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A SOCIOECONOMIC MODEL FOR ESTIMATING INDIRECT CONSEQUENCES OF EARTHQUAKE HAZARDS TO CULTURAL HERITAGE COMMUNITIES

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Abstract: *A socioeconomic model of the residents and visitors (i.e., users) and the local economy (i.e., production and consumption of goods, services, and small businesses) is proposed to simulate the core functions of a cultural heritage community. Given the direct infrastructure damages of an event, as those are derived by vulnerability and hazard assessment, the model is able to quantify the indirect losses per critical business sector as they evolve over time. This is accomplished by first deriving downtime estimates per sector, propagating the resulting disruptions through the demand-supply chain of the community, and then tracking their eventual recovery. The model is designed to accommodate the salient socioeconomic characteristics of the cultural heritage community, by giving heed to effects such as the adaptive behavior of the site visitors and the occurrence of an adverse event during a high or a low season for tourism. The methodology is finally illustrated and verified on the basis of several earthquake scenarios derived for the historical city of Rhodes, highlighting the potential usage of the tool during risk mitigation planning and post-event decision-making.*

Introduction

Natural (e.g., earthquakes, floods) and man-made (e.g., water contamination, explosions, fires) perils that have occurred recently worldwide have demonstrated that even modern societies remain vulnerable to extreme hazard events, and consequently they are prone to direct and/or indirect losses affecting the communities and their support systems. Direct impacts consist of damages to premises, equipment, vehicles, inventories, and eventually to human injuries or even fatalities. From an economic standpoint, the *direct cost* of an event is the repair or replacement cost of the damaged or destroyed assets, respectively, and it is commonly estimated by insurance companies following the occurrence of a disaster (Hallegatte, 2008). On the other hand, the *indirect cost* comprises the off-site business interruption, reduction in property values, and stock market effects (Kaushalya et al., 2014). With reference to Cultural Heritage (CH) communities, indirect costs can be substantially amplified if the catastrophic event occurs during the so called “high season”, since the annual income of the majority of the nearby, or otherwise associated to the CH site, businesses relies more on tourism rather than local consumption.

On account that not all threats can be averted (Cimellaro et al., 2016), enhancing the resilience of a community through preparedness and adaptation measures comprises the state-of-the-art approach to minimize the direct and indirect costs of a catastrophic event. Several approaches have been proposed for the quantification of community resilience, which can be classified into qualitative and quantitative ones (Liu et al, 2021). However, most of the studies investigated the disaster aftermaths from a macroeconomic standpoint, mainly focusing on the restoration process of the lifeline services (e.g., transport, electricity, water, sewage). Therefore, they disregarded essential factors that govern the post-disaster performance of small businesses, especially those that operate in CH sites, such as the increased vulnerability of old buildings within the historical center, possible demand outages due to reduction of tourist arrivals, supply bottlenecks, etc.

Based on the above, a fully quantitative business-based methodology has been developed and presented herein, which is based on the Adaptive Regional Input-Output (ARIO) model that was initially proposed by Hallegatte (2008) for simulating the failure propagations due to supply and demand outages. Yet, the proposed socioeconomic model goes one step beyond the current-state-of-the-art by (a) introducing a simplified business taxonomy (utilizing a set of distinct

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business sectors) to categorize the individual businesses operating on a CH site, (b) defining three performance indices to quantify the indirect economic losses due to infrastructure, supply, and demand disruptions, (c) employing for the first time the Vendor Dependence Tables (VDTs) that are commonly used in Business Continuity (BC) exercises to account for vendor disruptions and the adaptive tourist/resident consumption behaviour, and (d) considering the timing of the event and especially the effect of high/low season coinciding with its occurrence. Finally, the application of the proposed methodology for the resilience assessment of CH sites is showcased on the historical city of Rhodes by considering two hypothetical earthquake events of different seismic intensity.

Proposed socioeconomic model

Simplified business taxonomy

The proposed socioeconomic model employs an aggregation methodology to calculate the cascading failures and business interruptions after a hazard event, by defining and exploiting a business taxonomy approach for classifying the individual businesses that operate on a society linked to a CH site. Hence, the proposed method employs a low-resolution approach in terms of economy, aggregating companies or firms into discrete business sectors (or “nodes”), thus disregarding, e.g., the effect of proximity or other advantages of location in terms of attracting business. Each business sector is likely to contain organizations of different sizes, annual turnovers, scopes, etc. For instance, the “Accommodation” business sector may refer to all sorts of lodging services, from big hotels with several guest rooms down to small Bed & Breakfasts (BnBs).

