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# METHODOLOGY, SOFTWARE AND POLICY FOR OPTIMUM SEISMIC RESILIENCE OF HIGHWAY NETWORKS

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## ABSTRACT

Intercity networks constitute a highly important civil infrastructure in developed countries as they contribute to the prosperity and development of the connected communities. This was evident after recent strong earthquakes that caused extensive structural damage to key transportation components, such as bridges, tunnels and geotechnical works, that in turn led to a significant additional loss associated with the prolonged traffic disruption. In cases of seismic events in developed societies with complex and coupled intercity transportation systems, the interdependency between citizens' life and road functionality has further amplified the seismically-induced loss. Quantifying therefore, the resilience of road networks, defined as their ability to withstand, adapt to, and rapidly recover after a disruptive event, is a challenging issue of paramount importance towards holistic disaster risk mitigation and management. This study takes into account the above aspects of network resilience to earthquake loading and establishes a comprehensive, multi-criterion framework for mitigating the overall loss experienced by the community after an earthquake event. The latter is decoupled into the direct structural damage-related loss and the indirect loss associated with the travel delays of the network users, as well as the wider socio-economic consequences in the affected area. In order to reflect the multi-dimensional nature of loss, a set of time-variant, resilience-based indicators is herein introduced, while cumulative indicators are proposed for assessing the total loss incurred cumulatively throughout the entire recovery period. This probabilistic risk management framework is implemented into a software to facilitate informed decisions of the stakeholders, both before and after a major earthquake event, thus prioritizing the pre-disruption strengthening schemes and accelerating the inspection and recovery measures, respectively.

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### ABSTRACT

Intercity networks constitute a highly important civil infrastructure in developed countries as they contribute to the prosperity and development of the connected communities. This was evident after recent strong earthquakes that caused extensive structural damage to key transportation components, such as bridges, tunnels and geotechnical works, that in turn led to a significant additional loss associated with the prolonged traffic disruption. In cases of seismic events in developed societies with complex and coupled intercity transportation systems, the interdependency between citizens' life and road functionality has further amplified the seismically-induced loss. Quantifying therefore, the resilience of road networks, defined as their ability to withstand, adapt to, and rapidly recover after a disruptive event, is a challenging issue of paramount importance towards holistic disaster risk mitigation and management. This study takes into account the above aspects of network resilience to earthquake loading and establishes a comprehensive, multi-criterion framework for mitigating the overall loss experienced by the community after an earthquake event. The latter is decoupled into the direct structural damage-related loss and the indirect loss associated with the travel delays of the network users, as well as the wider socio-economic consequences in the affected area. In order to reflect the multi-dimensional nature of loss, a set of time-variant, resilience-based indicators is herein introduced, while cumulative indicators are proposed for assessing the total loss incurred cumulatively throughout the entire recovery period. This probabilistic risk management framework is implemented into a software to facilitate informed decisions of the stakeholders, both before and after a major earthquake event, thus prioritizing the pre-disruption strengthening schemes and accelerating the inspection and recovery measures, respectively.

### Introduction

Intercity transportation networks constitute a vital component of prosperity in modern, dense populated societies by facilitating the mobility of people, goods and services. Their smooth and uninterrupted operation is crucial for ensuring sustainability after extreme natural disasters. Earthquakes for instance, have caused extensive damage worldwide primarily to seismically sub-standard road or highway components (i.e., bridges, overpasses, tunnels etc) [1,2], as well as to adjacent geotechnical works that influence road functionality (e.g. slopes). These damages have led to enormous direct and indirect loss to the affected areas [3]. Direct loss is related to the repair of the damaged components, if one for the sake of quantification, neglects the priceless loss of human life, while indirect loss refers to the reduced functionality of the road network and the subsequent increase of travel time, the disturbance to social and professional life, business interruption, additional transportation cost and environmental implications [4,5].

