A MESOECONOMIC RESILIENCE FRAMEWORK FOR REGIONAL SEISMIC ASSESSMENT STUDIES

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Abstract: *On account that modern societies cannot be built on earthquake-proof infrastructure (e.g., buildings, roads, power supplies), increasing resilience through preparedness and adaptation measures is the state-of-art approach to reduce severe consequences to core community functions. From an economic standpoint, the impact of a disaster can be discretized into two parts: (i) the direct losses, which comprise the cost needed to repair/replace the damaged/destroyed assets and (ii) the indirect losses, which are related to the reduction of gross valued added during the post-event period. Currently, most regional risk assessment studies are focusing on the evaluation of the direct losses, either ignoring the indirect part or using qualitative approaches to coarsely assess its impact. In support of risk assessment and crisis mitigation planning, a meso-scale economic resilience framework is proposed that allows a quantitative estimate of indirect loss in tandem with conventional direct loss assessment. The model is based upon a sector-wide approach, in which the individual businesses operating within the community are aggregated into compact sectors. Subsequently, the post-event performance of each sector is assessed using three indices, (a) the infrastructure index to measure the reduced productivity of a sector due to direct infrastructure damages, (b) the input index to propagate disruptions in the supply chain by employing Vendor Dependence Tables, and (c) the output index to reflect the reduction of demand due to disruptions (a) and (b). The model is designed to accommodate the salient characteristics of modern urban societies, addressing complex socioeconomic aspects such as the adaptive behaviour of residents and visitors, and the capability of a sector to redistribute business traffic within or outside the community. The methodology is demonstrated in the historical city of Granada in Spain, using three hypothetical earthquake scenarios of incremental intensity and impact.*

1. Introduction

1.1. Direct and indirect losses

Regional loss assessment studies on past earthquakes have emphasized the great influence of the indirect component of losses on the capability of an urban community to absorb the initial shock and achieve recovery. From an economic point of view, 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 on/off-site business interruption, reduction in property values, and stock market effects. Especially in touristic regions, like many European historical cities, indirect costs can be substantially amplified if the seismic event occurs during the so called "high season", since the annual income of many business sectors relies more on tourism rather than local consumption.

To date, limited studies have been conducted for estimating or assessing the indirect costs of destructive earthquakes, mainly due to the difficulties in realizing the interdependencies between the individual business sectors (Sousa et al., 2022) and reflecting the socioeconomic attributes that characterize the urban community. One of the most well-established economic models for modeling failure propagations due to supply and demand outages is the Adaptive Regional Input-Output (ARIO) model proposed by Hallegatte (2008). ARIO is typically constructed using available statistics and Input-Output Tables (IOTs), which are downscaled from national to regional level to account for specific idiosyncrasies that characterize the examined region. Recently, a new mesoeconomic model has been proposed by Tsarpalis et al. (2023), which builds upon the traditional ARIO but goes one step further by implementing Vendor Dependence Tables (VDTs) to reflect the economic and societal relationships between a community's local businesses and their end users. The present paper delineates the basic principles of the proposed methodology and presents its application for assessing the indirect impacts of three seismic events to the city of Granada in Spain.

1.2. Proposed mesoeconomic model

The model is built upon a business taxonomy approach, which involves the aggregation of the individual businesses to distinct business sectors. The importance of each business sector to the local economy is reflected by its annual Gross Value Added (GVA), data that is typically available by national statistics authorities in the form of regional accounts. Along with the identification of the "supply" sectors, the model also employs the following five potential customer categories, so-called Final Demand Nodes (FDNs): (a) Residents, (b) Tourists, (c) Government, (d) Investments, and (e) Exports. While both "Residents" and "Tourists" comprise the local consumption component of an economic system, they are treated separately due to their substantially different consumption profile and impact on the community.

The post-event functionality of each supply sector is characterized by a performance index (*PerfIdx*), which is the ratio between the (typically reduced) GVA of the sector following the occurrence of the seismic 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. For instance, an earthquake that does not result in direct structural damages to the premises of a 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 as presented below.

A) The infrastructure index (InfraIdx)

InfraIdx measures the reduced production/service capacity of a 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.