The simplified business taxonomy that is developed each time should be tailored to the socioeconomic characteristics of the CH site at hand, and thus may vary significantly among different communities. For instance, if the CH site is located in a popular touristic destination, businesses such as bars, restaurants, and cafes play a crucial role to the local economy, and thus the “Food and beverage” business sector might need further taxonomic discretization/refinement to account for the particularities of each business subsector. On the other hand, sectors such as “Manufacturing” or “Agriculture” might be less important in terms of their contribution to the total annual Gross Value Added (GVA) and the opposite approach (i.e., further aggregation) may be justified.

Along with the aforementioned identification of the supply business sectors, the following five potential customer categories, which were called in the proposed methodology “Final Demand Nodes (FDNs)”, are defined: Residents, Tourists, Government, Investments, and Exports. While both “Residents” and “Tourists” comprise the local consumption component of an economic system, they are herein treated separately due to their substantially different consumption profile and hence impact on the CH region. It should be kept in mind that each FDN has a dynamic response to the socioeconomic changes that are likely to be triggered by an aggravated hazard event, since they are affected by attributes that are difficult to quantify (such as fear, irrationality, and politics) and hence may not be sufficiently predicted by classical purely-economic models.

Downtime diagrams and index decomposition

To quantify the indirect losses of a catastrophic event in the economy of a CH site, a *performance index* (*PerfIdx*) can be assigned to each business sector. Herein, we define *PerfIdx* as the ratio between the (typically reduced) GVA of the business sector following the occurrence of a hazard event and the GVA under ordinary conditions, assuming a structurally static economic model, i.e., structural changes over long time periods are ignored. For simplicity, *PerfIdx* is bounded between 0% (total loss of performance) and 100% (full performance), which implies that a business sector cannot “bounce forward” during the recovery phase (i.e., *PerfIdx* ≤ 100%). Evidently, *PerfIdx* is a time-varying vector function that depends not only on the operability of the considered business sector, but also on the socioeconomic impacts of the disaster on the CH site. For instance, a natural disaster that does not result in direct structural damages to the premises of a business sector, may still lead to severe loss of performance (i.e., loss of GVA) due to supply outages or reduction of tourist arrivals during the recovery phase. To depict the individual socioeconomic factors affecting the performance of a business sector, *PerfIdx* is discretized into three distinct scalar components:

1. The infrastructure index (*InfraIdx*) that measures the reduced production/service capacity of a business sector due to “infrastructure damages”. As infrastructure damages we define

herein all the factors that hamper the operability of a business unit except supply outages, as those are treated separately by the *InputIdx*. Therefore, *InfraIdx* is calculated as the percentage of the fully operating business units belonging to a particular business sector at a given time step.

2. The input index (*InputIdx*) that captures the propagating effect of supply outages, according to the so-called, *Vendor Dependence Tables* (VDTs). VDTs are tools frequently used in Business Continuity (BC) to evaluate the dependence of an organization on its vendors. Assuming that the organization has N vendors, its corresponding VDT comprises N rows, where each row contains a series of indices that capture the progressive (over time) loss of productivity of the investigated business sector due to complete supply disruption from a particular vendor, ranging from 1 (to denote full productivity) to 5 (to denote no productivity). An example VDT for the “Retail trade” sector is depicted in Table 1. VDTs can also be defined for FDNs, expressing their adaptive consumption behaviour to disturbances on essential supplies and services. For instance, Table 2 shows the VDT assumed in the socioeconomic model of Rhodes for the “Tourists” FDN, in which high dependency is given on the “Accommodation” sector, as tourists mainly use temporary lodging during their vacations. In contrast, in the VDT of “Residents”, the row corresponding to “Accommodation” can be filled with index 1, reflecting the fact that citizens’ capability to work is unaffected by hotel shutdowns. On the other hand, high dependency can be given to the “Real estate” sector, which also pertains to buildings with primary residential use.
3. The output index (*OutputIdx*) that measures the propagating reduction of the demand during the recovery phase. *OutputIdx* is mainly related to (i) the intermediate business-to-business consumption and (ii) the FDN demand (e.g., tourists, residents, etc.). Herein, both components (i) and (ii) are considered by propagating the reduced demand via a so-called *Input-Output Table* (IOT). The IOT is a NxN matrix (N is the total number of business sectors plus the number of FDNs), in which each cell o_{ij} represents the normalized consumption of goods of business sector i by business sector (or FDN) j. Thus, each row of the IOT sums to 1, i.e., $\sum_{j=1}^{N} o_{ij}$ for i = [1, N]. The o_{ij} values can be derived by normalizing the complete national IOT as given by Timmer et al. (2015), assuming that the site under consideration follows a similar business-to-business and business-to-consumer economic profile.

