard scenario. Finally, the computation of indirect losses presented in Eq. 2 makes no assumption about the shape of the resilience curve but assumes that a finite resilience loss index can be computed.

3 CASE STUDY

This study applies the proposed framework to a five-story reinforced concrete office building. The building's structural configuration and dimensions are based on a previous study by Bianchi et al. [31]. However, this study considers a different hazard scenario and incorporates modifications to the façade system and building components.

The building has a rectangular floor plan of 32m × 18m. The horizontal load-resisting system consists of frames in the longer direction and walls in the shorter direction. The building has an inter-story height of 3.8 m. The lateral-resisting system is designed as a low-damage structure using the PREcast Seismic Structural System (PRESSS) [20-24] . This system employs post-tensioned unbonded tendons and damping devices to dissipate energy during seismic events and minimize residual drift.

The building also incorporates low-damage non-structural components. Specifically, the façade consists of cladding panels with U-shaped flexural plates [35] as upper connections in the frame direction, and point-fixed glass curtain walls in the wall direction. Additionally, suspended ceilings and internal partitions are designed to reduce seismic damage by integrating simple detailing modification as discussed in [36-37].

To carry out the analysis, fragility curves are needed to describe the performance of the components. Fragility curves for the low-damage structural components were developed by Matteoni et al. [38], while consequence functions were estimated based on engineering judgment. Concerning non structural element, the already available database provided by PACT [25], was extended with low-damage components curves from Bianchi and Pampanin [39].

The replacement cost per unit gross floor area was assumed to be \$2,200.46 USD/m² (\$204.43 USD/ft²), based on the Hazus Inventory Technical Manual [40] for usage class COM4 (Office, Mid-rise), referenced to the year 2022. The PACT tool [25] was employed to perform the loss assessment, incorporating inflation-adjusted prices to match the same reference year as the reconstruction cost.

For seismic scenarios, the building is assumed to be a non-essential facility with no pre-arranged general contractor or engineer. However, the asset is considered insured. For flood scenarios, the building is also assumed to be insured, with no pre-arranged engineer or restoration mobilization contract. However, no constraints are imposed on the restoration and cleanup budget. The median impeding factor values were taken from the REDi guidelines for floods and earthquakes [17, 18]. The procurement time for long lead time components was assumed to be 12 weeks.

The cost related to the downtime of the building is estimated from the Hazus Inventory Technical Manual [40], assuming it to be equal to the total loss of income for a COM4 building. The estimated daily cost of a total loss of building functionality was thus assumed to be \$14.96 USD/m² (\$1.39 USD/ft²).

With a gross floor area of 579 m² (6200 ft²), the total replacement cost is estimated at \$6,337,330 USD, while the daily downtime cost is estimated at \$43,090 USD.

3.1 Hazard scenarios

Two scenario events were selected to carry out the investigation, one for seismic and one for flood. The seismic intensity was chosen to be relative to an high seismicity area in Italy on soil class C. The chosen return period for the seismic action was 975 years (peak ground acceleration at bedrock 0.334 g). To perform the analyses, 11 spectral-compatible unscaled ground motions were selected from the Engineering Strong Motion database [41]. The non-linear time history analyses were carried out on two separate 2D numerical models for both principal directions of the building. Details about the modeling approach can be found in [38, 42].

Concerning the flood extreme event, an intensity relative to a return period of 500 years for a medium flood hazard zone in Italy was considered, leading to an internal flood depth of 0.781 m. The choice of a lower return period is due to the availability of hazard curves for flooding events.

4 RESULTS AND DISCUSSION

The analyses were conducted following the approach described in Section 2, to derive both cost and downtime values for each building component.