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Direct and indirect loss associated with future seismic events affecting highway networks and their secondary roadways is assessed probabilistically [6–9], by coupling structural/geotechnical vulnerability [10–12] with the hazard at the site(s) of interest [13–15], as well as the altered traffic flow [16] and the wider economic, social and environmental consequences of both infrastructure failure and traffic diversion. Key in assessing the community loss is the concept of network resilience that encompasses the dimensions of network capacity, redundancy and recovery time to express its ability to withstand and adapt to a natural disaster, while being able to recover and restore the services offered quickly. Following the basic idea placed by Bruneau et al. [17] different studies aim to quantify resilience. Most of these efforts consist of models of general use [18,19] that may be applied to different kinds of complex systems such as hospitals [20], lifelines [21], energy systems [22] and infrastructure networks [23]. Due to the interdependency and complexity of roadway networks, as well as their extension in large geographical areas, quantification of resilience and informed decision-making based on the resilience metrics, face several challenges that hinder the practical application of such innovative concepts in existing roadway networks.

This paper presents a summary of a robust, multi-dimensional, easily applicable, decision-making framework for the quantification and efficient management of road network resilience to seismic hazard that treats all the prevailing uncertainties [24] with a balanced degree of sophistication. More precisely, it further aims to:

- develop a semi-probabilistic, multi-event, seismic hazard approach, specifically tailored to the salient features of network resilience analysis,
- integrate multi-phase, traffic analysis, considering that immediately after the natural disaster a critical network component (bridge, tunnel, etc) may either retain 100% of its traffic carrying capacity, operate partially, or be completely closed. In the latter two cases, the network recovers gradually while traffic adapts to the new network conditions of each post-earthquake phase.
- introduce resilience-based and cumulative roadway resilience indicators to quantify the degree of satisfaction of pre-defined resilience objectives such as: network redundancy, integrity of the network components, access to critical services, environmental aspects, minimum disruption of the financial activity and commerce.

With the aid of an open, GIS-based software ad-hoc developed for this purpose, the above methodological framework permits roadway stakeholders to form alternative risk management strategies to minimize earthquake-induced loss prior to a major seismic event and optimize the time and resources needed to restore functionality after the earthquake disaster.

### **Overview of the probabilistic resilience framework**

The methodology presented herein has been developed in the framework of the research program Retis-Risk ([www.retis-risk.eu](http://www.retis-risk.eu)) for the seismic risk assessment and resilience enhancement of interurban roadway networks. It is programmed as a standalone GIS software and is applied for the case of the interurban roadway network of the Western Macedonia prefecture, in Greece. Herein, the methodology, illustrated in Fig. 1, is demonstrated directly through the case study to demonstrate both the concept and its applicability. Egnatia Highway A2, is a recently constructed highway that extends from the western port of Igoumenitsa to the eastern Greek–Turkish border running a total of 670 km within a challenging earthquake prone region with design PGA varying from 0.16-0.24g. Egnatia Highway crosses the prefecture studied and consists the backbone of its road network, being complemented by several secondary roads that serve to the regional

transportation needs (Fig. 1, left). For the purposes of this pilot application both the main highway of the region under study and the secondary road system with speed limits lower than 90km/h are modelled with a total number of 263 bidirectional links and 283 traffic nodes [25].

### **Key components of the network system**

The set of key network components, that is, the structures and geo-structures whose failure may lead to road closure, is the first to be identified. Key components are assumed to be the bridges, overpasses, slopes and tunnels across the network. Given the structure of the interurban system studied, it is only bridges and tunnels that are studied in the particular case study, however, the methodology permits all the classes mentioned above. Overpasses of the secondary network are also neglected for simplicity given their smaller size, simpler structural systems and minor effect to the overall network resilience. Again, if deemed appropriate, their vulnerability can also be accounted for, both by the methodology and the software developed, which are structure-, size- and importance-independent. Effectively, any class of highway critical components with a known, common probability of exceeding pre-defined damage states and lead to road closure can be modelled as a distinct class. The same applies to special structures (i.e., long bridges or important tunnels) where a single structure can consist a class of each own. In the framework of the case studied, a total number of 74 dual branch (i.e. directions) key components were identified within the network system. Since the traffic along each network link is bi-directional, each identified key component comprises of two identical branches with a unique ID number per pair.

### **Pre-earthquake traffic conditions**

An Origin-Destination (OD) matrix is used to describe the initial, pre-earthquake, travel demands within the entire network for all possible combinations, extracted from a relevant study carried out by the stakeholder. Given the travel demands and the additional input of the traffic capacity of every network link, pre-earthquake traffic flows over the whole network are calculated according to Zhou et al. [16] It is noted that the OD matrix used herein, refers to travel demands during the typical hour of a normal day and thus appropriate scaling factors are applied to the results whenever daily traffic data are deemed.