#	**Retail trade**	**2d**	**4d**	**1w**	**2w**	**1mo**	**2mo**
1	Retail trade	5	5	5	5	5	5
2	Business, scientific and technical activities	2	2	3	4	5	5
3	Financial services and insurance activities	2	2	3	3	3	4
4	Wholesale trade	2	3	4	5	5	5
5	Manufacturing	1	1	1	1	2	2
6	Agriculture, forestry, fishing	1	1	1	2	2	2
7	Real estate activities	1	1	1	1	1	2
8	Trade and repair of motor vehicles and motorcycles	1	1	1	2	2	2
9	Construction	1	1	1	1	2	2
10	Accommodation	1	1	1	1	1	1

Table 1. Example VDT for the “Retail trade” business sector.

At each time step, a distinct triplet of (*InfraIdx*, *InputIdx*, *OutputIdx*) is calculated for each business sector, following a mesoeconomic methodology to account for cascading failures and socioeconomic impacts. A brief description of the failure propagation methodology is provided in the following section. Ultimately, the overall performance index (*PerfIdx*) is calculated as the minimum value of its three key sub-indices:

$$PerfIdx = \min(InfraIdx, InputIdx, OutputIdx) \tag{1}$$

#	Tourists	2d	4d	1w	2w	1mo	2mo
1	Retail trade	3	4	4	5	5	5
2	Business, scientific and technical activities	1	1	1	1	1	1
3	Financial services and insurance activities	1	1	1	1	1	1
4	Wholesale trade	1	1	1	1	2	2
5	Manufacturing	1	1	1	1	1	1
6	Agriculture, forestry, fishing	1	1	1	1	1	1
7	Real estate activities	1	1	1	1	1	1
8	Trade and repair of motor vehicles and motorcycles	1	1	1	1	2	2
9	Construction	1	1	1	1	1	1
10	Accommodation	4	5	5	5	5	5

Table 2. Example VDT for the "Tourists" FDN.

Forward and backward propagation of failure

The socioeconomic impact analysis starts at $t = 0$ hours where the catastrophic event occurs and leads to several direct losses, such as damages to premises and critical infrastructure. These direct losses and their restoration process are assumed to have already been pre-processed by the user in order to derive the *InfraIdx* diagram of each business sector (a procedure to realize such diagrams is proposed in the following application examples). Essentially the socioeconomic model uses *InfraIdx* as input in order to calculate the cascading disruptions in the supply (*InputIdx*) and demand (*OutputIdx*).

Firstly, at each timestep t the model updates the *InfraIdx* value of each business sector based on the recovery functions provided by the user. Then, for each business sector the algorithm checks the corresponding VDT to identify which vendors are experiencing infrastructure or supply disruptions (i.e., *InfraIdx* < 100% or *InputIdx* < 100%). For each of these vendors, a time counter is assigned in the corresponding rows of the VDT in order to calculate their supply status (i.e., Conditions 1 to 5). To account for the effect of supply bottlenecks, the time counter with the worse supply condition is used to calculate the *InputIdx* of the considered business sector. Accordingly, the algorithm updates the *InputIdx* of all sectors and re-checks the VDTs until the failure propagates to the FDNs (e.g., tourists, residents). This procedure is called *forward propagation of failure*. In the next timestep $t+dt$, the time counters are updated (e.g., they move horizontally in the VDT, see Table 1) to calculate the new supply status of the vendors. If any of the disrupted vendors returns to normal conditions (i.e., *InfraIdx* = *InputIdx* = 100%), the relevant counter resets.

After the disruptions reach the FDNs, the algorithm continues by assessing their impact to the final consumers. The response of an FDN to aggravated adverse event is challenging to be quantified, as it is related to socioeconomic factors such as politics, fear, community demographics, etc. For instance, a short-term shutdown of the restaurants and bars in a CH site might deteriorate its overall reputation, which will consequently lead to reservation cancellations by individual tourists or tourist groups. As a first step, the proposed model assumes that the demand of an FDN is linearly related to the total *InputIdx* (according to its corresponding VDT) it receives from the businesses of the CH site, while in the future it can be upgraded to account for more complex socioeconomic relationships. Essentially, a VDT is used for each FDN (e.g., Table 2) and is updated in the same manner as those of the business sectors, while the demand of the FDN is assumed to be equal to the calculated *InputIdx*. Based on these final demands, the algorithm loops over all business sectors to update their *OutputIdx*, a procedure that is called *backward propagation of failure*.