B) The input index (InputIdx)

This index 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 Condition 1 (to denote full productivity) to 5 (to denote no productivity). VDTs are also defined for FDNs, expressing their adaptive consumption behaviour to disturbances on essential supplies and services.

An example VDT for the "Retail trade" sector is depicted in Table 1. We notice that higher dependency is assigned to the "Wholesale trade" sector (100% loss after 2 weeks) as most retailers strongly rely on wholesale agencies for the supply of their merchandise. On the other hand, the sector is more resilient to outages from the “Finance & Insurance” (row 6) sector, as the loss of functionality is less steep (indices increase slower with time) and less severe (50% loss of functionality after 2 months). Finally, disruptions in the “Food & beverage” sector (row 9) lead to no impact on “Retail trade” (0% loss of functionality), which indicates that these two sectors do not have any interaction.

The employment of VDTs to propagate failure in the supply chain can be more advantageous than utilizing traditional IOTs, as the former can be constructed by either purely economic data (where they end up being normalized IOTs) or by using more qualitative approaches, such as processing of census data, expert opinion, or engineering judgement.

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

#	Retail trade	2 days	4 days	1 week	2 weeks	1 month	2 months
1	Real Estate	1	1	1	1	1	2
2	Professional & Technical	2	2	2	3	3	4
3	Agriculture	1	1	1	1	2	2
4	Wholesale trade	2	3	4	5	5	5
5	Retail trade	5	5	5	5	5	5
6	Finance & Insurance	1	1	2	2	3	3
7	Accommodation	1	1	1	1	1	1
8	Arts & Entertainment	1	1	1	1	1	1
9	Food & beverage	1	1	1	1	1	1
10	Warehousing	1	1	1	1	2	2

C) The output index (OutputIdx)

OutputIdx measures the propagating reduction of the demand during the recovery phase. *OutputIdx* is mainly related to (a) the intermediate business-to-business consumption and (b) the FDN demand (e.g., tourists, residents, etc.). Herein, both components (a) and (b) are considered by propagating the reduced demand via a so-called Input-Output Table (IOT). The IOT is a *N*x*N* 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., $\sum_{j=1}^{N} o_{ij} = 1$ 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.

D) The Mesoeconomic Engine

The impact analysis starts at *t* = 0 hours where the seismic 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 within a conventional damage/loss and recovery analysis in order to derive the *InfraIdx* diagram of each business sector. Essentially the 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, the algorithm checks the corresponding VDT of each sector 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. Quantifying the response of an FDN to aggravated adverse event is challenging, as it is related to socioeconomic factors such as politics, fear, community demographics, etc. 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 site, while in the future it can be upgraded to account for more complex socioeconomic relationships. Essentially, a VDT is used for each FDN 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.

The described algorithm has been encoded in the Mesoeconomic Engine, which is a software application that was developed during the H2020 project HYPERION (HYPERION, 2019). The engine is written in Python language and utilizes the NetworkX package (Aric et al., 2008) for the creation and manipulation of the network structures formulated by the business sectors and their interdependencies. The analysis output is exported into a JSON database along with a set of figures that provide the user with a graphical illustration of the main results. A snapshot from such file is illustrated in Figure 1. The left side of the figure under the caption “Downtime Diagrams” contains a set of time history diagrams for the sectors’ *InfraIdx*, which is essentially the input required by the engine. The complete model network is shown in the middle, where each node corresponds to a particular supply sector or FDN, while the edges of the graph represent the supply connectivity of the business sectors, as defined by the VDTs (grey colour correspond to Condition 1, red to Condition 5, etc.). Finally, the right side comprises time history diagrams of selected results requested by the user (e.g., loss of GVA for a specific sector, or total loss of GVA for the community).

