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D5.5 HYPERION resilience framework

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[1] **R**=Document, report; **DEM**=Demonstrator, pilot, prototype; **DEC**=website, patent fillings, videos, etc.; **OTHER**=other

[2] **PU**=Public, **CO**=Confidential, only for members of the consortium (including the Commission Services), **CI**=Classified, as referred to in Commission Decision 2001/844/EC

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ACRONYMS AND ABBREVIATIONS

ARIO	Adaptive Regional Input-Output
BC	Business Continuity
CC	Climate Change
CH	Cultural Heritage
FDN	Final Demand Node
GVA	Gross Value Added
HRAP	Holistic Risk Assessment Platform
IO	Input-Output
IOT	Input-Output Table
MHVM	Multi-Hazard Vulnerability Module
VDT	Vendor Dependence Table

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Executive Summary

Deliverable D5.5, namely “HYPERION resilience framework”, documents the work undertaken in Task 5.5 “Socioeconomic, Community and Organizational Resilience Framework/Engine”.

A socioeconomic model of the residents and visitors (i.e., users), the local economy (i.e., production and consumption of goods, services and small businesses), and the local governance is generated, offering a hierarchical model for the functions of a core community related to a Cultural Heritage (CH) site. Initially, a comprehensive literature review is undertaken on aspects that are relevant to the resilience of a system as well as on the existing state-of-the art methodologies to simulate the community restoration process in the aftermath of a catastrophic Climate Change (CC) or non-CC aggravated adverse event. Owing to the above, the proposed model employs a combination of such macro/microeconomic approaches to quantify the indirect losses of a disaster by considering disruptions in the supply and in the demand chain. In particular, the individual local businesses operating in an area related to a CH site are aggregated into several compact business sectors. The annual Gross Value Added (GVA) of each sector is obtained by exploiting already available national/regional economic data. The performance of each sector at a given time following the occurrence of a catastrophic event is assessed by means of three indices: (a) the infrastructure, (b) the input, and (c) the output index. The infrastructure index measures the reduced production capacity of a business sector due to facility and lifeline disruptions, while the input index is used to account for supply outages. Finally, the output index is introduced to account for the propagating reduction of the demand during the post-event recovery phase, a condition that is likely to lead into severe economic losses even if for businesses that remain fully functional in terms of indices (a) and (b). To propagate failures in the supply chain, the developed methodology introduces the Vendor Dependence Tables (VDTs) that are routinely used in the Business Continuity (BC) practice, while the cascading demand disruptions are treated via an Input-Output Table (IOT) approach. The proposed model is also designed to accommodate the salient socioeconomic characteristics of a CH 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. The methodology is verified on the basis of several hypothetical disaster scenarios that are likely to affect simple economic systems. The outcomes of the aforementioned validation studies are then exploited to eventually develop the socioeconomic model of a complex CH community.

1 Introduction

1.1 Background

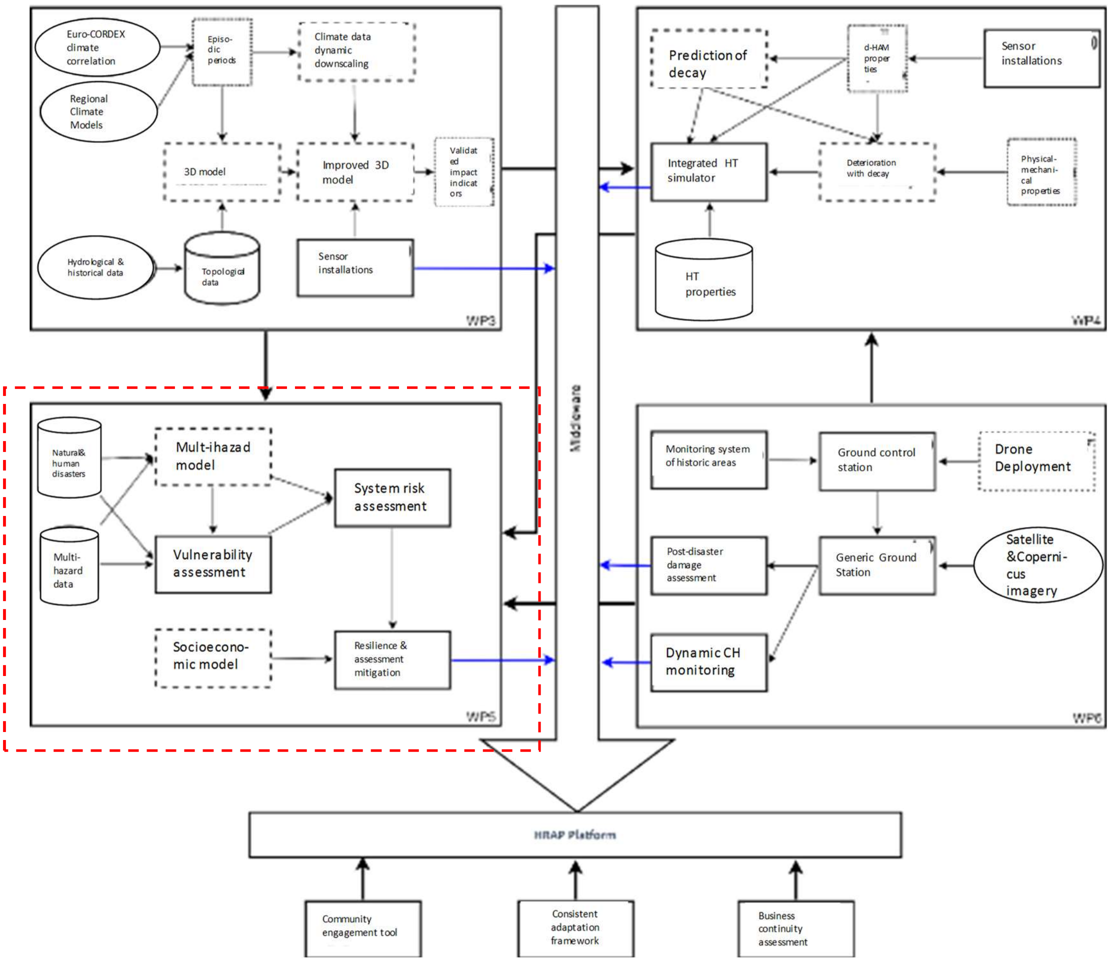
Deliverable D5.5 “HYPERION resilience framework” summarizes the work undertaken for establishing a methodology that enables the socioeconomic, community, and organizational resilience assessment of CH sites when those are subjected to a spectrum of Climate Change (CC) or non-CC aggravated hazards. The overall framework will be encoded on top of the structure/infrastructure resilience software that was developed in Task 5.4, eventually completing the integrated Holistic Risk Assessment Platform (HRAP) engine that supports the simulations of Task 5.6 and forms the basis for the development of the enterprise-level HRAP tool that is foreseen in Task 7.1.