Finally, the proposed model takes into account the capability of a business sector to overproduce if necessary. Businesses, indeed, are rarely operating in their full production capacity and labor and hence they are often able to increase their production during crisis (Hallegatte, 2008). For instance, if 5 out of 10 hotels are forced to shut down as a result of infrastructure damages caused by a catastrophic event, the actual *InfraIdx* of the "Accommodation" sector might be greater than 5/10=50%, as the remaining 5 hotels may have available rooms to serve a certain portion of the extra demand that was created due to the loss of functionality of the hotel premises that were damaged. However, if the disaster occurs during high season, the non-disrupted hotels will probably be completely full and they will not be able to satisfy the increased demand. As such, two overproduction approaches are offered by the proposed model: (a) a time-independent increase of the impacted *InfraIdx* (e.g., if the "Retail trade" sector has *InfraIdx* of at least 50%, a +10% overproduction can always be activated) and (b) a time-dependent overproduction (e.g., if the "Accommodation" sector has *InfraIdx* of at least 50%, a +10% overproduction can be activated, but only during the low season months).

Examples of application for the historical city of Rhodes

Rhodes socioeconomic and exposure models

The application of the proposed methodology for the resilience assessment of CH sites is showcased for the historical city of Rhodes, which is the principal city of the island of Rhodes. The city has approximately 50,000 inhabitants based on the latest 2020 demographics (Wikipedia, 2022) and comprises several CH assets with significant natural beauty and historical value. The most famous CH asset is the citadel of Rhodes, built by the Knights Hospitaller, and is one of the best-preserved medieval towns in Europe, which in 1988 was designated as a UNESCO World Heritage Site. Apart from its historical importance, Rhodes is also a coastal town hosting the main marine port of the island and, as a result, it has become a popular international tourist destination.

The influence of tourism on the structure of Rhodes' economy can be highlighted by comparing the annual GVAs of the city's most important business sectors. This step comprises the aggregation of the individual firms operating within the city of Rhodes into compact business sectors. In particular, we employed a combination of the 1-digit (19 business sectors) and 2-digits business classification (73 business sectors) of the NACE rev. 2 taxonomy (Eurostat, 2008) to define a simplified taxonomy that consists of 23 business sectors. The identified business sectors were those with the highest GVAs, while the rest were aggregated for simplicity to a single sector, namely "Other services". Herein, for illustrative purposes we focus only on 10 out of the 23 sectors, which are those that will be considered later during the socioeconomic impact analysis. Table 3 depicts the annual GVAs of each one of the 10 considered business sectors, using the economic data provided by the Hellenic Statistical Authority (ELSTAT).

Based on Table 3, the "Wholesale trade" sector is the most critical one (i.e., the one with the highest GVA) for the city of Rhodes, an observation that is anticipated to hold for the majority of the developed societies, since almost all organizations rely on their vendors for the supply of essential goods and utilities rather than on directly purchasing them from e.g., the manufacturers or on directly producing them. The next most important sector for the city of Rhodes is the "Real estate activities" sector, which includes both incomes from the renting and sale of premises and profits created by real estate agencies. The third critical sector is the "Retail trade", which is the final link in the supply chain from producers to consumers and comprises grocery stores, gift shops, supermarkets, etc. Regarding tourism, sectors like "Accommodation" (hotels, BnBs, etc.), "Food and beverage" (restaurants, bars, etc.), and "Creative, arts and entertainment activities" (theaters, cinemas, museums, etc.) reflect a large percentage of the city's overall annual GVA, at a total of 16%. The aforementioned "Retail trade" sector can also be considered as a tourism-based industry, as there are many small retail shops within the historical city whose annual profits vastly depend on tourist arrivals during high season, while many of them are even closed during low season.

#	Description	GVA (€ mill.)	GVA (%)
1	Wholesale trade	112.80	13.81%
2	Real estate activities	93.99	11.51%
3	Retail trade	64.10	7.85%
4	Accommodation	60.15	7.37%
5	Food and beverage services	50.31	6.16%
6	Business, scientific and technical activities	33.77	4.13%
7	Warehousing and support activities for transportation	28.41	3.48%
8	Financial services and insurance activities	23.27	2.85%
9	Creative, arts and entertainment activities	20.18	2.47%
10	Other services	29.64	3.63%

Table 3. Business taxonomy for the city of Rhodes (showing the 10 considered sectors).