For the seismic event, 200 samples were run using PACT [25], and the total loss for each realization was computed for the selected hazard scenario. Downtime was evaluated for the 50th percentile of losses (i.e., the 50% probable maximum loss), and the REDi [17] framework was employed to estimate the repair sequence and delay time to functional recovery. It is worth noting that a more rigorous approach would involve using the expected values of downtime and impeding factors from all realizations (instead of a selected percentile) to construct the expected resilience curve. However, the primary scope of this paper is to present the framework for computing indirect losses. Therefore, only one resilience curve was sampled for the seismic event. As a result, the resilience curve was obtained just for the realization correspondent to the 50th percentile of the repair costs. Once the curve was derived, the indirect losses were computed through the proposed resilience loss index.

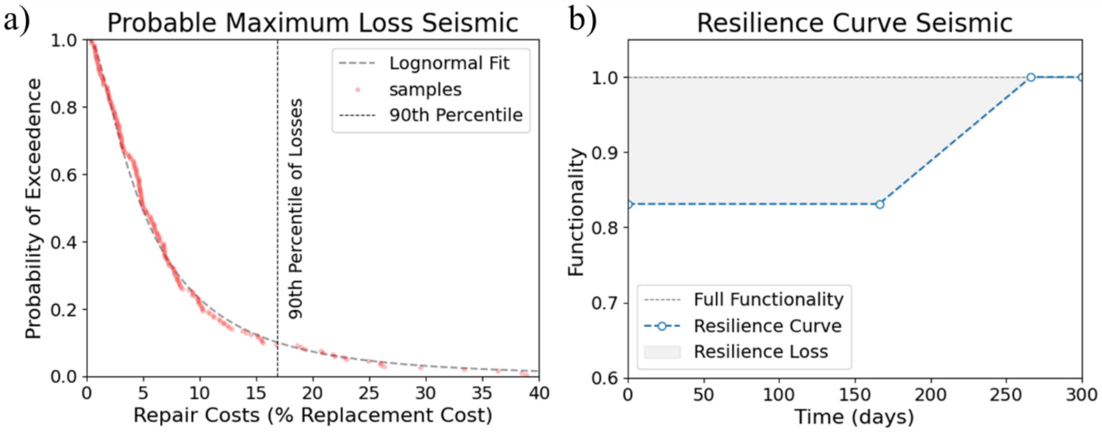

Figure 3: Representation of the a) probable maximum loss for the seismic event, computed for direct loss (repair costs) and, b) the resilience curve corresponding to the 50th percentile of realizations.

To build the resilience curve, the initial functionality drop was defined from the 90th percentile of losses, or the loss corresponding to a 10% probability of exceedance [31] (Figure 3a) - typically used by finance industry Once the curve was derived (Figure 3b), the indirect losses were computed using the resilience loss index. The expected losses conditioned on the event were estimated to be approximately $475,188 USD, or 7.5% of the replacement value of the structure. Meanwhile, the probable maximum loss (corresponding to a 10% probability of exceedance) was estimated to be around 16.9% of the reconstruction cost of the asset. These values are relatively modest due to the implementation of an integrated low-damage system, also considering the chosen intensity.

Regarding downtime, despite the limited number of damaged components, impeding factors are expected to significantly increase the total downtime. The primary contributors to delays in the repair phase are elevators and mechanical equipment, which are subject to long procurement times. These findings highlight that even in a low-damage system, asset functionality can be jeopardized by outside factors. Addressing these constraints is crucial for achieving a faster recovery and thus limiting indirect losses.

Despite the low initial drop in functionality, the resilience index indicates an expected functionality loss of 36.5 equivalent days (i.e., equivalent to 36.5 days of 0% functionality). By applying the proposed framework, the indirect losses expected for the asset, under the assumptions outlined in Sections 2 and 3, and expressed as a loss of income, can be estimated at approximately $1.572 million USD, or about 24.8 % of the replacement cost of the structure.

