SEISMIC RISK, DIRECT, AND INDIRECT LOSSES FOR THE HISTORIC CITY OF RHODES

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Abstract: *A risk assessment model is developed for the historic city of Rhodes, Greece, with a focus on the buildings, residential and commercial, that are at risk from earthquakes, the main hazard that the city faces. The structural integrity of the buildings of Rhodes is tested under a stochastic event set of spatially correlated ground motion fields. They are generated with the OpenQuake platform via an event-based probabilistic seismic hazard analysis for 10,000 years using the 2020 European Seismic Hazard Model. All commercial or mixed-use buildings are assigned to corresponding lines of business according to census data and expert opinion, while using data from the 2020 European Seismic Risk Model to determine vulnerability functions, and from HAZUS-MH to assess the related downtime. The assessment takes as input the exposure model, the hazard, and the vulnerability of the assets to return the direct and the indirect losses per line of business. This allows the determination of the direct consequences to the city, translated to the economic losses to rebuild or renovate the damaged buildings. Stemming from the direct losses and especially the downtime, a mesoeconomic model is employed to determine the losses caused by business interruption on an event-by-event basis. By thus providing a comprehensive assessment of the risk faced by the city, the model can be used to develop a socioeconomic impact model and support the development of financial mitigation tools.*

1. Introduction

An urban seismic risk model is developed for the city of Rhodes, in the context of the TwinCity and HYPERION projects. The city of Rhodes is of great cultural significance, being a UNESCO world heritage site, while hosting one of the highest ratios of tourists per resident in Europe. In addition, it is located in an area of high seismicity that has experienced numerous catastrophic earthquakes since ancient times. A conventional assessment includes the building stock of the city, e.g. as in Silva et al. (2015) or Kohrangi et al. (2021), and can be expanded to include other infrastructure, based on the desired level of detail. In this occasion, the main path followed to assess the risk, and consequently the losses, for the city consists of: the creation of an exposure model that describes the assets of the city, the definition of the fragility and vulnerability of these assets, and the calculation of the aggregated direct losses for the city. The direct monetary losses are defined based on the cost to repair or replace the buildings that were damaged after an earthquake (Bazzurro and Park 2007, Aslani et al., 2012, Kohrangi et al., 2021). The direct losses, though, are not the only ones the city will suffer from. The damaged buildings will not be able to continue serving their purpose until they become again operational. Based on the severity of the event and the amount of direct damage it will cause, a lot of businesses will seize to function till the damages are repaired, thus generating losses that propagate between business that are interacting with each other. This failure propagation due to supply and demand outages are modeled based on the socioeconomic model proposed by Tsarpalis et al. (2023). Those losses will affect the property values and stock market and can become more intense in the case of Cultural Heritage areas that host highly vulnerable and impactful structures. Therefore, calculating the direct losses per different line of business, while knowing the economic relationship between each sector, allows the determination of the indirect losses, meaning the losses the city will endure due to the interruption of the business sectors. This data can, consequently, be used to design proper measures for the risk mitigation (Kaushalya et al., 2014).

2. Exposure model for the city of Rhodes

The creation of a detailed exposure model requires an extensive amount of information and data to realistically portray a complex system, like the one of a populous urban city. The Hellenic Statistical Authority, ELSTAT (2021), provides data from the 2011 Census per city block, including information about the number of buildings, the age and the material as well as their usage. Unfortunately, publication of the 2021 census data is still pending, limiting the representativeness of the exposure model.

The taxonomy employed conforms to the 2020 European Seismic Risk Model (ERSM20, Crowley et al., 2021). For the city of Rhodes 39 classes were used, with the main material (structural system) types shown in Table 1, incorporating all possible combinations of height and age. So, there are classes for different height levels (Low, medium, high rise) and different build code (Low/Medium/High code) based on the year of construction. It should be noted that there are no High-Rise unreinforced/reinforced masonry buildings, Low-Code steel structures, or Medium/High-Rise wood buildings, thus resulting to 39 classes in total. The main construction material in Rhodes is reinforced concrete (RC), with unreinforced masonry (URM) appearing mainly in the medieval city of Rhodes, which is the UNESCO world heritage site and therefore a site of great cultural and economic interest. Other materials—such as wood, steel, and reinforced masonry—also appear in smaller numbers. In Figure 1 the most common building material of each block is shown in different colours, showcasing the division between the old city (URM – light blue) and the more prevalent newer parts (RC – blue). According to their usage, buildings were also classified to different occupancy categories (or lines of business) as follows:

- Accommodation
- Food & beverage
- Offices
- Retail Stores
- Residential
- Wholesale trade & warehousing
- Others

The invested value of the building stock, estimated via the replacement cost for the entire city, is presented in Table 2. Replacement cost was estimated by assuming an average value of 1200 euros per m^2 of covered area. The percentages of buildings belonging to each material type or occupancy is shown in Figure 2.