1.2 Scope and objective

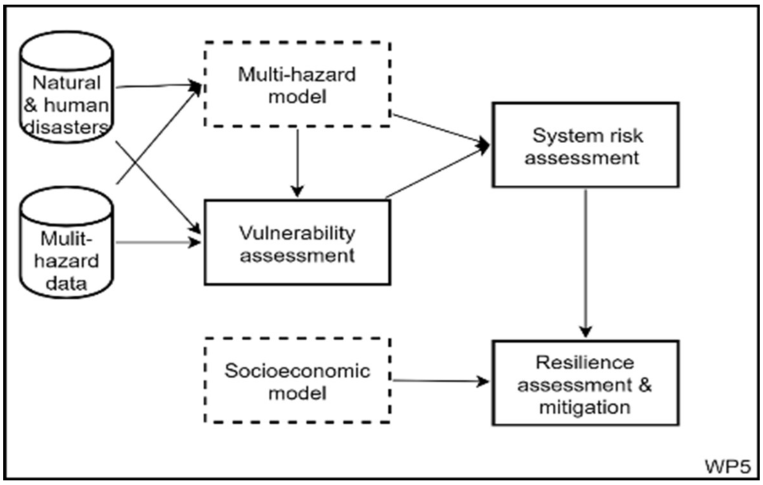
The overall objective of Task 5.5, namely “Socioeconomic, Community and Organizational Resilience Framework/Engine”, is to generate a socioeconomic model for quantifying the impacts of catastrophic events on the community level of CH areas as well as to simulate their post-event restoration process. The proposed model is designed to be holistic but also expandable, allowing for easy-to-implement modifications to accommodate the specific conditions at the considered CH site or integrate newly obtained information. Once the initial input data are collected to feed the tool, the developed methodology allows almost effortlessly to run pre-event “what-if” scenarios to undertake an initial rapid post-event analysis for assessing the socioeconomic impacts of adverse events on a community level. The assessment could be constantly updated with newly obtained data along with the outcomes of ongoing background simulations so as to always deliver accurate and up-to-date output. Ultimately, the proposed tool is anticipated to assist the CH operators and managers, cultural authorities, policy makers, etc. towards assessing the overall resilience of an entire CH area, considering both its assets and users/inhabitants.

1.3 Position of the socioeconomic tool in the HYPERION Ecosystem

The HYPERION high-level logical architecture is presented in Figure 1, as defined in Deliverable D2.3 “Architecture Specification” (Krommyda et al., 2020). The dashed red rectangle depicts the position of the “Multi-Hazards Modelling, Vulnerability, and Impact Assessment of the historic areas” that is foreseen in WP5 in the HYPERION Ecosystem. In particular, hazard simulators read hazard scenario inputs and feed their output into the HRAP platform. HRAP in turn, feeds the hazard input into the multi-hazard vulnerability modules (MHVMs) as well as into the socioeconomic model, that is presented in this deliverable. Then, risk and resilience assessments are performed, and the results are returned back to the middleware for storage.



(a) Entire HYPERION Ecosystem



(b) WP5 module: socioeconomic model

Figure 1: Position of the socioeconomic model (a) in the HYPERION Ecosystem and (b) in WP5.

1.4 Definition of resilience

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 CH sites, 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 the tourism rather than the 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. Due to its multifaceted nature, resilience has been a buzzword that is used by a great deal of scientific fields, and thus a variety of definitions can be found in the pertinent literature. According to Cimellaro et al. (2016), community resilience can be decomposed into seven dimensions: (i) population and demographics, (ii) environment and ecosystem, (iii) organized government services, (iv) physical infrastructure, (v) lifestyle and community competence, (vi) economic development, and (vii) social-cultural capital. The same authors use the following simple mathematical definition of resilience, which is also graphically illustated in Figure 2:

$$R(\vec{r}) = \int_{t_{OE}}^{t_{OE}+T_{LC}} Q_{TOT}(\vec{r}, t)/T_{LC} dt \qquad (1)$$

where $Q_{TOT}(t)$ is a global functionality-performance function of the considered area (e.g., local, regional), t_{OE} is the time instant when the event occurs, T_{LC} is the control time for the period of interest, and $\vec{r}$ is a spatial vector defining the position in the region in which the resilience is evaluated.