### **Network portfolio value, repair cost ratio and traffic capacity evolution relationship**

A re-construction cost was calculated for each one of the 74 dual branch key components assuming a value of 17.000€m for the (twin) bridges and overpasses and 20.000€m for the tunnels. Based on the length of each component, the total value of the network portfolio was approximately assessed to 630 million euros. Moreover, a damage state-specific repair cost ratio was defined for all the key components according to Basoz et al. [26] assuming ratios of 0.03, 0.25, 0.75 and 1 for Damage State 1 (DS1) to Damage State 4 (DS4), respectively. A closure period of 0, 7, 150 and 450 days is assigned to the four damage states, DS1 to DS4, for all key network components, assuming that after this period, 100% of the traffic carrying capacity is regained. Notably, the above variables are open in the software for user-defined parameterization.

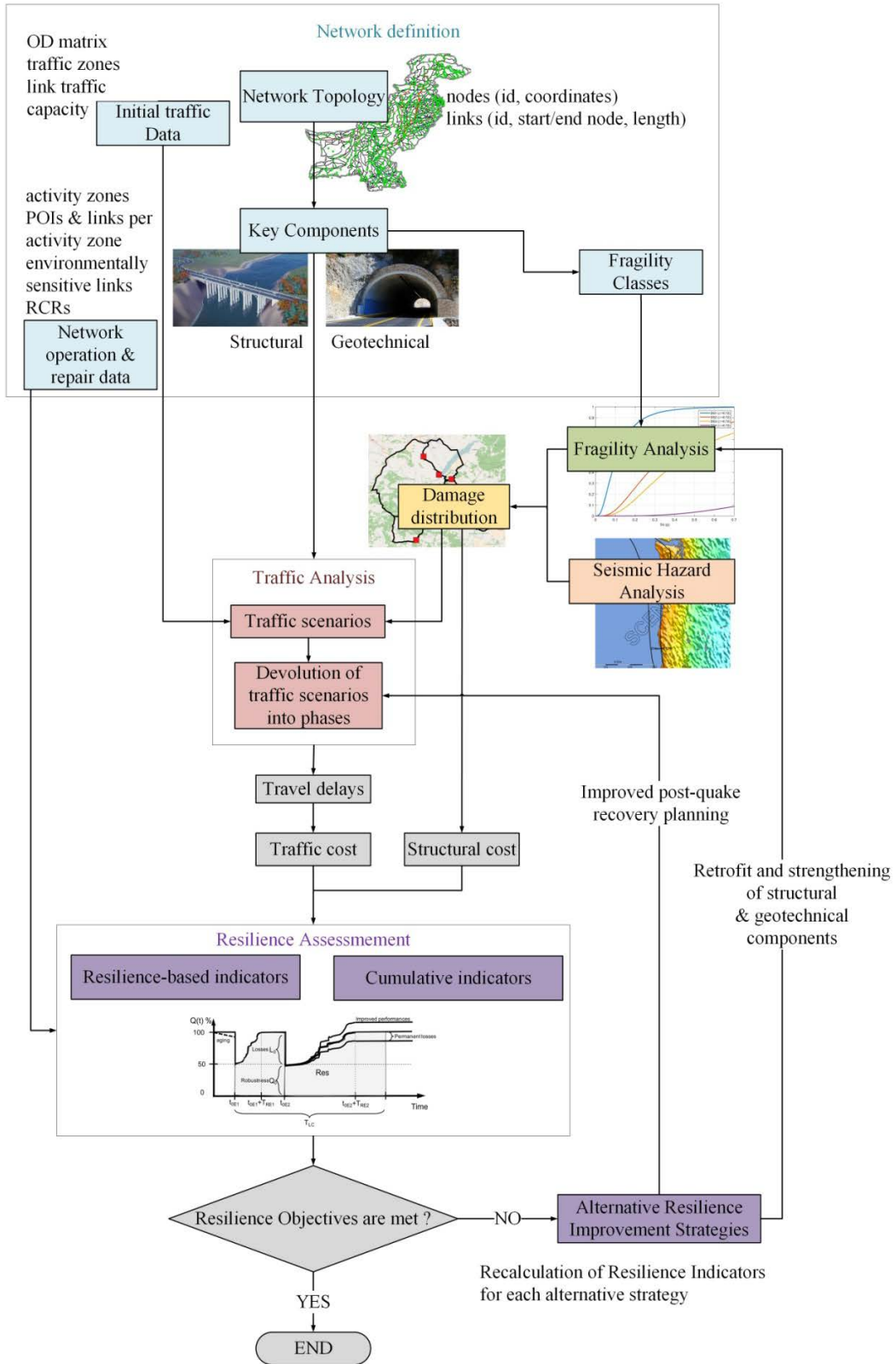


Figure 1. General workflow of the proposed framework

## Seismic hazard analysis

The integration of seismicity from different earthquake sources that is expressed in the form of conventional seismic hazard maps, is not applicable for the case of the post-earthquake traffic distribution, as the latter depends on the individual probability of operation of each network key component, which depends on the specific seismic scenario examined and the corresponding spatial distribution of the Intensity Measures (IM) of interest [27,28]. For this reason, hazard is herein assessed independently for each one of  $m$  seismic sources potentially affecting the network and for a set of  $k$  different return periods defined by the stakeholder. In the case studied, eleven seismic sources ( $m=11$ ) were identified, located either within the case