Table 1. Taxonomy of building typologies adopted for Rhodes.

Abbreviation	Material
RCF	Reinforced Concrete Frame
RCW	Reinforced Concrete Wall
URM	Unreinforced Masonry
RM	Reinforced Masonry
S	Steel
W	Wood

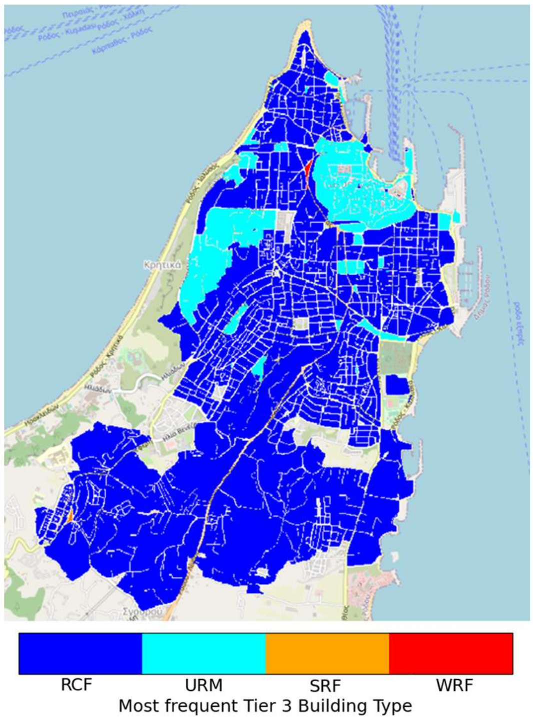
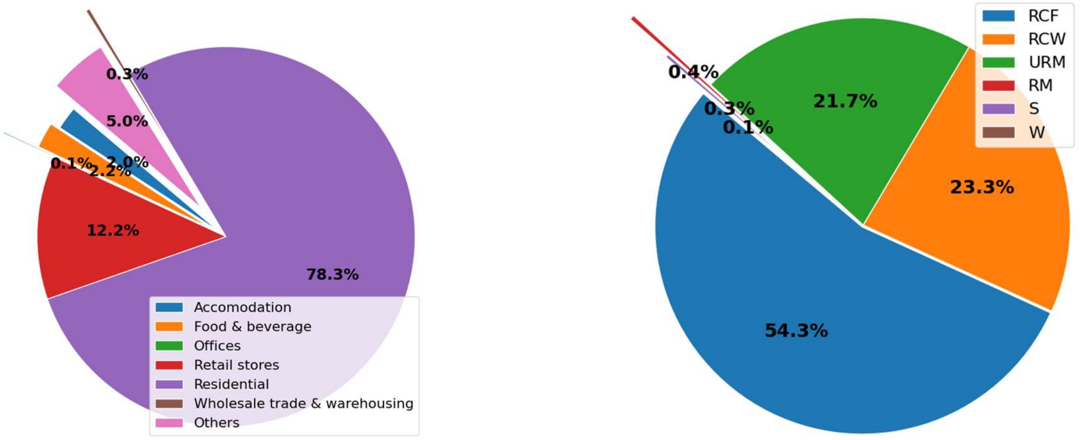


Figure 1. Dominant building typology per block for Rhodes, Greece.

Table 2. Replacement cost per line of business for Rhodes (in million euros).

Line of business	**Replacement Cost (million €)**
Others	282
Residential	4414
Wholesale trade & warehousing	20
Food & Beverages	120
Accommodation	109
Retail Stores	672
Offices	6
Sum	5624



(a) (b)

Figure 2. Percentages of buildings (a) per line of business (or occupancy) and (b) per building material.

3. Hazard, Fragility & Vulnerability

The seismic hazard is represented in the model via the intensity measure (IM) and its return period. The type of IM used in an analysis is directly linked with the type of building investigated. In the case of a whole city it is not easy to find an optimal IM: a (pseudo)spectral acceleration (Sa) at a period of 1 sec is appropriate for a midrise semi-flexible building, while a URM structure is better represented by an Sa at 0.1s or the peak ground acceleration. Employing multiple IMs would seem advantageous, but it carries the cost of needing (and storing) multiple ground motion fields, correlated across space and different periods. To reduce the amount of hazard data and simplify the pertinent calculations, a single IM is employed at the loss of some fidelity. The IM of choice in this case study is Sa(1s).