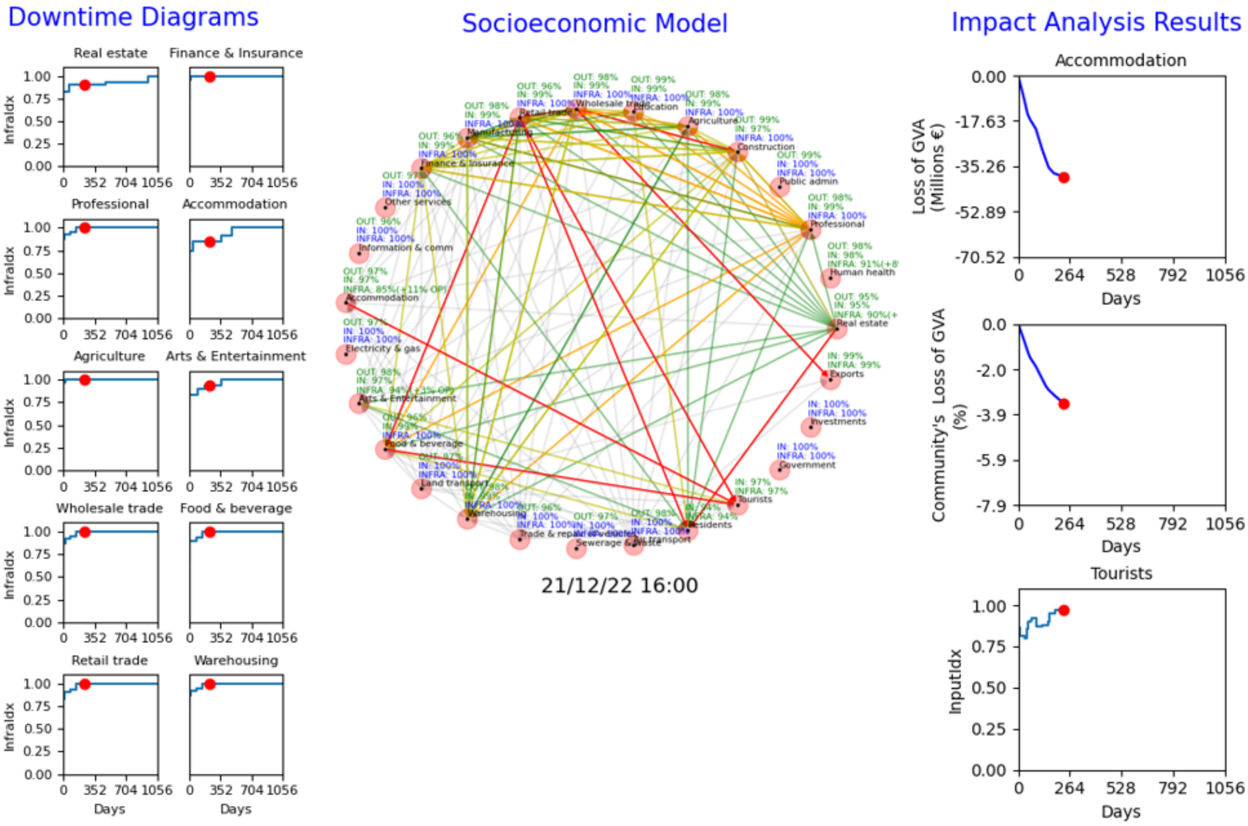


Figure 1. Snapshot from a GIF file exported by the Mesoeconomic Engine.

2. Granada mesoeconomic and exposure model

The application of the proposed methodology for regional risk assessment studies is showcased in the historical city of Granada, which is the capital city of the province of Granada in Spain. The city has approximately 230,000 inhabitants based on 2018 demographics (Wikipedia, 2023) and comprises several cultural heritage assets with significant natural beauty and historical value. Among these, the Alhambra is a medieval Nasrid citadel and palace that is located close to the city center and has become one of the most visited tourist sites in Spain.

The first step of the methodology comprises the aggregation of the individual businesses operating within the city into compact sectors. In particular, we employ a combination of the 1-digit and 2-digits business classification of the NACE rev. 2 taxonomy (Eurostat, 2008) to define a simplified taxonomy that consists of 22 business sectors. The identified business sectors are those with the highest GVAs, while the rest are aggregated for simplicity to a single sector, namely "Other services". Herein, for illustrative purposes we focus only on 10 out of the 22 sectors, which are those that will be considered later during the mesoeconomic analysis. Table 2 depicts the annual GVAs of each one of the 10 considered business sectors, using economic data provided by the Spanish National Statistics Institute (Instituto Nacional de Estadística, INE).

Table 2. Business taxonomy for the city of Granada and expected business interruption times per DS.