study area or in its immediate vicinity. For every fault, ground motion maps associated with the  $k=4$  return periods, namely 100, 475, 980 and 1890 years, were generated leading to a sample of  $kxm$  maps depicting the spatial distribution of intensity for every return period and source combination.

## Fragility analysis

For every bridge and overpass key component of this study, a set of four fragility curves was generated for the four damage states considered, namely DS1 to DS4, corresponding to minor, moderate, extensive damage and collapse, respectively (Fig. 2, left). As already mentioned, bridges and overpasses are organized in classes of identical fragility, while for important bridges of the network a bridge-specific methodology is followed involving nonlinear static and incremental dynamic response history analysis. For simplicity, the stock of the 28 twin tunnels of the network was grouped into one gross tunnel fragility class based on relationships expressed in terms of peak ground velocity. In order to be consistent with the PGA-based maps developed, a transformation of PGV to PGA was performed according to Wald et al. [29]. Figure 2 (right) illustrates a sample fragility map showing the most probable Damage States of each key component on the basis of the PGA spatial distribution calculated for a sample seismic source (i.e., “Kozani”) and a return period of 475 years. As anticipated for a newly constructed highway that confronts to Eurocode 8, most critical components do not exceed DS1 and DS2 for the particular return period.

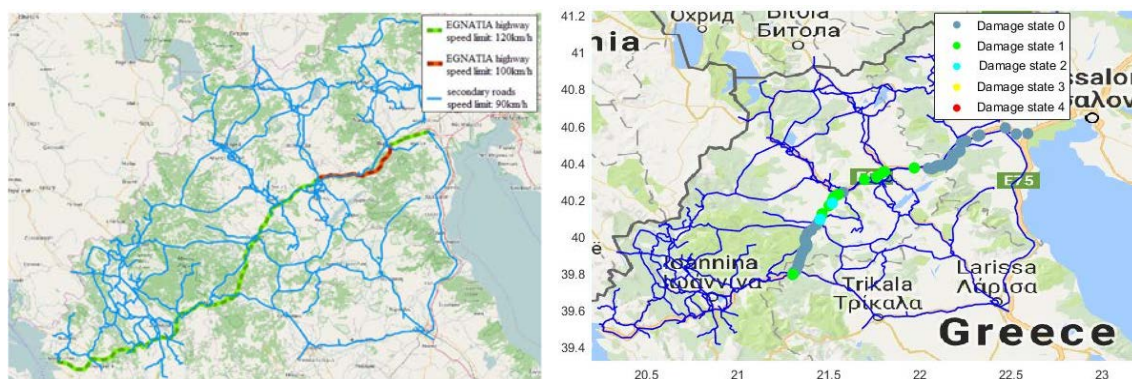


Figure 2. Sample fragility distribution map showing the most probable DS for every key component (left). Closed links for the recovery phase of the first 7 days, for the 475y map of “K” seismic scenario (right).