The IM values were calculated via event-based probabilistic hazard analysis (PSHA) through the OpenQuake engine (GEM, 2021) based on the 2020 European Seismic Hazard Model (ESHM20, Danciu et al. 2021). For simplicity, only part of the logic tree was employed, using the ground motion prediction equation of Cauzzi et al. (2014) for an investigation time of 10,000 years using the correlation model proposed by Jayaram and Baker (2009). A stochastic event set (SES) is created to generate long term assessment of impact. While results combining impact assessment from all scenarios in the SES are more informative, it is often the case that one seeks answers for specific what-is and what-if scenarios. Indicatively, results are shown for two arbitrary high-impact events that were chosen from the SES. The epicenter and the magnitude as shown in Figure 3: (i) an M6.1 event at 19 km from the centre of the city with rupture depth of 13.2 km and (ii) an M7.3 at 94 km and with rupture depth of 100km. The ground motion fields for the two events are shown in Figure 4.

The fragility curves and the vulnerability of the buildings were provided from ESRM20 and they determine the amount of damage that is expected upon the structure. By applying the fragility curves per event, the damage state (DS) of each building is determined. The damage states description is summed up as follows: no damage (DS0), slight (DS1), moderate (DS2), extensive (DS3), or complete damage (DS4). To define the number of buildings in each damage state, the IM values closest to each block is paired with the centroid of the block and the probability of being in each damage state is multiplied by the number of buildings inside the block. Subsequently, the buildings of all the blocks are summed per material and DS, and are presented for the chosen events in Figure 5 as percentages of the total number of buildings. The more vulnerable part of the city is the historical core, mainly comprising URM buildings. These are presented separately in a map in Figure 6, allowing us to observe in detail the effect of the events in the downtown.

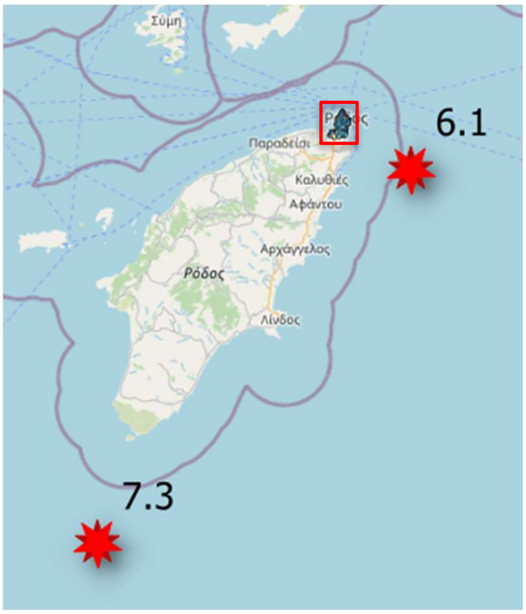
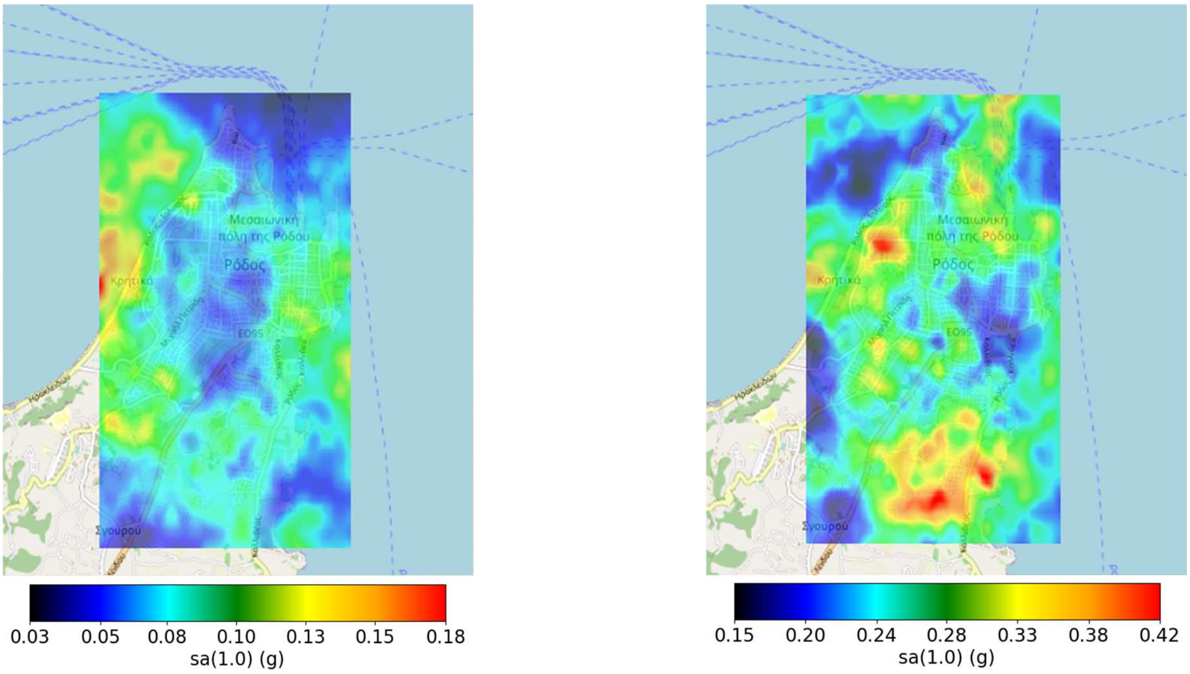
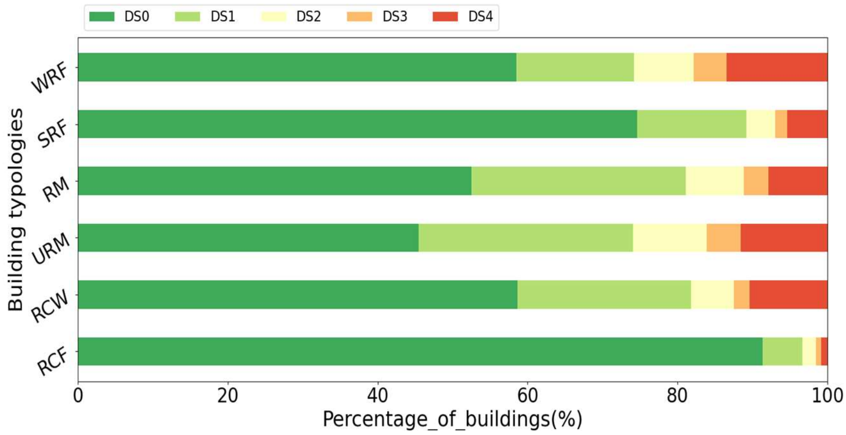