#	Sector	GVA (€ mill.)	GVA (%)	DS1 (days)	DS2 (days)	DS3 (days)	DS4 (days)
1	Real Estate	1733.68	10.98%	0	60	480	960
2	Professional & Technical	1369.78	8.68%	2	5	5	11
3	Agriculture	1123.80	7.12%	2	9	72	144
4	Wholesale trade	841.38	5.33%	0	45	360	480
5	Retail trade	712.04	4.51%	0	1	6	24
6	Finance & Insurance	584.56	3.70%	2	90	180	360
7	Accommodation	491.60	3.11%	1	18	81	144
8	Arts & Entertainment	417.62	2.65%	1	9	81	144
9	Food & beverage	409.66	2.59%	1	9	81	144
10	Warehousing	251.97	1.60%	1	18	81	144

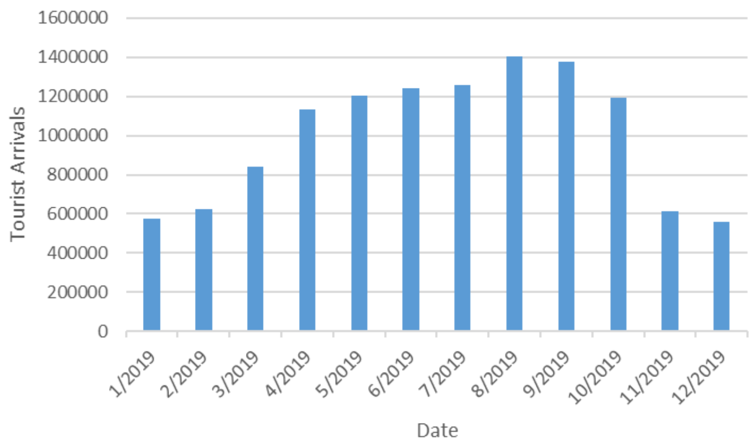


Figure 2. Monthly tourist arrivals in 2019 for the city of Granada (INE, 2019).

Based on Table 2, the most important sector of the city (in terms of GVA) is the "Real estate activities", which includes both incomes from the renting and sale of premises and profits created by real estate agencies. Next come the "Professional & Technical" and "Agriculture" sectors, which highlight the significant industrial activity in Granada, primarily concentrated in the city outskirts. Regarding tourism, sectors like "Retail trade" (grocery stores, gift shops, etc.), "Accommodation" (hotels, BnBs, etc.), "Food & beverage" (restaurants, bars, etc.), and "Arts & Entertainment" (theaters, cinemas, museums, etc.) reflect a large percentage of the city's overall annual GVA. It should be noted that their revenues are not constant throughout the year but vary in accordance with the high season of tourism. In the mesoeconomic model, this effect is captured by assuming that the monthly GVA produced by the tourist-based sectors under normal (i.e., pre-event) conditions are proportional to the tourist arrivals. Figure 2 shows the number of monthly visitors for the city during 2019 (data provided by INE), where the high season is identified from June to October.

Finally, to facilitate the physical vulnerability assessment that is required as input by the Mesoeconomic Engine, herein a sector-based exposure model is realized for Granada. In particular, we employ census data from national statistics (INE) to retrieve information regarding the type of building material, the number of stories, and the age of construction (low-/medium-/high-code). At total of 15 building typologies have been identified, ranging from Unreinforced Masonry, Medium-Rise, Low-Code buildings (code URM-MR-LC) predominantly located in the historical centre of the city, to Reinforced Concrete, High-Rise, High-Code (code RC-HR-HC) structures located in the city's residential zones.

3. Seismic assessment

3.1. Generation of seismic events and mesoeconomic analysis

Three seismic events are selected for the city of Granada representing a "moderate damage", 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. 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 three events are shown in Table 3. Moreover, the table contains the total direct losses (in mil. €) of each event, as estimated by an accompanying seismic assessment study, which is excluded herein for the shake of brevity.

Table 3. Seismological characteristics of considered events.