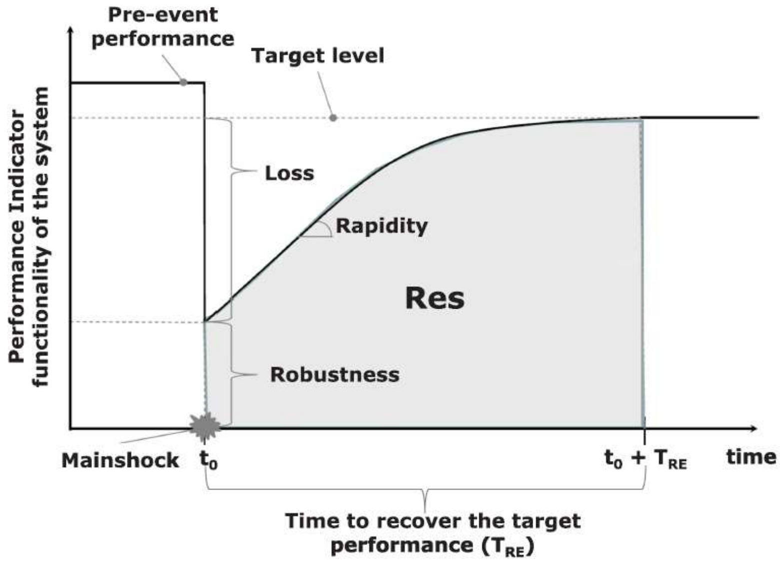


Figure 2: Definition of resilience (Cimellaro et al., 2016).

Intuitively, resilience can be defined as the capability of a system to absorb the initial shock (robustness), respond, and adapt in order to maintain functionality and hasten recovery (rapidity) (Franchin and Cavalieri, 2014). With reference to Figure 2 resilience corresponds to the gray shaded area. In that sense, resilience can be broken down into two main components: the inherent and the adaptive resilience (Rose, 2009; Graveline and Grémont, 2017). Inherent resilience is a built-in characteristic of the system and pertains mitigation mechanisms that exist prior to the disaster (e.g., efficient stocking of essential supplies in case of vendor shutdowns). Adaptive resilience is related to the ability of planning, analyzing, and deciding rationally under stress, to better cope with the emergency situations during and after the occurrence of a hazard event (e.g., the ability to substitute vendors outside of the impacted area in case of supply outages).

Several approaches have been proposed for the quantification of the community resilience, which can be classified into **qualitative** and **quantitative** ones (Liu et al, 2021b). In the **qualitative** resilience methodologies, in order to assess the socioeconomic consequences of a disaster, one typically sets a conceptual framework to identify the key factors that influence the post-disaster recovery process of the community, which are then expressed in terms of community resilience indices (e.g., Rose and Krausmann, 2013; Cutter, 2012). On the other hand, the **quantitative** approaches employ empirical (Chang and Rose, 2012; Liu et al., 2021a), simulation-based (Miles and Chang, 2013; Inoue and Todo, 2019), or decision-based (Dhulipala and Flint, 2020; Burton et al., 2018) models to assess the socioeconomic impact of a disaster, by considering the cascading effects of disruptions on critical infrastructure and essential supplies. However, most of the aforementioned studies investigated the disaster aftermaths from a macroeconomic standpoint, mainly focusing on the restoration process of the lifeline services. Therefore, they disregarded essential factors that govern the post-disaster performance of small businesses, especially those that operate in CH sites. For instance, the annual Gross Value Added (GVA) of a CH site highly relies on tourist arrivals and thus, the occurrence of a catastrophic event during the high season (i.e., the time of the year where most of the tourists are visiting the site of interest) can potentially result in more severe impacts, leading to devastating economic and reputation losses if sufficient risk mitigation precautions are not taken, compared to those that are expected if the same event occurs during the low season.

To efficiently tackle the abovementioned adverse consequences, a business-based fully quantitative methodology is developed 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 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 effect of high/low season occurrence of the event. Several application examples of different complexity are presented in this deliverable to demonstrate the different features as well as the effectiveness of the proposed methodology. Those applications initially account for simple economic systems, to illustrate the intrinsic characteristics of the proposed socioeconomic model, to finally advance to a case study application for the city of Rhodes in Greece−which is one of the HYPERION demonstration sites that involves the consideration of several hypothetical disaster scenarios for which we are assessing the socioeconomic impact.

2 Proposed Socioeconomic Model

2.1 Simplified business taxonomy

The proposed socioeconomic model employs an aggregation methodology to calculate the cascading failures and business interruptions that are likely to occur following the occurrence of a hazard event, by defining and exploiting a business taxonomy approach for classifying the individual businesses that operate on a society that is linked to a CH site. Hence, the proposed approach disregards the spatial distribution of the firms/business operating at the site of interest and instead combines them into distinct nodes, where each node represents a particular business sector. Each business sector is likely to contain organizations of different size, annual turnover, scopes, etc. For instance, the “Accommodation” business sector may refer to all short of lodging services, from big hotels with several guest rooms down to small Bed & Breakfasts (BnBs), as for instance it is illustrated in Figure 3 for the city of Rhodes.