Figure 3. Map displaying the epicentre of two scenarios of seismic events, a moderate nearby M6.1 and a stronger but further away M7.3. The city of Rhodes lies in the northern tip of the island, as indicated by the red rectangle.

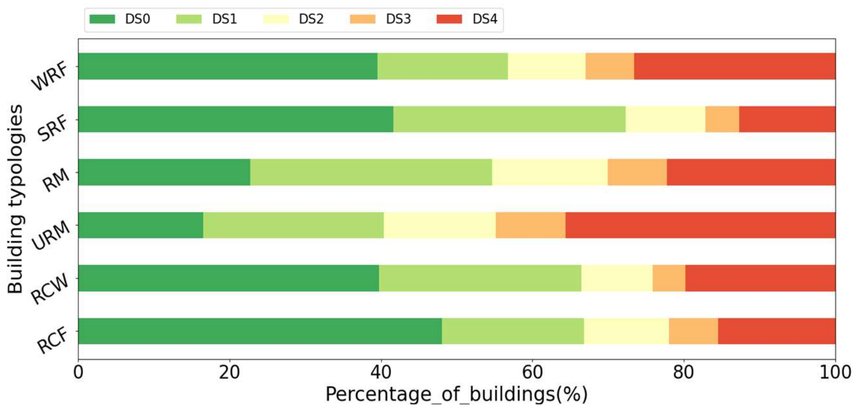


(a) M6.1, R=19km (b) M7.3, R=94km

Figure 4. Ground motion fields of Sa(1s) for the two scenario events of Figure 3.