#	Description	Magnitude	Distance from city center [km]	Rupture depth [km]	Direct losses [mil. €]
1	Moderate damage	M6.1	23	13.2	1478
2	High damage	M7.3	123	15	2052
3	Very-high damage	M6.5	23	13.2	8999

Subsequently, a detailed vulnerability analysis is conducted for each event to derive the post-event recovery diagrams (or the *InfraIdx* diagrams) of the 10 considered business sectors, using the methodology described in Tsarpalis et al. (2023). In brief, first we evaluate the Damage State (DS) of each building in the city based on the seismological characteristics of the event and the exposure model of Granada, from no damage (DS0) to complete damage (DS4). Thereafter, the expected business interruption times of HAZUS 4.2 SP3 (2020) are employed to evaluate the downtime (in days) of each building according to its DS (e.g., DS0, DS1) and primary use (e.g., commercial, residential). The expected downtimes per DS and sector are illustrated in Table 2. For instance, commercial buildings in DS3 and primary use "Accommodation" need 81 days to fully recover while residential ones with primary use "Real Estate" require 480 days.

Ultimately, the produced downtime diagrams are fed into the Mesoeconomic Engine, which employs the failure propagation algorithm to calculate business interruptions. For each event, two sub-scenarios are examined: one where the event occurs in January (winter, low season) and one where it occurs in June (summer, high season). The total indirect losses per sector and event are depicted in Figure 3, in mil. €. Blue bars pertain to the low season sub-scenarios while red to the high season ones. As the primary use of most buildings in the city is residential, the "Real estate" sector faces significant indirect losses in all scenarios, which are mostly related to demand outages by the "Residents" FDN. For instance, in high season Event #2 (high damage) and Event #3 (very-high damage), the sector faces total indirect losses equal to 200 and 978 mil. €, respectively (11.5% and 56.4% of sector's annual GVA, respectively). Significant losses are observed also in the industrial (e.g., "Agriculture") and supply chain (e.g., "Wholesale trade") sectors, mainly due to the reduced demand that propagates backwards from the service sectors (e.g., "Retail trade").

Another noteworthy observation is that the ratio between the indirect and direct costs increases with increased seismic intensity, a well-known tendency that has been observed during actual post-disaster portfolio studies (Hallegate, 2008). Focusing on the low season sub-scenarios, the estimated total community indirect and direct losses are as follows: (a) for Event #1 equal to 487 and 1478 mil. €, respectively (ratio 26%), (b) for Event #2 equal to 1081 and 1478 mil. €, respectively (ratio 53%), and (c) for Event #3 equal to 5570 and 8999 mil. €, respectively (ratio 65%).