Business	Units	GVA (mill. €)	GVA (%)
"Hotel AA"	1	10.51	4.0
"Motel BB"	1	3.22	1.2
"Motel AB"	1	1.49	0.6
"Hotel AC"	1	7.82	3.0
…	…	…	…
"BnB BC"	2	6.67	2.5
Total	58	262.96	100

Figure 3: Derivation procedure of the "Accommodation" business sector for the city of Rhodes, combining the GVAs and capacities of different lodging firms.

The simplified business taxonomy that is developed each time for the site of interest 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 tourism 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 GVA and an inverse approach (i.e., aggregation) may be justified.

For illustrative purposes, the proposed business classification/taxonomy methodology was applied and consequently demonstrated for the city of Rhodes in Greece, which constitutes one of the four HYPERION demo sites. 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". The adopted business taxonomy that is deemed to be representative for the city of Rhodes is given in Table 1, along with the annual GVAs of each one of the defined business sectors, using the economic data provided by the Hellenic Statistical Authority (ELSTAT). For applications to the other HYPERION CH sites (i.e., Tønsberg, Venice, and Grenada) some adjustments may be needed to the proposed taxonomy, yet those modifications are expected to be minor and easy to implement.

Table 1: Proposed business taxonomy for the city of Rhodes (23 business sectors).

#	Full Name	GVA (€ mill.)	GVA (%)
1	Wholesale trade, except of motor vehicles and motorcycles	112.80	13.81%
2	Real estate activities	93.99	11.51%
3	Retail trade, except of motor vehicles and motorcycles	64.10	7.85%
4	Accommodation	60.15	7.37%
5	Food and beverage services	50.31	6.16%
6	Education	44.65	5.47%
7	Human health and social work activities	36.22	4.43%
8	Business, scientific and technical activities	33.77	4.13%
9	Warehousing and support activities for transportation	28.41	3.48%
10	Wholesale and retail trade and repair of motor vehicles and motorcycles	24.27	2.97%
11	Financial services and insurance activities	23.27	2.85%
12	Manufacturing	23.00	2.82%
13	Creative, arts and entertainment activities	20.18	2.47%
14	Agriculture, forestry, fishing	12.44	1.52%
15	Water transport	34.30	4.20%
16	Land transport and transport via pipelines	32.33	3.96%
17	Electricity, gas, steam and air conditioning supply	31.85	3.90%
18	Public administration and defense; compulsory social security	21.52	2.63%
19	Construction	12.13	1.49%
20	Media and communication	10.54	1.29%
21	Air transport	9.48	1.16%
22	Sewerage, waste collection, treatment and disposal activities; materials recovery, remediation activities and other waste management services	7.38	0.90%
23	Other services	29.64	3.63%
SUM		816.71	100%

The “Wholesale trade” business sector comprises 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 the real estate agents and the incomes from the rental and sale of premises. Moreover, as the city of Rhodes is a popular tourism region, the

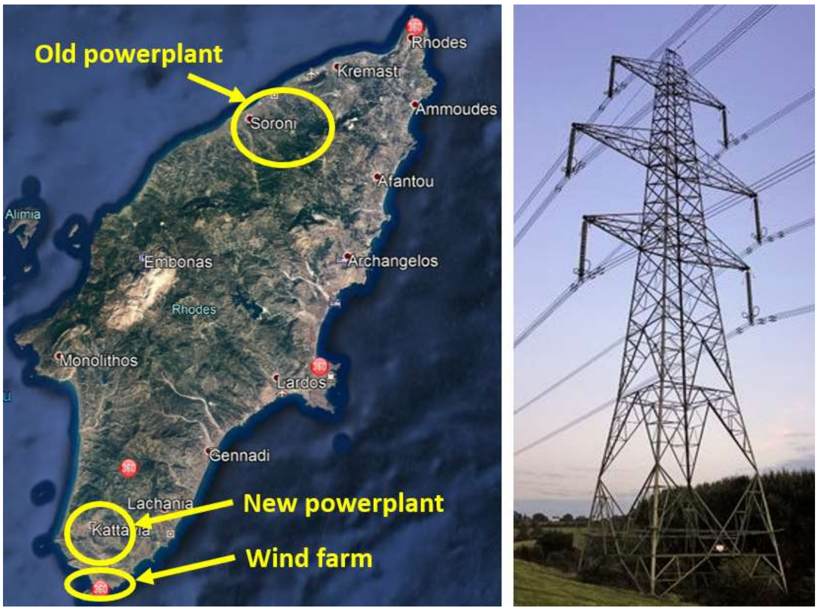
"Accommodation" (hotels, BnBs, etc.) and "Food and beverage" (restaurants, bars, etc.) sectors reflect a large percentage of the city's overall annual GVA. Finally, the business sectors with indices from #15 to #22 in Table 1 correspond to critical infrastructure and lifeline services, such as power supply, water supply, sewage, etc. While these sectors are treated separately in the proposed socioeconomic model through the introduction of the so-called "infrastructure index" (which is presented in the following sections), they are also considered herein for completeness.