To facilitate the vulnerability assessment that is required as input by the socioeconomic analysis, herein a sector-based exposure model is realized for the historical city of Rhodes. In particular, we employ census data from national statistics (ELSTAT) to retrieve information regarding the number of stories, age, and building material of each building in the city. Moreover, we assume that the main structural characteristics that dominate seismic performance are the type of building material and the lateral loading-resisting system. Thus, the following building typologies are considered: (i) Reinforced Concrete Frame (RCF), (ii) Unreinforced Masonry (URM), (iii) Reinforced Masonry (RM), (iv) Reinforced Concrete Wall (RCM), (v) Steel (SRF), and (vi) Wood (WRF). Notably, most buildings fall into the RCF typology (>75%), while URM is also common (~20%) but mainly within the historical centre, which comprises a popular tourist zone with several shops, cafes, and restaurants. Finally, census data regarding the primary use of each building are collected, such as residential, retail, manufacturing, etc. Then, a mapping between primary use and business sectors is performed, which results into a detailed exposure model for Rhodes where each building is characterized by a specific building typology (from i to vi) and business sector (from 1 to 10).

Selection of seismic events and derivation of InfraIdx diagrams

Two seismic events are selected for the city of Rhodes representing a “high damage” and a “very-high damage” scenario, respectively. The events are chosen from a stochastic event set (SES) for a given investigation time. The SES is produced by an event-based probabilistic seismic hazard analysis (PSHA) with a single ground motion prediction equation by Cauzzi et al.(2014). The analysis is performed via the open-source OpenQuake engine (GEM, 2021) and is based on known seismic sources and the potential realizations of seismicity for the given site per the 2013 European Seismic Hazard Model (ESHM13, Woessner et al. 2015). The main seismological characteristics of the two events are shown in Table 4. Notably, while both events have comparable magnitude and rupture depth, the “very-high damage” happens in a much closer distance to the city center, which is expected to result in more severe consequences to the CH community.

Event #	**Description**	**Magnitude**	**Distance from city center [km]**	**Rupture depth [km]**
1	High damage	M6.7	43.0	13.2
2	Very-high damage	M6.5	9.3	13.2

Table 4. Seismological characteristics of considered events.

Following the selection of the two events, a detailed vulnerability analysis is conducted to derive the post-event recovery diagrams (or the *InfraIdx* diagrams) of the 10 business sectors. In particular, the analysis includes the following steps:

1. For each building block, evaluate the spectral acceleration at 1 sec, i.e., *Sa*(1s), based on the seismological characteristics of the event.
2. For each building block, use fragility curves derived from the 2020 European Seismic Risk Model (ESRM20, Crowley et al., 2021) to determine the damage state (DS) of each building typology. A total of five DSs are considered, from “no damage” (DS0) to “complete damage” (DS4). For instance, block 5 was impacted by an *Sa*(1s) equal to 0.15g from event 1, which (using the pertinent fragility curve) is translated to DS2 (“moderate damage”) for typology RM.
3. For each building block, determine the number of buildings per DS and business sector. This can be done by mapping the results from the building typologies to the business sectors using the exposure set of Rhodes. For instance, in block 5 there are 3 hotels (i.e., sector “Accommodation”) in DS2 (typology RM) and 2 in DS4 (typology URM).
4. Aggregate the results from all building blocks to evaluate the number of buildings per DS and business sector. For instance, event 1 caused 30 hotels to be in DS0, 10 in DS1, 15 in DS2, etc.
5. Determine downtimes per business sector and DS using the expected business interruption times of HAZUS 4.2 SP3 (2020), namely from Table 11-8 and 11-9 of the manual. For

instance, hotels that are in DS1 require 0 days to start operating again, in DS2 45 days, in DS3 180 days, etc.

6. Derive the final *InfraIdx* diagram of each business sector using the number of buildings per DS (Step 4) and the downtimes per DS (Step 5).

Figure 1 illustrates the generated set of *InfraIdx* diagrams for each event, representing the loss of functionality of the 10 considered business sectors due to infrastructure damages. Specifically, for the “Real estate” sector, its *InfraIdx* diagram is generated by aggregating the downtimes of the buildings assigned as “Residential” in the exposure model of the city. The period of interest is set equal to 1056 days (~35 months), which is 1.1 times the maximum interruption time needed by the sectors to return to 100% functionality, as given in the tables of HAZUS 4.2 SP3 (2020). Finally, a time-dependent overproduction capability is considered for the tourist-based sectors (i.e., retail, accommodation, food & beverage), while a time-independent overproduction equal to 10% is assumed for the rest.