## Traffic Analysis

Having generated  $m=11$  different seismic maps for each return period, a corresponding set of traffic scenarios is then developed, under the simplifying assumption that immediately after an earthquake a key network component may either retain the 100% of its traffic carrying capacity (i.e., remain intact and hence, fully operational) or close and completely lose its traffic capacity. Along these lines, each one of the 74 key components is assumed to perform in a binary manner, associated to a value of either 1 (fully functional) or 0 (closed) based on whether the damage induced exceeds a critical, level of damage (in our case  $DS_{cr}=DS2$ ). Given the individual Damage State probabilities computed for the critical components per seismic map and return period, a Monte Carlo (MC) analysis is employed assuming 10 initial traffic scenario samples, that correspond to the state of open and closed network links of each map. Hence, a group of  $11 \times 10 = 110$  initial traffic scenarios is generated for each one of the  $k=4$  earthquake return periods. Every initial traffic scenario is then decomposed to several phases that evolve in time based on the stepwise opening of the key components throughout the recovery period.

## Seismic risk assessment of the “as-built” network

The total cost associated with each earthquake event  $k$  ( $k$  taking values from 1 to 4 for the 100, 475, 980 and 1890 years return period), is the sum of the cumulative direct cost of structural damage within the network and the indirect, earthquake-induced total traffic cost. Based on the repair cost ratios defined and the probability of attaining every damage state, the Estimated Structural Cost  $ESC_{k,m}$  due to earthquake with return period  $k$  stemming from a source  $m$  is derived for each one of the  $i=\{1..74\}$  key network components as:

$$ESC_{k,m} = \sum_{i=1}^{74} D_{i,k,m} \quad (1)$$

where:  $D_{i,k,m} = TBC_i \cdot (RCR_1 \cdot P_{DS1}^{i,k,m} + RCR_2 \cdot P_{DS2}^{i,k,m} + RCR_3 \cdot P_{DS3}^{i,k,m} + RCR_4 \cdot P_{DS4}^{i,k,m})$  and  $TBC_i$  is the total cost of re-constructing key component  $i$  calculated based on its length and the re-construction cost per meter values defined,  $\{RCR_1^i, RCR_2^i, RCR_3^i, RCR_4^i\} = \{0.03, 0.25, 0.75, 1\}$  are the repair cost ratios that correspond to damage states DS1 to DS4, and  $P_{DS}^{i,k,m}$  is the probability that the damage of the key component  $i$  exceeds DS1 to DS4 for the case of seismic source  $m$  and an event return period  $k$ . The earthquake-induced *traffic* cost (TC) is then calculated for every Monte Carlo simulated traffic scenario. This cost refers to the *additional* traffic cost during the entire recovery period of that particular traffic scenario (again for each seismic source  $m$  and an event return period  $k$ ), and as such, it is the sum of the product of each phase duration, times the corresponding additional travel cost [25]:

$$TC_{k,m,n_{samp}} = \sum_{p=1}^{P_{k,m,n_{samp}}} EC_{k,m,n_{samp},p} \cdot t_{k,m,n_{samp},p} \quad (2)$$

where:

$EC_{k,m,n_{samp},p}$ : is the *additional* travel cost due to travel delays during phase  $p$  of the  $n_{samp}$  traffic scenario sampled from the  $m^{th}$  IM distribution of earthquake  $k$  calculated according to [30]

$t_{k,m,n_{samp},p}$ : is the duration of phase  $p$  of the  $n_{samp}$  traffic scenario sampled from the  $m^{th}$  IM distribution of event  $k$

$P_{k,m,n_{samp}}$  : is the total number of recovery phases associated with  $n_{samp}$  traffic scenario sampled from the  $m^{th}$  IM distribution of event  $k$

Subsequently, the estimated traffic cost ( $ETC$ ) can be associated to every seismic map, as the mean of the costs calculated for the 10 Monte Carlo samples (i.e., each one for each phase) simulated from that map:

$$ETC_{k,m} = \frac{\sum_{n_{samp}=1}^{10} TC_{k,m,n_{samp}}}{10} \quad (3)$$

The maximum of the estimated structural and traffic cost out of the 11 cases of individual seismic sources leads to the envelope total network cost ( $TNC_k$ ) and identifies the *critical seismic source* that has the higher contribution to the overall loss among equiprobable possible costs corresponding to the 11 seismic sources.