Along with the aforementioned identification of the supply business sectors, the following five potential customer categories, that were called in the proposed methodology "Final Demand Nodes (FDNs)" were defined: Residents, Tourists, Government, Investments, and Exports. While both "Residents" and "Tourists" comprise the local consumption component of an economic system, they were herein treated separately due to their substantially different consumption profile and hence impact on the CH region. The "Government" FDN refers to the government consumption expenditure (e.g., equipment, infrastructure, and payroll) and gross investment. The "Investments" FDN is related to the private domestic investments or the capital expenditures (e.g., purchase of equipment and machineries by a manufacturing company). Finally, "Exports" refer to the total intra/international exports of the CH region economy. The latter are essentially the goods and services that the investigated CH economy produces and exports to other economies. It should be kept in mind that each FDN has a dynamic response to the socioeconomic changes that are likely to be triggered by a CC or non-CC 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.

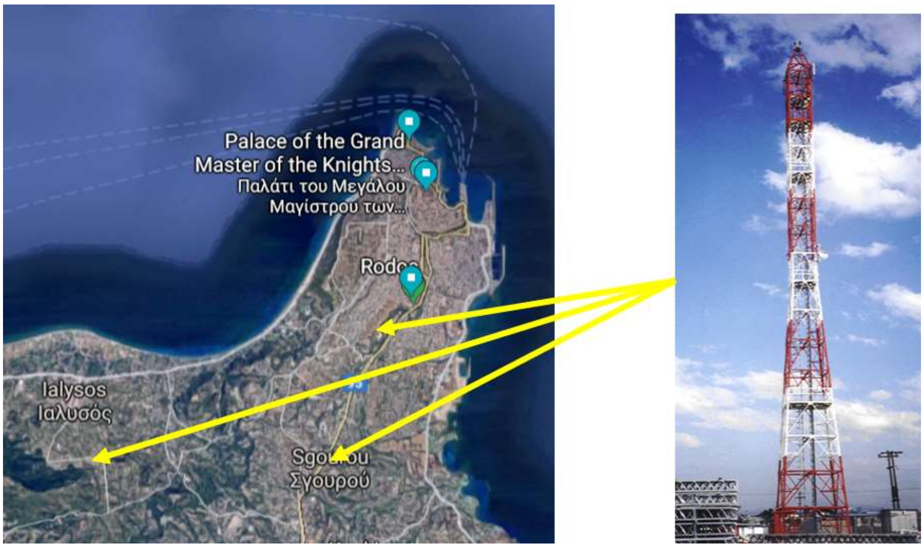
2.2 Critical infrastructure and lifeline services

The resilience of **critical infrastructure & lifeline services** (transport, electricity, water, sewage, etc.) plays an important role in the community's overall performance during and following a disaster event. The importance of a critical infrastructure may vary across communities at different locations with different demographic characteristics. For instance, marine or air transportation infrastructure might be more crucial for a site located in an island compare to a mainland site, since the latter can also rely on road transportation to satisfy import and export demands. Moreover, businesses that operate on developing countries often use for their daily activities more traditional means that are not highly dependent on the technological advancements, and hence, are more tolerant to disruptions in, for example, the power supply (Asgary et al., 2012) or the telecommunications.

For the case study application in the city of Rhodes, four critical infrastructure networks were identified, these being: (i) the power generation, transmission & distribution network, (ii) the telecommunication network, (iii) the water & sewage network, and (iv) the transportation network. Figure 4(a)-(d) schematically illustrates each one of the aforementioned networks and their spatial distribution across the island of Rhodes. Electric power in Rhodes is generated primarily by two powerplants, i.e., an old one located near the capital city and a new one located in the far south part of the island. Secondarily electricity is also produced by a wind farm that is located near the new powerplant (see Figure 4(a)). On the other hand, the telecommunication network comprises several lattice towers which are mostly located in the north part of the island (Figure 4(b)). Drinking water is transmitted to the city of Rhodes from the Gadoura lake through a main water line, whereas wastewater is collected into the sewage treatment plant that is located nearby the city of Rhodes (see Figure 4(c)). Finally, the transportation network (see Figure 4(d)) comprises the road network, the marine port (inside the city), and the airport (located near the city). It should be noted that for the island of Rhodes, no distinction was required between the cargo and non-cargo marine port. Yet, this might not be the case of other sites.

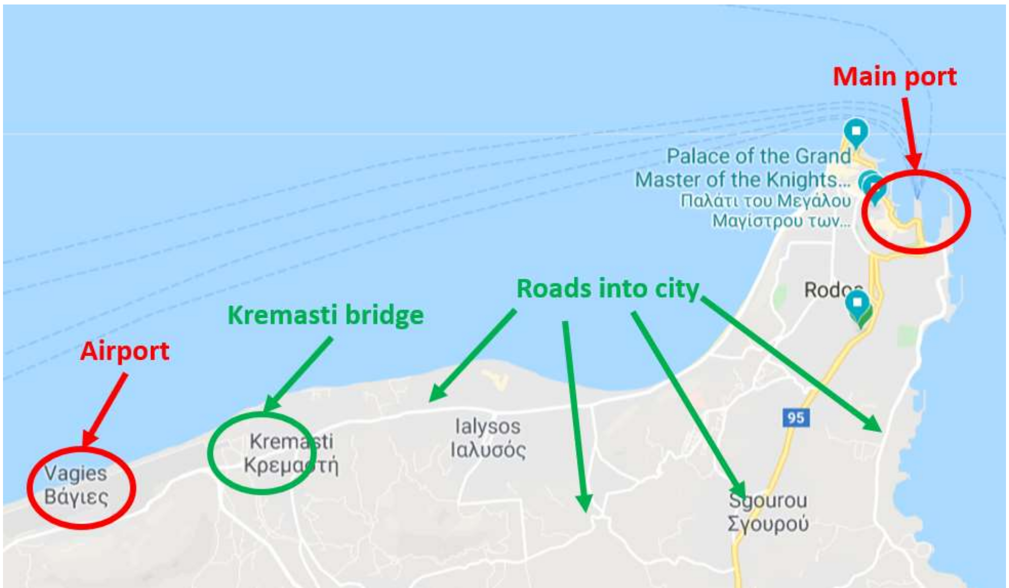


(a)