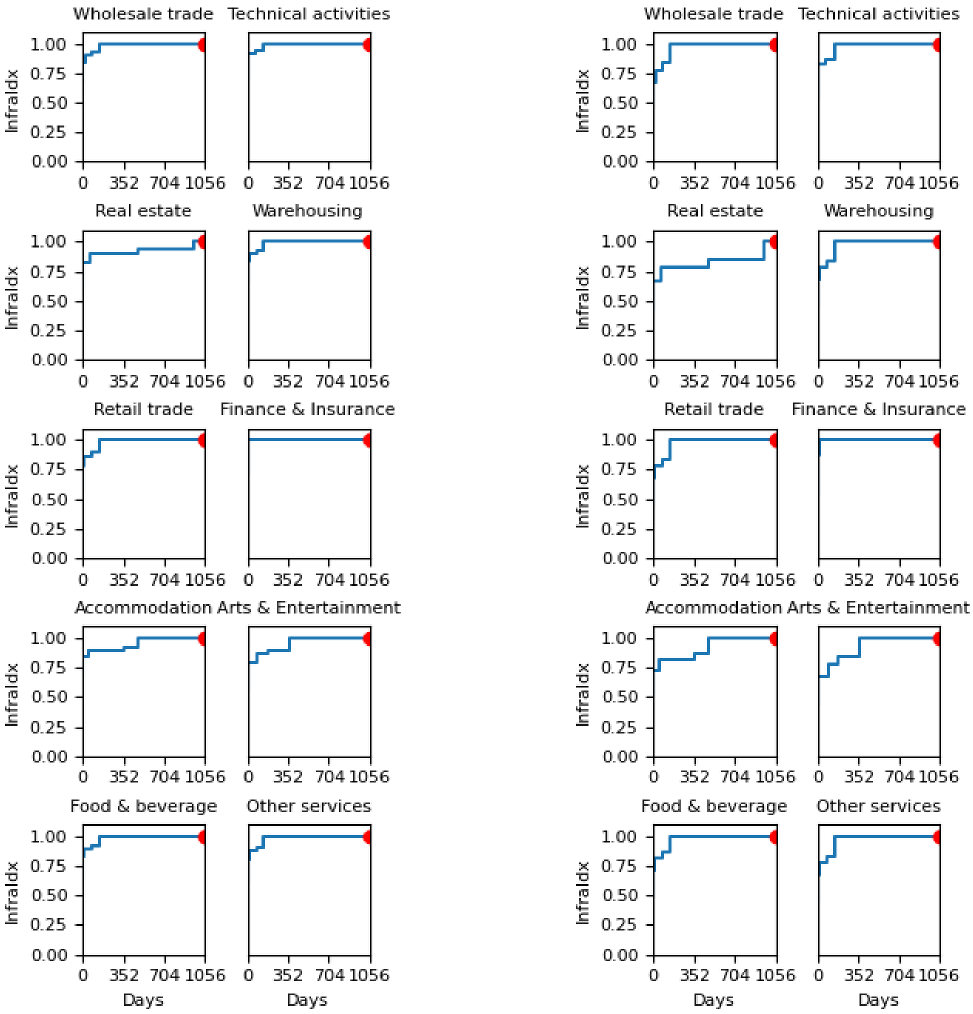
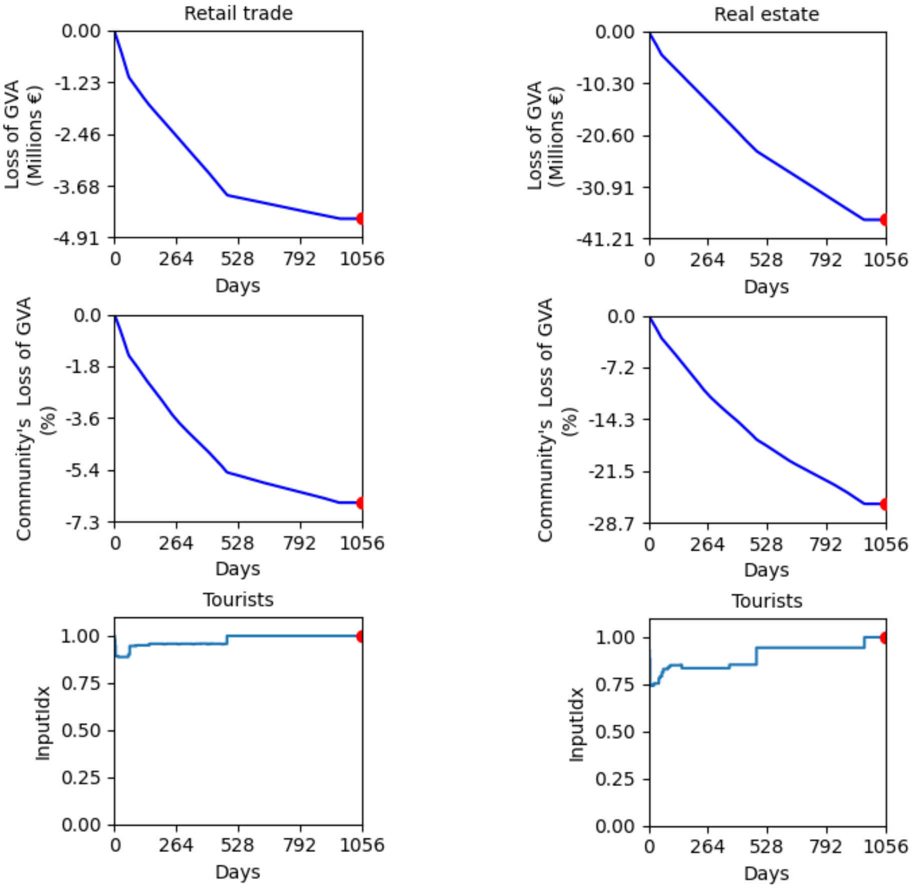