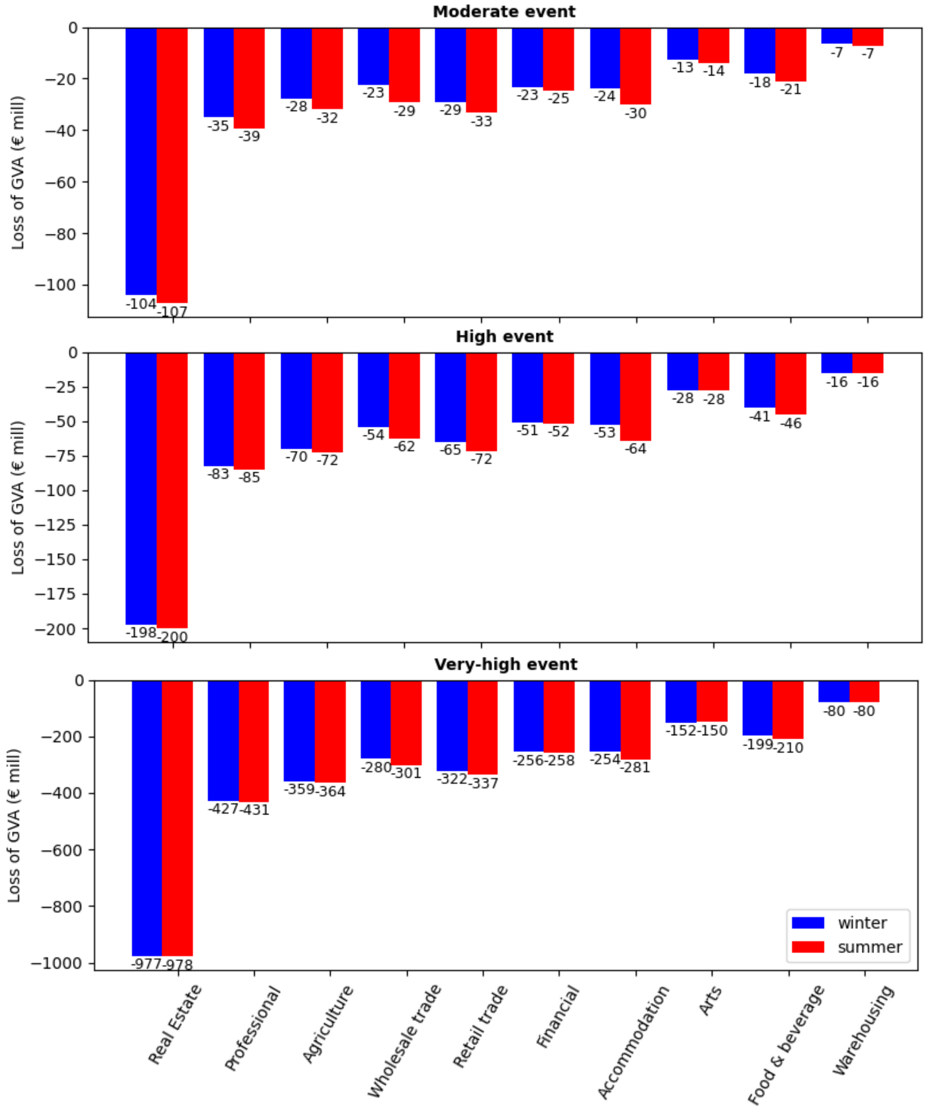


Figure 3. Indirect losses per business sector for the three seismic events.

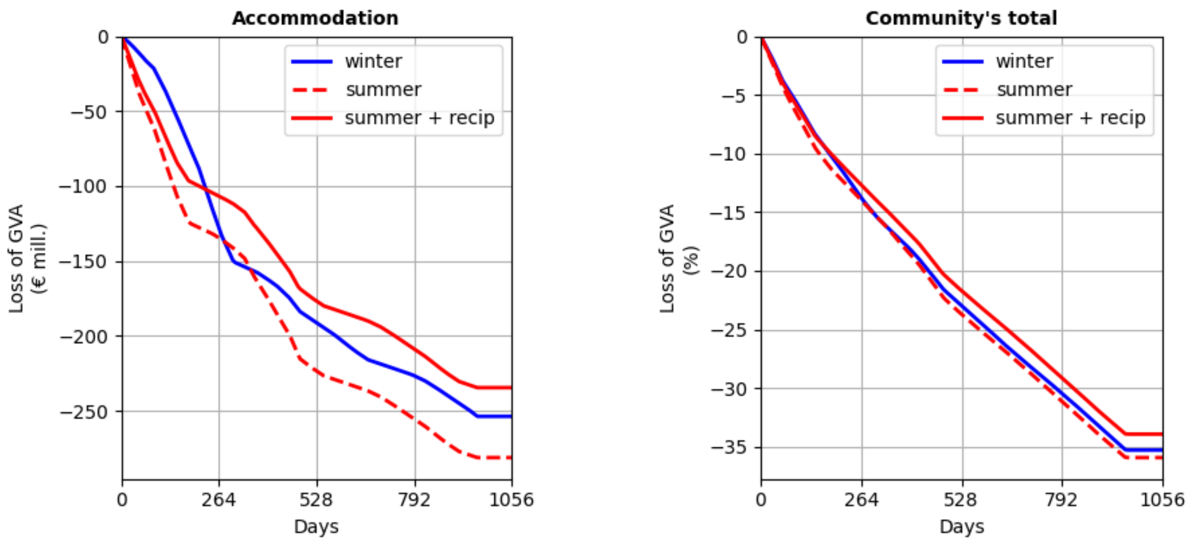
Finally, the timing of the event seems to exert a significant influence at moderate seismic intensities, while its effect fades out for more severe earthquakes. More specifically, for Event #1 the high season sub-scenario resulted in +28% increase of total indirect losses, whereas for Event #2 in +4.6% and for Event #3 in +1.8%. This trend can be attributed to the fact that most business sectors typically require 2 to 3 months to recover from moderate damages, as indicated by the downtimes for DS2 in Table 2. Consequently, when the event occurs during low season, the businesses have sufficient time to fully regain functionality and to be able to satisfy the increased demand during the upcoming high season. On the other hand, more severe damage states (DS3 and DS4) require more than 12 months for complete recovery and, thus, the effect of low/high season is balanced out over the longer restoration time periods.