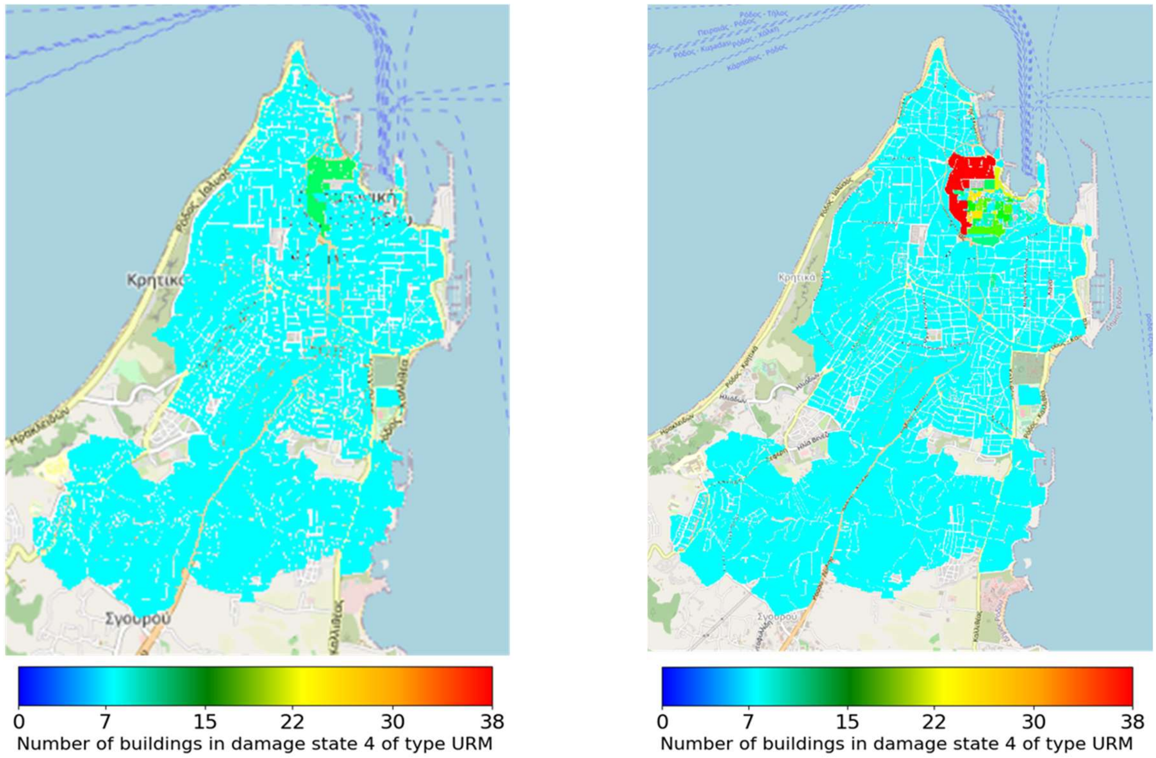


(a) M6.1, R=19km



(b) M7.3, R=94km

Figure 5. Percentage of buildings in each DS per building typology for the two scenario events.



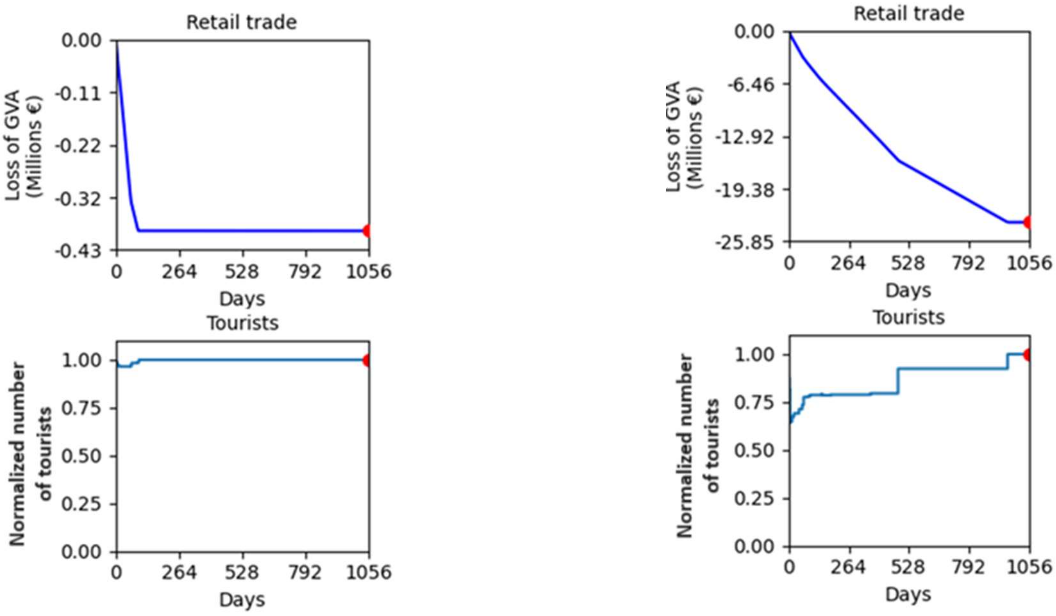
(a) M6.1, R=19km (b) M7.3, R=94km

Figure 6. Number of URM buildings in DS4 for the two scenario events.