(b)

(c)



(d)

Figure 4: Schematic layout of the critical infrastructure networks for the city of Rhodes: (a) the power generation, transmission & distribution network, (b) the telecommunication network, (c) the water & sewage network, and (d) the transportation network.

2.3 Downtime diagrams and recovery process

Various methods for modelling the **macroscopic recovery process** of a community exist in the literature (Burton et al., 2018; Chang and Rose, 2012). Those methods are focusing mainly on the reconstruction of critical infrastructure and the definition of community resilience indices (Cutter, 2012). On the other hand, the **microscopic**

recovery phase of individual businesses has not received equal attention in the international literature, even though small/medium businesses often substantially contribute to the economy of a society by providing a great deal of jobs, goods and services, as well as tax money. Asgary et al. (2012) identified several factors that are likely to affect the restoration process of small businesses, such as (a) the facility and inventory damages, (b) the lifeline disruptions, (c) the supply outages, (d) the experience gained from previous disasters, (e) the government and family support, etc. Businesses that have an efficient recovery plan, that comprises a key component of adaptive resilience, can not only survive a disaster, but could also take benefit from it and "bounce forward" to greater performance levels (de Vries and Hamilton, 2021). Generally, larger organizations adopt more active and passive hazard adjustments than small businesses (Sadiq, 2011), as the latter usually do not employ an explicit business continuity plan (Zhang et al., 2009). Moreover, small businesses often operate on a specific location and, thus, are more vulnerable in demand reductions as they cannot spread and transfer their risk. The recent paradigm of the global Covid-19 pandemic showcased how several small businesses operating on CH sites were enforced to permanently cease their operation, as fear and public health measures harshly decreased tourist arrivals (Donthu and Gustafsson, 2020).

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 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 multi-variant time 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 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 capture the individual socioeconomic factors affecting the performance of a business sector, *PerfIdx* is discretized into three key components: (a) the infrastructure index (*InfraIdx*) (b) the input index (*InputIdx*), and (c) the output index (*OutputIdx*). A detailed description of each one of these components is provided in the subsequent sections. At each time step, a distinct set of (*InfraIdx*, *InputIdx*, *OutputIdx*) is calculated for each business sector, following a hybrid (macro/microscopic) methodology to account for cascading failures and socioeconomic impacts. Ultimately, the overall performance index *PerfIdx* is calculated as the minimum value of its three key sub-indices:

$$PerfIdx = \min(InfraIdx, InputIdx, OutputIdx) \tag{2}$$

2.3.1 Infrastructure index (*InfraIdx*)

The infrastructure index (*InfraIdx*) 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*. For instance, infrastructure damages could be related to structural damages in facilities or to nonstructural damages in the machineries of a business unit, to disruptions in critical infrastructure, to poor crisis management by the owner/ municipal authorities, etc. Based on these disruptions, a binary 0 or 1 value is assigned to each business unit, with 0 denoting that the unit is completely nonfunctional and 1 that the unit retains its maximum production capacity (i.e. we disregard partial functionality, an assumption which however is deemed to be rational for hazards affecting the structural and nonstructural integrity of a business). Hence, a microscopic business-unit-based approach is used to calculate the macroscopic *InfraIdx* of each business sector, as described below.

To further elaborate on this aspect, one may consider a hazard event that occurs at time $t = 0$, which causes disruptions to critical infrastructure, facility damages, and hinders labor as the employees are unable to reach their working premises. As a result of these disturbances, each $i = [1, N_j]$ business unit belonging to the j business sector (N_j being the total number of business units of sector j), needs a t_{ij} time to recover from the shock. *InfraIdx* is calculated as the percentage of the fully operating business units belonging to a particular business sector at a given time step. For instance, let assume an “Accommodation” sector that comprises 10 hotels, in which right after the occurrence of the hazard, 9 out of the 10 hotels were forced to close. Of the 9 closed units 5 were closed due to severe power and water supply disruptions, whereas the remaining 4 were closed mainly due to the fact that they sustained minor structural damages (whereas they are also likely to be affected by the water/supply disruptions). In that case, the infrastructure index of this sector at $t = 0$ is equal to 10%. Assume now, that after 2 days the power and water supply was fully restored in all hotels experiencing such problems. Hence the 4 out of the 9 hotels that they were initially closed solely due to the power/water supply disruptions were reopened. In that case, a total of 5 hotels are functional, which results in an *InfraIdx* of 50%. The remaining 5 hotel units that suffered minor structural damages required from 7 to 15 days to get back to “business as usual”. The complete downtime (i.e., *InfraIdx*) diagram of the aforementioned “Accommodation” sector according to the descripted disruption and restoration scenario is presented in Figure 5.