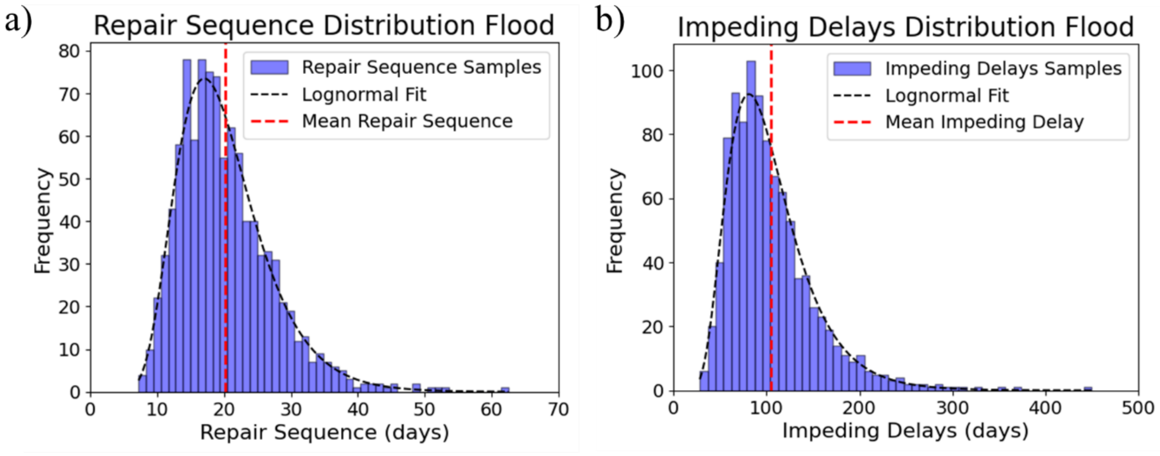

Figure 4: Sampled realizations for a) repair sequence for the damaged components, and b) impeding delays for the flood event.

For the flood event, 1,000 samples were run for the selected scenario. Unlike the seismic scenario, all samples of both repair sequence and impeding factors were analyzed to compute a probabilistic distribution of the resilience curve. Each realization of the resilience curve shares the same initial drop value, chosen as the 90th percentile of losses or the loss corresponding to a 10% probability of exceedance, like the earthquake scenario (Figure 5a). For each resilience curve realization, the resilience loss index was computed to obtain a distribution of the indirect losses. The choice of a higher number of realizations was related to the propagation of uncertainties from the damage realizations, thru the downtime estimation and finally to the indirect losses.

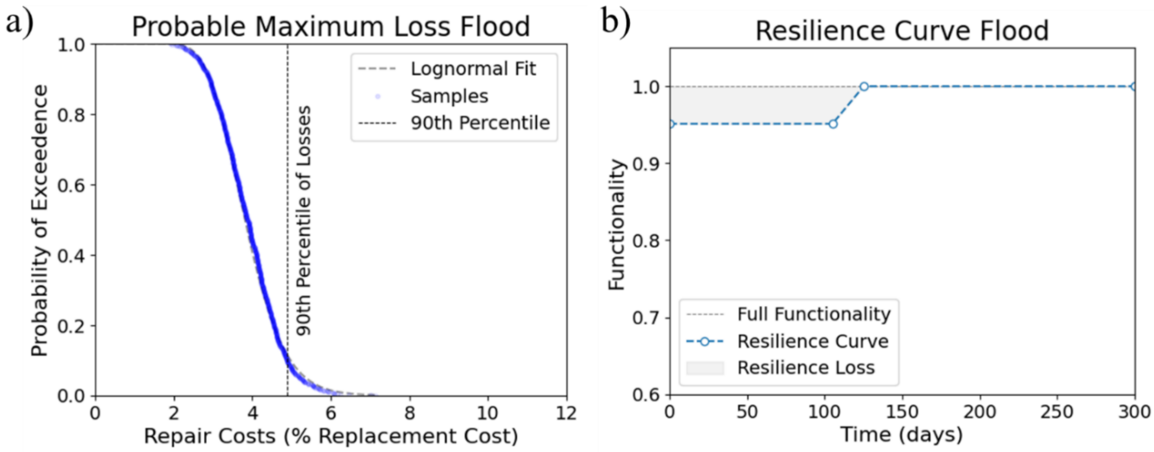

Figure 5: Realizations for a) direct losses (repair cost) and relative probable maximum losses, and b) expected resilience curve representing the average realization of impeding factors and repair sequence.