4. Direct & Indirect Losses

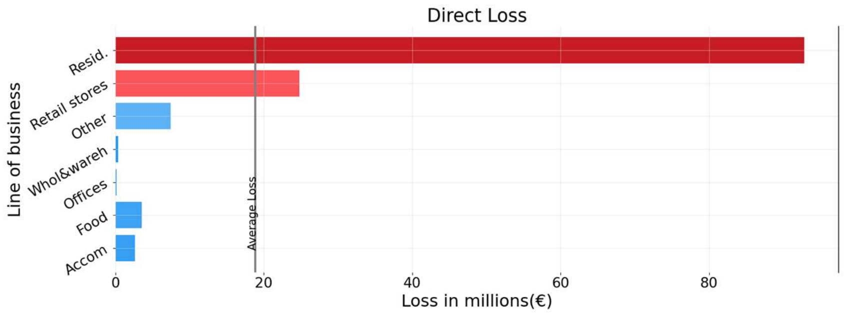
The risk assessment provides results for an SES, with damages calculated per line of business of the buildings. The direct damages are calculated using the vulnerability provided by ERSM20 per building taxonomy. As far as the indirect losses are concerned, the factor that is taken into consideration for their calculation is the downtime of the buildings and the associated business interruption. HAZUS (2020) provides information regarding the recovery time for a building to be fully functional based on its DS and occupancy. For the city of Rhodes, a mesoeconomic model is created, describing the relationship between each business sector and connecting the effect that the disruption of each will have to all the interdependent sectors, as developed by Tsarpalis et al. (2023). The combination of this data provides the necessary input to determine the indirect losses the city will sustain after a catastrophic event. Still, to achieve a seamless combination, one needs to be able to map the business sectors reported for the building stock (driving direct losses) and the overall economy (causing indirect losses). For example, the building stock may be classified as “Wholesale & Warehousing”, while the wholesale and warehousing sectors are tabulated separately for the economy, necessitating the splitting of the building stock to the two categories. Thus, local information and expert opinion was employed to match the two similar yet not identical sets of business sectors for the city of Rhodes.

The mesoeconomic model operates on the basis of Gross Value Added (GVA), which is a measure of the contribution to Gross Domestic Product made by an individual producer, industry or sector. In Figure 7 the progression of the loss of GVA over time is presented along with the time needed for the number of tourists to recover to pre-event standards. The period of 1056 days (~35 months) represents the maximum time needed for a residential building in DS4 to return to 100% functionality per HAZUS, multiplied by 1.1 for adding adequate time for the economic system to stabilize back to its initial (pre-disaster) state. The direct and indirect losses for the chosen events are shown in Figure 8 and Figure 9 per business sector.

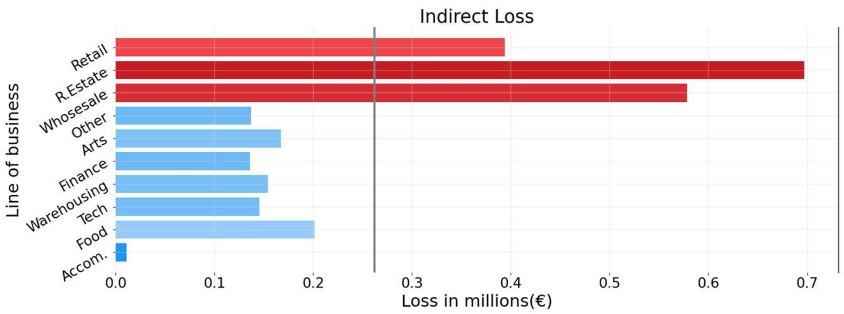


(a) M6.1, R=19km (b) M7.3, R=94km

Figure 7. Time history diagrams showing indicative results on the GVA loss for the Retail trade sector and the percentage of tourists visiting Rhodes, from the socioeconomic impact analysis of the two scenario events. To recover after the events, it takes (a) 116 days and (b) 938 days respectively.