Figure 1. InfraIdx diagrams of the considered business sectors for the high-damage (left) and the very-high damage event (right).

Socioeconomic analysis results

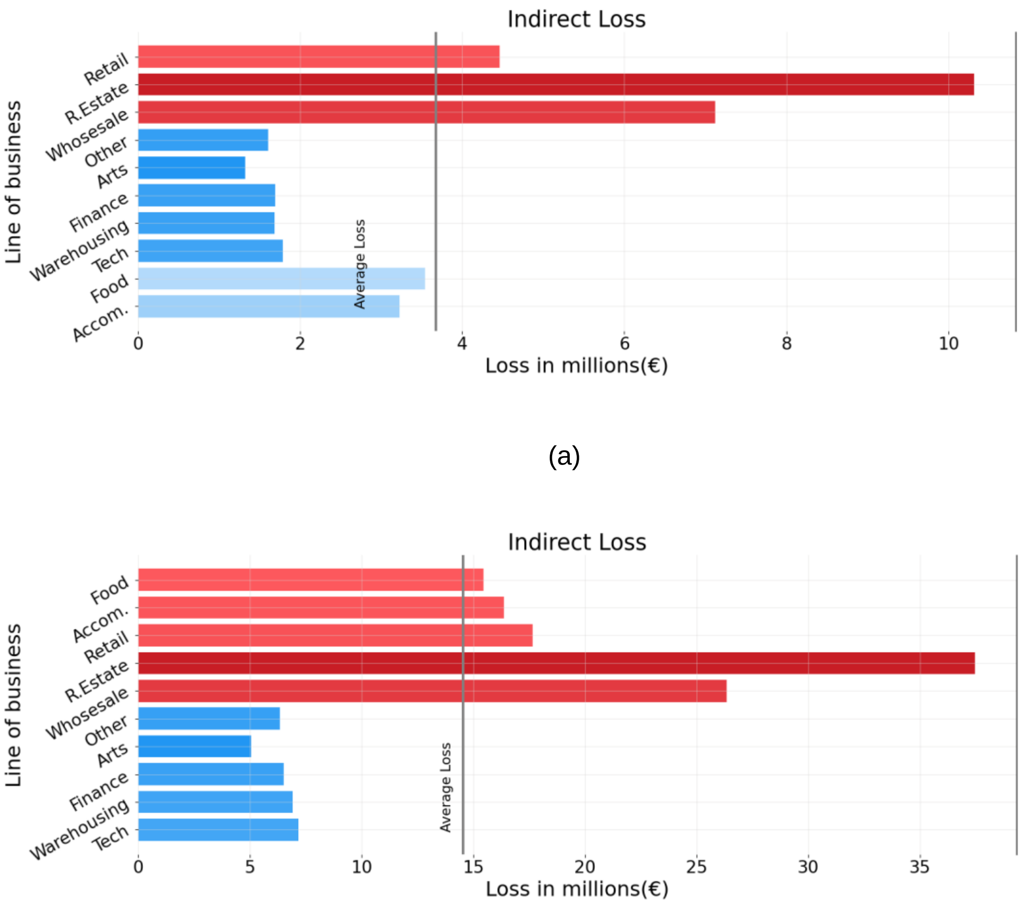
Subsequently, the produced diagrams are fed to the socioeconomic model, which employs the failure propagation algorithm to calculate business interruptions. Figure 2 illustrates three time history diagrams from the socioeconomic impact analysis of each event, namely the loss of GVA (in € mill.) recorded by the sector with the highest indirect losses, the community’s total indirect losses in terms of % of city’s annual GVA, and the *InputIdx* of the “Tourists” FDN. One can observe that immediately after the occurrence of the events (day 0), the city experiences the maximum rate of GVA loss. This rate decreases as the infrastructure damages are gradually repaired with the help of insurance claims, until the slope becomes zero at the end of the period of interest (day 1056). The “high-damage” event resulted in 6.6% total loss of GVA for the community, while the “very high-damage” one reached 26.1%. Moreover, disruptions to sectors like “Retail”, “Accommodation”, and “Food & beverage” led to reduction of the *InputIdx* of the “Tourists” FDN, which essentially reflects the impact of the events on tourism and the consequent drop of final demand.