By applying the REDi [17] methodology, each realization was used to sample both the impeding factors and the repair sequence (Figure 4). The resilience curves were then derived, and indirect losses were computed accordingly. The expected direct losses conditioned on the event were estimated to be approximately $246,537 USD, or 3.89% of the replacement value of the structure. Meanwhile, the probable maximum loss, relative to a 10% probability of exceedance, was estimated at 4.88% of the reconstruction cost of the asset.

For flooding events, it is important to note that since damage is concentrated on the lower floors, losses expressed as a percentage of reconstruction costs tend to be modest, as they are normalized based on the entire structure's value. Regarding downtime, once again, impeding factors contribute significantly to the total downtime. For the flood event, the resilience index indicates an expected functionality loss of 5.61 equivalent days. Like the earthquake analysis, by applying the framework presented in Section 2, the expected indirect losses for the asset, expressed as a loss of income, can be estimated at approximately $241,747 USD, or about 3.81% of the replacement cost of the structure (Figure 5b).

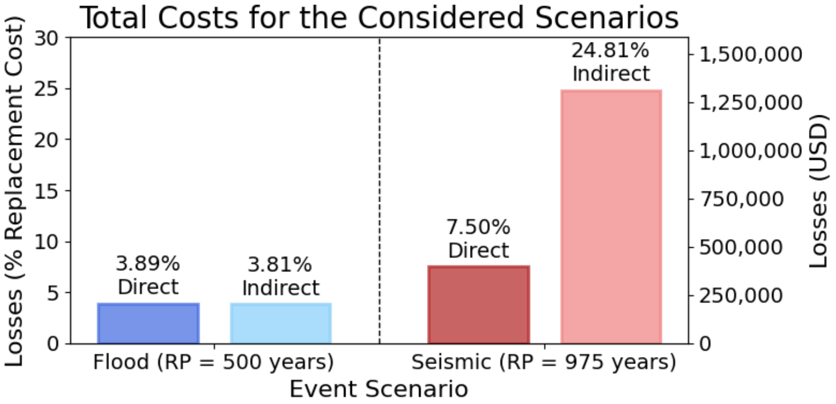

Figure 6: Overview of direct and indirect losses for both seismic and flood scenarios, expressed both in USD and percentage of reconstruction cost (RP = Return Period).

The results can be leveraged to inform decisions on cost reduction strategies related to these hazard events. In the case of seismic events, it is evident that mitigating impeding factors would be the most effective approach, as they account for most losses (Figure 6). For flood events, similar magnitudes of direct and indirect losses suggest that mitigation strategies should be chosen based on a cost-benefit analysis. The decision to prioritize reducing direct or indirect losses may depend on the relative cost of interventions on structural components versus measures to mitigate impeding factors, such as securing contractors on demand or establishing pre-arranged financing lines to enhance resilience to extreme events.

Given two different return periods were chosen regarding the two events, the values of losses for the two different hazards cannot be directly compared one to the other, as they represent events with different probability of occurrence. However, the aim of the paper was not to compare different hazards but rather comparing direct and indirect losses within the same scenarios.

It is also important to note that the values presented assume a loss of income under a 0% recapture ratio, which is highly conservative. It is unlikely that building operations would result in a total loss of income. Alternative recovery paths, accounting for partial income recovery, could be modeled as different resilience curve scenarios, and their effects could be incorporated into the framework.