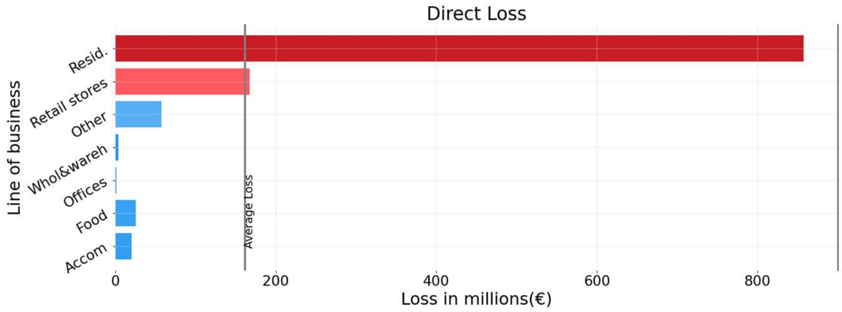


(a)

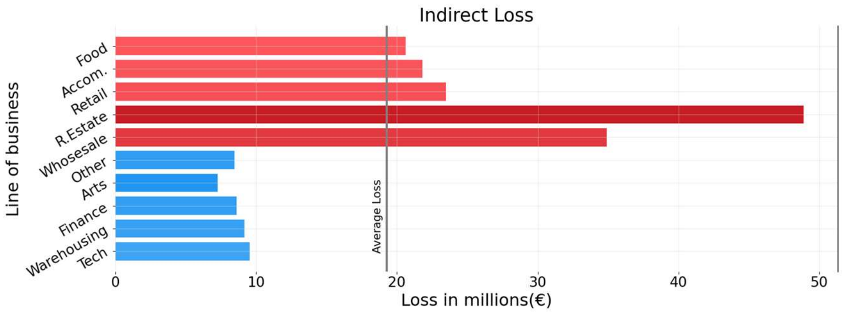


(b)

Figure 8. (a) Direct and (b) Indirect loss of buildings per line of business for an earthquake of M6.1, R=19km. Note that the horizontal lines are not the same.



(a)



(b)

Figure 9. (a) Direct and (b) Indirect loss of buildings per line of business for an earthquake of M7.3, R=94km. Note that the horizontal lines are not the same.

5. Long-term results

Aggregating all the events in the SES, the average annual direct loss per city block is shown in the map in Figure 10, staying near zero for the modern suburbs but exceeding 0.3 million euros per block in the vulnerable city centre. This map indicates the areas of interest that should be mainly taken into consideration when making decisions regarding mitigation actions. Also, it gives information about the amount of money that should be saved (e.g. in the form of bonds or insurance coverage) by the local authorities to potentially cover the losses created by a catastrophic event. Additionally, the aggregated average annual loss for the whole city, both in terms of direct and indirect loss is shown in Figure 11. Aside from the total indirect losses it is important to pinpoint the most affected business sector, which will require higher support, thus the distribution of the average annual indirect loss per business sector is shown in Figure 12, and its percentages in Figure 13 in a pie chart for better visualization. The average annual direct loss (AAL) for the city of Rhodes is 17.9 mil. €, while the replacement cost (RC) for the whole city is 5624.3 mil. €. Therefore, the ratio of the AAL to the RC is 0.32 %.

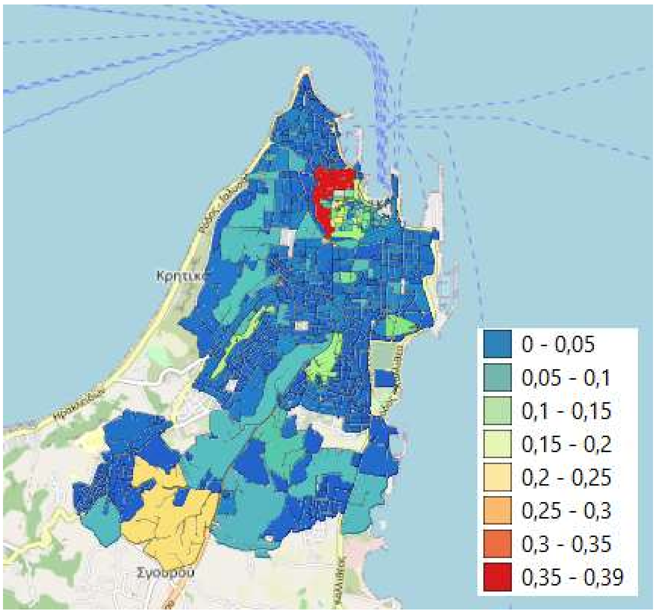


Figure 10. Average annual direct loss in million € per city block.