3.2. Business continuity strategy

As a final application of the proposed methodology, a Business Continuity Strategy (BCS) is examined herein for the province of Granada, which implements reciprocal agreements between local firms. In general, reciprocal agreements involve two individuals or groups with similar objectives who agree to assist each other. When applied to a community level, they allow for a resilience load balancing between similar sized local businesses that operate within the same sectors, essentially offering faster business resumption and product/service availability to the residents/visitors following the occurrence of an adverse event. Based on pre-approved mutual actions, reciprocal agreements facilitate rapid response to incidents/disasters affecting the local tourist traffic and revenue streams, thus assisting the survival of the local businesses and the reputation retention of the community.

In this example, the hotels operating in the historical city of Granada are assumed to exploit reciprocal agreements for redistributing their traffic to other hotel-partners that are in the nearby municipalities in case one or more of them are experiencing service disruptions. Hence, in case of a disaster that forces several hotels to suspend their operation, the tourists will not have to leave the area, but will be directed to the remaining hotel-partners of the agreement. A contract is signed between the disrupted and non-disrupted hotels to share the turnover stemming from the transferred tourists in a 50-50 split.

To showcase the advantage of the proposed strategy, an additional mesoeconomic analysis is conducted for Event #3 (high season), which incorporates the aforementioned BCS. Subsequently, the analysis results are compared with those from the previous section. Figure 4(a) illustrates time history diagrams depicting the loss of GVA for the “Accommodation” sector. It is observed that through the adoption of reciprocal agreements, the sector indirect losses are significantly reduced throughout the entire recovery period, as the hotels of the city maintain a percentage of their profits thanks to the 50-50 sharing. Moreover, the strategy not only safeguards the GVA of the "Accommodation" sector but also preserves the revenue streams of other sectors in the tourism industry. This is indicated in Figure 4(b), where the total community indirect losses are also mitigated by a total amount of 315 mil. € in the scenario where the BCS is utilized.



(a) *(b)*

Figure 4. Time history diagrams for the very-high damage event, showing (a) the loss of GVA of the “Accommodation sector” and (b) the community’s total indirect losses in terms of % of city’s annual GVA.

4. Conclusions

A mesoeconomic model for quantifying the indirect losses of earthquake hazards is proposed, which has been encoded into the Mesoeconomic Engine software application. The model employs a business taxonomy framework, in which the individual businesses are aggregated into compact business sectors. The post-event functionality of each sector is measured by a performance index, which is further decomposed into three sub-indices, namely the infrastructure, input, and output indices. Disruptions to the supply chain are propagated by the input index using the Vendor Dependence Tables (VDTs, forward propagation of failure), while demand outages are addressed by employing normalized Input-Output Tables (IOTs, backward propagation of failure). The use of VDTs for propagating failure can provide enhanced flexibility with respect to traditional IOTs, as the former can be constructed by a combination of purely economic data and qualitative assessments.

Subsequently, the proposed model was illustrated and verified on three hypothetical seismic scenarios impacting the local economy of the city of Granada. It was found that the ratio between the indirect and direct losses increases with higher seismic intensity. Moreover, total community indirect losses experienced significant increase when the event occurred during the high season (summer), especially for moderate seismic intensities. Finally, a Business Continuity Strategy that incorporates reciprocal agreements between the hotels of the city was proposed, offering a solution to safeguard the economy of small businesses during the post-disaster reconstruction period. Overall, the model is anticipated to assist the city operators, loss assessors, and policy makers towards assessing the overall resilience of an entire urban area, considering both its assets and users/inhabitants. Despite its application to seismic hazards and tourism-based economies, it is actually generalizable to accommodate any considered source of risk and economic system.

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