5 CONCLUSIONS

This article introduces and applies a novel framework for estimating indirect losses by leveraging resilience curves. The framework was designed to be applicable to a wide range of extreme events, incorporating information regarding the asset usage class and the building response to the extreme events. It is demonstrated through a case study, subject to seismic and flood hazard. A probabilistic, component-based loss assessment approach is used to estimate both direct losses and expected downtime. The results of this probabilistic assessment inform the development of resilience curves, which are then used to evaluate indirect losses.

The findings demonstrate that the framework is applicable across multiple hazards and provides an estimation of income loss due to business interruption. The framework accounts for both the initial structural damage and downtime caused by impeding delays and repair durations. Results indicate that, in the case of flooding, indirect costs related to business interruption are comparable to direct costs, whereas for seismic events, indirect costs are expected to significantly exceed direct costs. This discrepancy arises because the building was designed to minimize direct economic losses from earthquakes, but no measures were implemented to mitigate downtime-related delays. This finding stresses the need for a comprehensive resilience strategy that not only reduces direct damage but also minimizes downtime. In the case of flooding, losses remain comparable due to the absence of preventive measures against flood risks for the building.

Future research should focus on developing a more robust, probabilistic-based definition of resilience curves. Additionally, the framework could be extended to conduct cost-benefit analyses to evaluate the effectiveness of mitigating impeding factors in reducing indirect losses.

6 AKNOWLEDGEMENTS

Authors acknowledge the financial support for Michele Matteoni's PhD scholarship provided by the PNRR funding scheme (Piano Nazionale di Ripresa e Resilienza, in Italian) as part of the National Research Centre CN1 on "HighPerformance Computing, Big Data and Quantum Computing"—Spoke 5 - Environment and Natural Disaster: Framework and methodologies for impact evaluation and risk mitigation, whose support is greatly appreciated. The authors also acknowledge the financial support from the European Union through the Horizon Europe Research Innovation Programme (Grant Agreement no. 101123467 MULTICARE—Multi-hazard low-carbon resilient technologies and multi-scale digital services for a future-proof, sustainable user-centred built environment).

REFERENCES

[1] UN Office of Disaster Risk Reduction (UNDRR), *Human cost of disasters*, 2020.

[2] Copernicus World Meteorological Organisation (WMO), *European State of the Climate Summary*. 2023.

[3] M. Valente, C. Del Prete, G. Facci, A. Martino, G.R. Grilli, F. Bravi, C. Reno, L. Ragazzoni. The 2023 floods in the Emilia-Romagna Region, Italy: A retrospective qualitative investigation into response strategies and criticalities. *International Journal of Disaster Risk Reduction*, **116**, 105089, 2025.

[4] S. Pampanin, A step-change for seismic risk reduction (towards a) national plan for the integrated seismic-energetic rehabilitation of the building stock. *Structural*, **242**, 2022. (in Italian)

[5] D. Rodrigues, H. Crowley, V. Silva, Earthquake loss assessment of precast RC industrial structures in Tuscany (Italy). *Bulletin of Earthquake Engineering*, **16**(1), 203–228, 2017.

[6] J.E. Daniell, B. Khazai, F. Wenzel, A. Vervaeck, The Worldwide Economic Impact of Earthquakes. *Proceedings of the 15th World Conference of Earthquake Engineering,* Lisbon, Portugal, 24-28 September, 2012.

[7] M. Di Ludovico, G. De Martino, A. Prota, G. Manfredi, M. Dolce, Relationships between empirical damage and direct/indirect costs for the assessment of seismic loss scenarios. *Bulletin of Earthquake Engineering*, **20**(1), 229–254, 2021.

[8] A. Mannella, M. Di Ludovico, A. Sabino, A. Prota, M. Dolce, G. Manfredi, Analysis of the population assistance and returning home in the reconstruction process of the 2009 L'Aquila earthquake. *Sustainability*, **9**(8), 1395, 2017.