While assigning the 0 (shutdown) or 1 (functional) binary value to the individual business units to derive the full downtime diagrams of a business sector, one should also consider the effect of interdependencies among the critical infrastructure networks. Recently, Cardoni et al. (2020) investigated the correlation between the buildings and the electrical distribution network by introducing a new network resilience index. The proposed methodology was then applied to data collected during two seismic events in Japan and Chile, highlighting a strong coupling between the restoration of power and telecommunication infrastructure systems. Indeed, as reported by Kajitani and Sagai (2009), the loss of power affects the Information

Technology (IT) infrastructure, leading to further delays on the restoration phase due to lack of information sharing between the government and the recovery parties. Electricity supply has a significant impact on all business sectors, as even a short-to-medium term disturbance can lead to production capacity losses of 94% to 98% (Liu et al., 2020). On the other hand, businesses seem to be more flexible on the water and gas disruption networks.

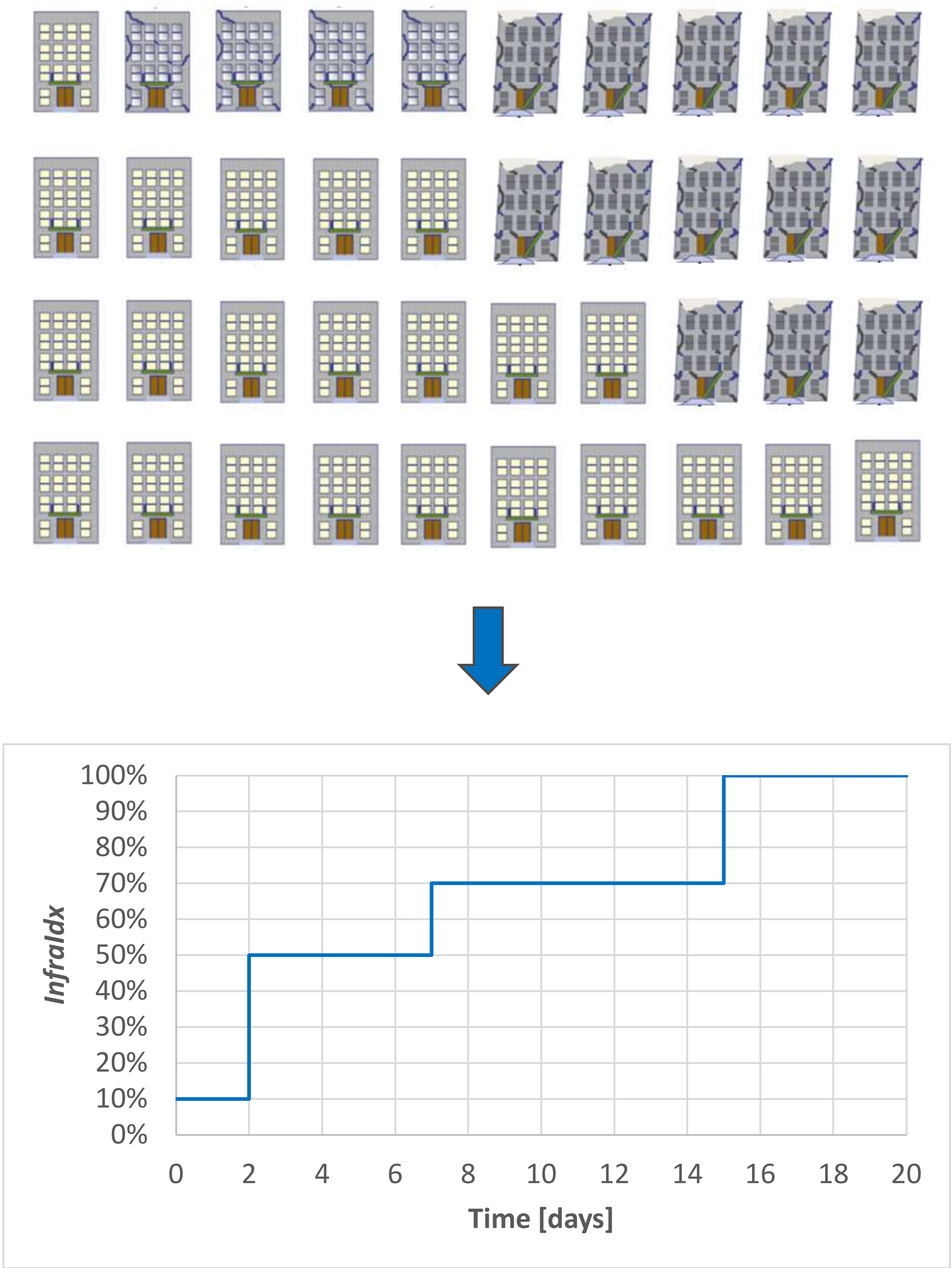


Figure 5: Evolution of the *InfraIdx* index with the restoration time for a business sector comprising 10 business units that experienced water/power supply disruptions and/or sustained minor infrastructure damages due to a catastrophic event.

2.3.2 Input index (*InputIdx*)

The *InfraIdx* that was discussed in Section 2.3.1 corresponds to the theoretical maximum production capacity of a business sector at a given time, on account of any potential lifeline and facility disruptions. On the other hand, the actual productivity of a business might be harshly reduced during a disaster due to supply outages, despite the business being fully functional/intact in terms of *InfraIdx*. To capture the propagating effect of reduced inputs, an input-output methodology is adopted herein, that is founded on the Adaptive Regional Input-Output (ARIO) model that was proposed by Hallegatte (2008). In this respect, a second index is defined, namely the input index (*InputIdx*), that needs to be calculated for each business sector node according to, the so-called in BC practice, **Vendor Dependence Tables** (VDTs).