(a) (b)

Figure 2. Time history diagrams showing indicative results from the socioeconomic impact analysis for (a) the high-damage and (b) the very-high damage event.

The total indirect losses of each sector and event are shown in Figure 3, in € millions. As the primary use of most buildings in the city is residential, the “Real estate” sector faced significant indirect losses, which are mostly related to demand outages by the “Residents” FDN. Essentially, the occupation of residential buildings with moderate to severe damages is assumed to be prohibited until insurance/government/owners pay off the repair costs, which leads to monetary losses due to reduced incomes from rents and sales of premises. Moreover, two sectors with significant indirect losses are the “Wholesale trade” (4.4 mil. €) and “Retail trade” (6.6 mil. €). Losses in the retail trade are attributed mainly to outages in the final demand (residents and tourists), which is backwardly propagated to the wholesale sector via the *OutputIdx*. High monetary losses are also reported in the “Food & beverage” and “Accommodation” sectors, which are credited to the reduction of sectors’ functionality (reduced *InfraIdx* and *InputIdx*) and the reduced tourist consumption. Finally, sectors related to financial and technical activities experienced less indirect losses, as their profit relies more on business-to-business (B2B) relationships rather than business-to-consumer (B2C) ones, and thus are more tolerant to reductions of the FDN demand.



(b)

Figure 3. Bar charts showing the indirect losses of each business sector for (a) the high-damage and (b) the very-high damage event.

Conclusions

A socioeconomic model for quantifying the indirect losses of catastrophic events was proposed, which was illustrated and verified on two hypothetical seismic scenarios impacting the local economy of the city of Rhodes. The model is anticipated to assist the CH operators and managers, cultural authorities, policy makers, etc. towards assessing the overall resilience of an entire urban area, considering both its assets and users/inhabitants. Despite its CH targeting, it is actually generalizable to accommodate any urban area or even larger region.

- The model employs a mesoeconomic approach to calculate indirect losses, in which the individual businesses are aggregated into compact business sectors. Information regarding the sectors can be easily acquired from available regional accounts and national statistics.
- The post-event functionality of each sector is measured by a performance index, ranging from 0.0 (no functionality) to 1.0 (full functionality). The performance index is decomposed into three sub-indices: (a) the infrastructure, (b) the input, and (c) the output index.
- At each timestep, the model receives as input the infrastructure indices (a), which are assumed to have been calculated by the user during pre-processing. For the case of seismic events, they can be estimated by mapping Damage States to downtimes using e.g., the expected business interruption times of HAZUS 4.2 SP3.
- Disruptions to the supply chain are propagated by the input index (b), using the Vendor Dependence Tables (VDTs) of the business continuity practice (forward propagation of

failure). VDTs shall reflect the actual supply network of the urban community and, thus, expert opinion and knowledge from previous disasters should be exploited during their construction.

- The cascading demand disruptions are treated by propagating the output index (c) using an Input-Output Table (IOT) approach (backward propagation of failure). IOTs are often available in a national scale and, thus, they need to be modified when applied to different urban areas with diverse socioeconomic characteristics.
- Indirect losses of CH communities can increase significantly if the event occurs during the so-called high season, as it can severely impact final consumers. Currently, the proposed model treats the consumption behaviour of residents and tourists as linear using VDTs, however a more complex relationship can be easily accommodated in the future.

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