[9] C. Benson, E.J. Clay, *Understanding the economic and financial impacts of natural disasters*, *Disaster Risk Management Series no. 4*, World Bank, 2004.

[10] R. Sousa, V. Silva, H. Rodrigues, The importance of indirect losses in the seismic risk assessment of industrial buildings – An application to precast RC buildings in Portugal. *International Journal of Disaster Risk Reduction*, **74**, 102949, 2022.

[11] S. Hosseini, K. Barker, J.E. Ramirez-Marquez, A review of definitions and measures of system resilience. *Reliability Engineering System Safety*, **145**, 47–61, 2016.

[12] S.A. Argyroudis, S.A. Mitoulis, L. Hofer, M.A. Zanini, E. Tubaldi, D.M. Frangopol, Resilience assessment framework for critical infrastructure in a multi-hazard environment: Case study on transport assets. *Science of The Total Environment*, **714**, 136854, 2020.

[13] G. Cremen, C. Galasso, J. McCloskey, Modelling and quantifying tomorrow's risks from natural hazards. *Science of The Total Environment*, **817**, 152552, 2022.

[14] F. Laurien, J.G.C. Martin, S. Mehryar, Climate and disaster resilience measurement: Persistent gaps in multiple hazards, methods, and practicability. *Climate Risk Management*, **37**, 100443, 2022.

[15] S. Hochrainer-Stigler, R. Šakić Trogrlić, K. Reiter, P.J. Ward, M.C. de Ruiter, M.J. Duncan, S. Torresan, R. Ciurean, J. Mysiak, D. Stuparu, S. Gottardo, Toward a framework for systemic multi-hazard and multi-risk assessment and management. *iScience*, **26**(5), 106736, 2023.

[16] M. Bruneau, S.E. Chang, R.T. Eguchi, G.C. Lee, T.D. O'Rourke, A.M. Reinhorn, M. Shinozuka, K. Tierney, W.A. Wallace, D. von Winterfeldt, A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*, **19**(4), 733–752, 2003.

[17] I., Almufti, M. Willford, *REDi™ Rating System: Resilience-based Earthquake Design Initiative for the Next Generation of Buildings*. ARUP, 2013.

[18] J. Hogan, I. Almufti, M. Ackerson, *REDi™ Rating System: Resilience-based Design Initiative for the Next Generation of Buildings – Floods*. ARUP, 2023.

[19] M. Burton, M. Nelson, *REDi™ Rating System: Resilience-based Design Initiative for the Next Generation of Buildings – Extreme Windstorms*. ARUP, 2022.

[20] M.J.N. Priestley, Overview of PRESSS Research Program. *PCI Journal*, **36**(4), 50–57, 1991.

[21] J. Stanton, W.C. Stone, G.S. Cheok, A hybrid reinforced precast frame for seismic regions. *PCI Journal*, **42**(2), 20–23, 1997.

[22] M.J.N. Priestley, S. Sritharan (Sri), J. R. Conley, S. Stefano Pampanin, Preliminary results and conclusions from the PRESSS five-story precast concrete test building. *PCI Journal*, **44**(6), 42–67, 1999.

[23] S. Pampanin, Emerging solutions for high seismic performance of precast/prestressed concrete buildings. *Journal of Advanced Concrete Technology*, 3(2), 207–223, 2005.

[24] H. Johnston, C. Watson, S. Pampanin, Shake table testing of an integrated low damage building system. *Second European Conference on Earthquake Engineering and Seismology*, Istanbul, Turkey, 24-29 August, 2014.

[25] Federal Emergency Management Agency (FEMA). *Seismic Performance Assessment of Buildings Volume 1 – Methodology – Report P-58-1*. Federal Emergency Management Agency, Department of Homeland Security, Washington DC, United States, 2018.

[26] O.M. Nofal, J.W. van de Lindt, T.Q. Do, Multi-variate and single-variable flood fragility and loss approaches for buildings. *Reliability Engineering System Safety*, **202**, 106971, 2020.