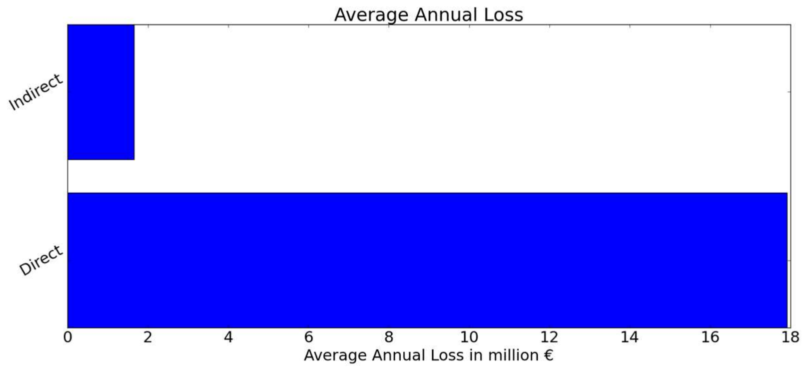


Figure 11. Aggregated average annual direct and indirect loss in million €.

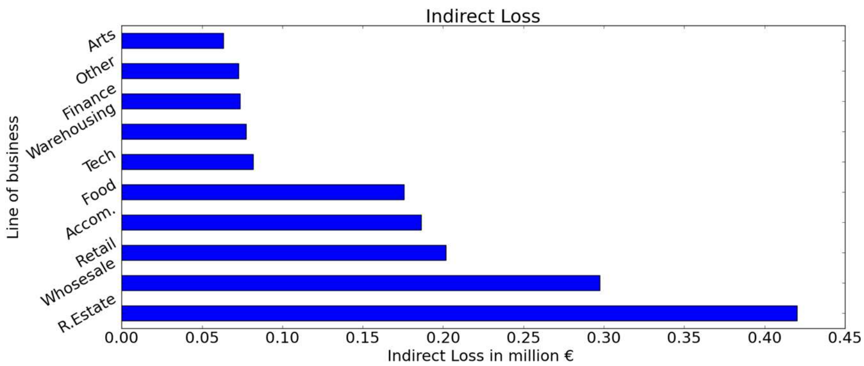


Figure 12. Average annual indirect loss distribution per line of business in million €.

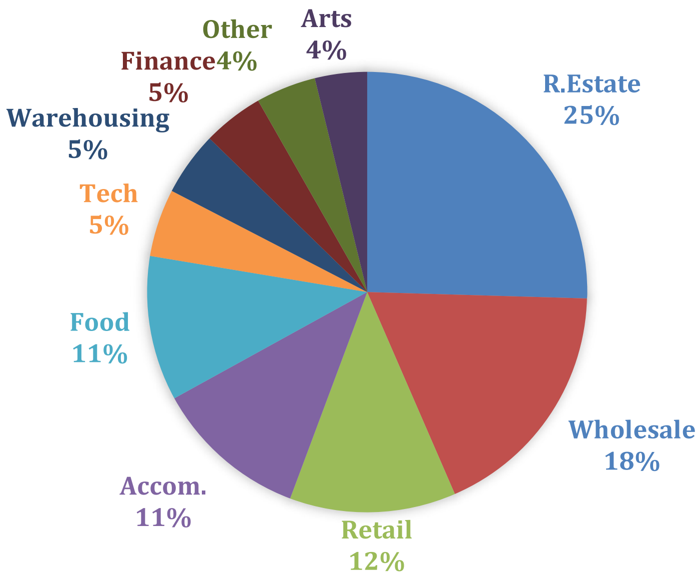


Figure 13. Percentage of average annual indirect loss distribution per line of business.

6. Conclusions

The seismic assessment of the city of Rhodes, Greece, is based on the creation of an efficient and detailed urban-scale model that combines information from public sectors (ELSTAT), European models (ESRM20, ESHM20), and regional input-output macroeconomic tables to simulate the behavior of the city after an earthquake. A probabilistic seismic hazard and risk analysis provides an SES with multiple potential scenarios of hazard-loss combinations. The medieval city contains most of the vulnerable buildings and carries the highest risk. Generally, the residential buildings are the ones that are responsible for most of the direct losses, also being the vast majority of the buildings in total. This also causes most indirect losses to appear in the real estate business that is directly connected to residential buildings. The indirect losses are significantly smaller than the direct losses. This may be explained in part by the use of a mesoeconomic model that only accounts for the GVA-based connections between different sectors, but does not necessarily consider the effect of lost housing on the workforce availability. Another important factor is that the indirect losses are highly season-dependent, as even a small earthquake can cause a disproportionally high indirect impact during the touristic season. By accounting for such underlying connections, the proposed model can help assess the capability of the city to function properly and help its timely recovery, avoiding the prolonged interruption of business and associated harm to the brand of city and its tourism.

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