### Resilience-based indicators

Resilience-based indicators, focus on the description of the time-variant nature of losses incurred by the community from the onset of the earthquake throughout the recovery period, and are introduced herein for the resilience-based assessment of the network ability to survive, adapt and recover after an earthquake. In order to explicitly reflect the time-dimension aspect, these indicators are distinctively evaluated for every traffic scenario arising from the MC simulation. More precisely, a set of qualitative resilience indicators are introduced accounting for the *Network functionality-time* relationship, given as a percentage of full network operation, which is the reference functionality before the earthquake, weighted by the importance of the links that remain operative after the earthquake. To further quantify the impact of the network disruption in the region of interest, a qualitative, also time-dependent, Consequence Vector  $\{ECO_p, CON_p, ENV_p\}$  is introduced. This is a three-component vector used for assessing earthquake loss to the wider financial life of the affected area, the connectivity among various Points of Interest (POIs) and the environment as illustrated in Fig. 3 [25,30].

### Risk management and mitigation strategies

Having identified the direct and indirect cost associated with every return period as well as the qualitative resilience indicators reflecting the wider consequences of the earthquake event, alternative risk mitigation strategies are developed and comparatively assessed. A retrofit scheme is developed for the particular bridges leading to updated fragilities or reduced probability of failure for the same Intensity Measure. The updated fragilities were in this case approximately derived by multiplying the mean threshold value of the corresponding “as-built” components by 1.3, for all DSs. A second risk management strategy consisting of improved post-earthquake response expressed through an improved traffic carrying capacity-time relationship was also considered. In this case, closure periods were assumed to be lower due to better recovery planning and were updated to 0, 4, 100 and 300 days instead of 0, 7, 150 and 450 days for Damage States 1 to 4, respectively. Figure 4 depicts the resulting estimated structural, traffic and total cost for different earthquake return periods for the case of the “as-built” network as well as the two risk management strategies (i.e., bridge retrofit or improved recovery planning) due to the seismic