[27] J. Ciurlanti, S. Bianchi, M. Matteoni, B. Polidoro, M. Palmieri, S. Pampanin, Multi-hazard risk assessment of traditional vs. low-damage reinforced concrete buildings. M. Papadrakakis, M. Fragiadakis eds. *10th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Rhodes Island, Greece, 15-18 June 2025.

[28] M. Ciampoli, F. Petrini, G. Augusti, Performance-based wind engineering: Towards a general procedure. *Structural Safety*, **33**(6), 367–378, 2011.

[29] B. Alduse, W. Pang, S.K. Tadinada, S. Khan, A framework to model the wind-induced losses in buildings during hurricanes. *Wind*, **2**(1), 87–112, 2022.

[30] A. Merhi, B. Andow, H. Cruzado, C. Letchford, F. Lombardo, A framework for post-windstorm functional recovery of non-residential buildings applied to hospitals. *Reliability Engineering System Safety*, **253**, 110508, 2025.

[31] S. Bianchi, Integrating resilience in the multi-hazard sustainable design of buildings. *Disaster Prevention and Resilience*, **2**(3), 2023.

[32] X.Y. Cao, D.C. Feng, Probabilistic resilience assessment framework of structures considering the combined functionality-recovery-duration uncertainty. *Mechanical Systems and Signal Processing*, **223**, 111856, 2025.

[33] R.R. Singh, M. Bruneau, A. Stavridis, K. Sett, Resilience deficit index for quantification of resilience. *Resilient Cities and Structures*, **1**(2), 1–9, 2022.

[34] D. Cardone, A. Flora, M. De Luca Picione, A. Martoccia, Estimating direct and indirect losses due to earthquake damage in residential RC buildings. *Soil Dynamics and Earthquake Engineering*, **126**, 105801, 2019.

[35] A. Baird, A. Palermo, S. Pampanin, Controlling seismic response using passive energy dissipating cladding connections. *Proceedings of the 2013 NZSEE Conference*, Wellington, New Zealand, 26–28 April, 2013.

[36] A.S. Tasligedik, S. Pampanin, A. Palermo, Low damage seismic solutions for non-structural drywall partitions. *Bulletin of Earthquake Engineering*, **13**, 1029–1050, 2014.

[37] A. Pourali, R.P. Dhakal, G.A. MacRae, A.S. Tasligedik, Fully-floating suspended ceiling system: Experimental evaluation of the effect of mass and elastic isolation. *Proceedings of the 16th World Conference on Earthquake Engineering*, Santiago, Chile, 9–13 January, 2017.

[38] M. Matteoni, J. Ciurlanti, S. Bianchi, S. Pampanin, Fragility curves for low-damage rocking dissipative connections of precast concrete buildings. *Proceedings of the 3rd fib Italy YMG Symposium on Concrete and Concrete Structures*, Turin, Italy, 9-10 November, 2023.

[39] S. Bianchi, S. Pampanin, Fragility Functions for Architectural Nonstructural Components. In Journal of Structural Engineering. *American Society of Civil Engineers*, **148**(10), 2022.

[40] Hazus FEMA, *Hazus Inventory Technical Manual, Hazus 6.0*. Federal Emergency Management Agency, Washington DC, United States, 2022.

[41] L. Luzi, G. Lanzano, C. Felicetta, M.C. D’Amico, E. Russo, S. Sgobba, F. Pacor, *ORFEUS Working Group 5, Engineering Strong Motion Database (ESM) (Version 2.0)*. Istituto Nazionale di Geofisica e Vulcanologia (INGV), 2020.

[42] S. Bianchi, J. Ciurlanti, S. Pampanin, Comparison of traditional vs low-damage structural and non-structural building systems through a cost/performance-based evaluation. *Earthquake Spectra*, **37**, 366–385, 2020.