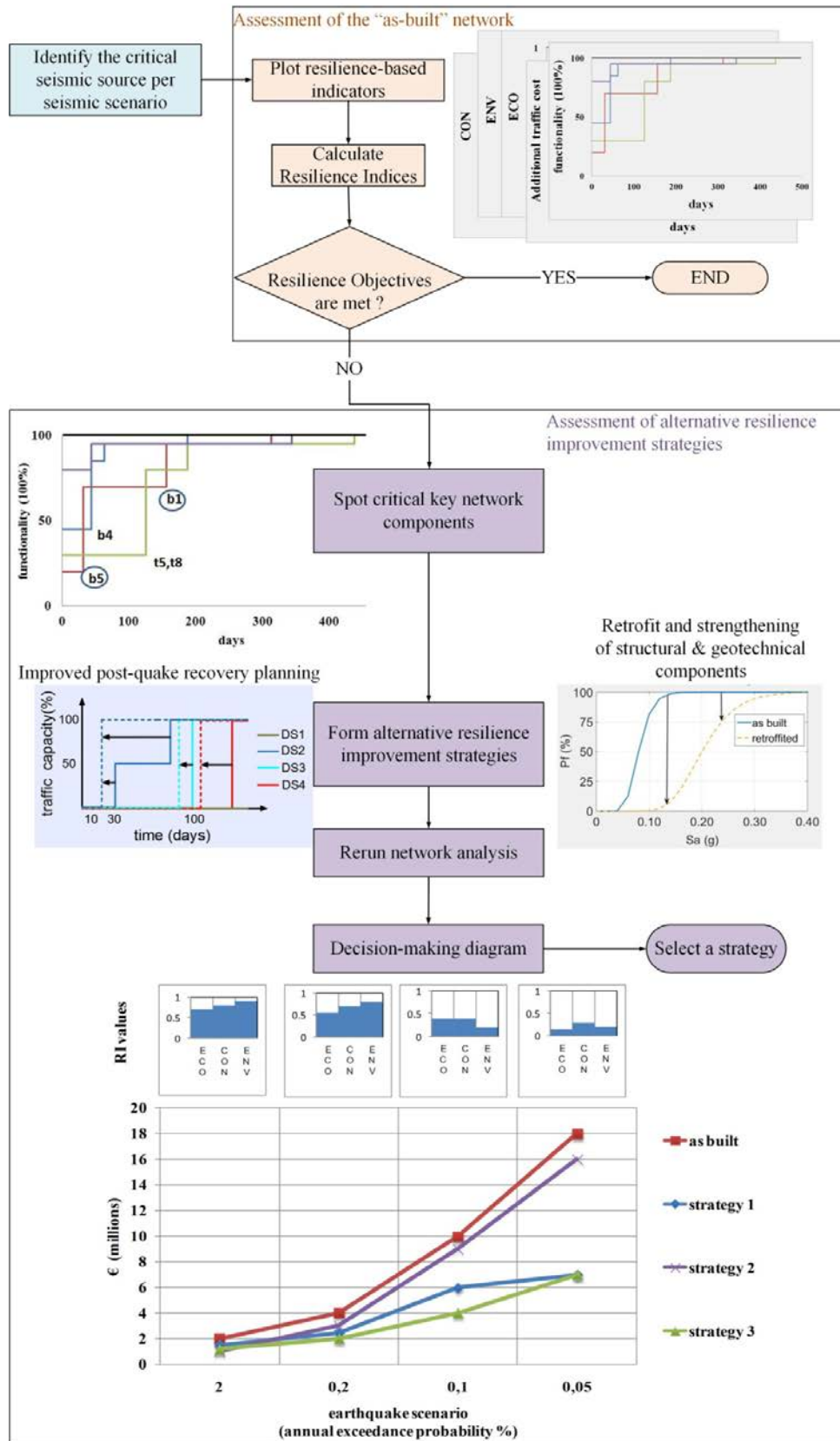


Figure 3. Workflow for the proposed decision-making process.

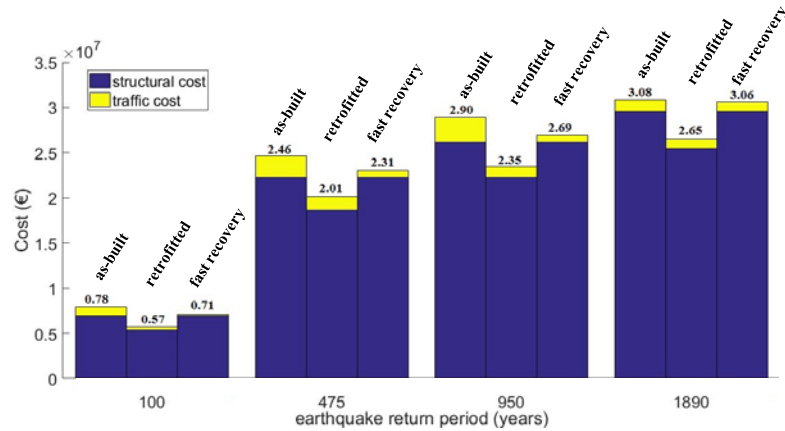


Figure 4. Expected costs for the four seismic scenarios for the case of the “as-built” network and the two risk mitigation strategies.

maps derived from the critical seismic source. Retrofit of selected key components is found to be more effective compared to the recovery plan enhancement for all the examined return periods. This is because, in this particular network, structural cost, which is essentially unaffected by an improved recovery, is the much higher than traffic cost. However, both risk management strategies contribute to a non-negligible, yet small (5-18%), extent to the the estimated total network cost reduction again due to the high resilience and low expected loss of the “as-built” network.

## Conclusions

In this study, a holistic framework is presented for the multi-criterion assessment and management of the seismic resilience of roadway networks through a balanced treatment of different sources of uncertainty that contribute to the overall network seismic risk, namely, vulnerability and hazard, coupled with refined traffic and consequences analysis. Several, novel, resilience-based and cumulative indicators are introduced for reflecting the time-variant nature of losses and providing a compact and more easily to interpret estimate of the extent of the losses incurred by the community after a major seismic event as well as throughout the entire recovery period. The holistic estimate of the direct (structural) and indirect (traffic) monetary loss as well the wider financial, network connectivity and environmental impact of seismic events with different probability of occurrence is used as a means to describe the evolution of network functionality and resilience taking explicitly into account its gradual recovery. The proposed framework is implemented into a GIS-based software and constitutes a useful decision-making tool for the stakeholders, to quantify and improve the resilience of their roadway network, by testing and adopting the most appropriate alternative resilience improvement strategy.

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