VDTs are tools frequently used in BC to evaluate the dependence of an organization to its vendors. An example of a VDT for the “Retail trade” business sector is provided in Figure 6. Each line of the VDT contains a series of indices, capturing 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). For instance, supermarkets typically receive their goods by the “Wholesale trade”. Depending on the size of its own inventory and the consumption demand, a small-scale supermarket might remain fully operational in case of complete vendor disruptions for up to one day. This is characterized as Condition 1, where the company does not experience any operational issues due to the supply outages, and corresponds to 0% loss of productivity. However, if the supply disruptions persist over time, the business will be inevitably impacted and will downgrade from Condition 1 to Conditions 2, 3, and 4 which reflect a 25%, 50% and 75% loss of productivity, respectively, while Condition 5 (see Figure 6) that reflects the complete loss of its service capacity (100% loss of productivity eventually leading to its shutdown) will be reached two weeks away from the disruptions associated with the “Wholesale trade”.

As can be inferred from Figure 6, not all vendors are equally important to a certain business sector. The importance of each vendor to the considered business sector is reflected on how fast the operability of the sector downgrades from Condition 1 to Condition 5 in case of severe supply reductions related to such vendor. One should also note that business sectors that correspond to critical infrastructure (e.g., marine port, electricity, gas) do not affect the *InputIdx* via the VDT (i.e., a constant Condition 1 through time), as their effect have been already accounted by the *InfraIdx*. As VDTs are site- and business-specific, a reliable estimation can be derived by means of expert opinion, efficient collection of data (e.g., questionnaires), and statistical processes. Moreover, if more than one vendors experience disruptions, the most critical (according to the VDT, i.e. earliest attainment of the highest Condition) will be considered during the calculation of the *InputIdx*, a state that is characterized as “supply bottleneck”.

#	Retail trade	0h	1h	2h	4h	8h	12h	1d	2d	4d	1w	2w	1mo	2mo	∞
3	Retail trade, except of motor vehicles and motorcycles	5	5	5	5	5	5	5	5	5	5	5	5	5	5
8	Business, scientific and technical activities	1	1	1	1	1	1	1	2	2	3	4	5	5	5
11	Financial services and insurance activities	1	1	1	1	1	1	1	2	2	3	3	3	4	5
1	Wholesale trade, except of motor vehicles and motorcycles	1	1	1	1	1	1	1	2	3	4	5	5	5	5
12	Manufacturing	1	1	1	1	1	1	1	1	1	1	1	2	2	2
14	Agriculture, forestry, fishing	1	1	1	1	1	1	1	1	1	1	2	2	2	2
2	Real estate activities	1	1	1	1	1	1	1	1	1	1	1	1	2	2
10	Trade and repair of motor vehicles and motorcycles	1	1	1	1	1	1	1	1	1	1	2	2	2	3
19	Construction	1	1	1	1	1	1	1	1	1	1	1	2	2	2
4	Accommodation	1	1	1	1	1	1	1	1	1	1	2	2	3	3
5	Food and beverage services	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	Education	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9	Warehousing and support activities for transportation	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	Creative, arts and entertainment activities	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15	Water transport	1	1	1	1	1	1	1	1	1	1	1	1	1	1
21	Air transport	1	1	1	1	1	1	1	1	1	1	1	1	1	1
23	Other services	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	Human health and social work activities	1	1	1	1	1	1	1	1	1	1	1	1	1	1
16	Land transport and transport via pipelines	1	1	1	1	1	1	1	1	1	1	1	1	1	1
17	Electricity, gas, steam and air conditioning supply	1	1	1	1	1	1	1	1	1	1	1	1	1	1
18	Public administration and defense; compulsory social security	1	1	1	1	1	1	1	1	1	1	1	1	1	1
20	Media and communication	1	1	1	1	1	1	1	1	1	1	1	1	1	1
22	Sewerage, waste collection, treatment, etc.	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 6: Example VDT for the “Retail trade” business sector.

2.3.3 Output index (*OutputIdx*)

The last index that is needed in order to estimate the performance index *PerfIdx* according to Eq. (2), is the output index (*OutputIdx*). This index is utilized to measure the propagating reduction of the demand during the recovery phase. In fact, it is possible for a business sector to experience severe economic losses due to the reduced consumption, without the sector sustaining any direct facility/infrastructure damages (i.e., decrease of *InfraIdx*) or experiencing supply outages (i.e., decrease of *InputIdx*). *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., $\sum_{j=1}^{N} o_{ij}$ 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 CH site follows a similar business-to-business and business-to-consumer economic profile. A segment of the normalized IOT that was used for the city of Rhodes is given in Figure 7.

	Wholesale trade	Real estate activities	Retail trade	Accommodation	Restaurants	…
Wholesale trade	0.004497	0.000212	0.002431	0.012018	0.012018	
Real estate activities	0.062648	0.000158	0.051271	0.003257	0.003257	
Retail trade	0.011383	0.000056	0.005590	0.043901	0.043901	…
Accommodation	0.001072	0.000358	0.000775	0.000801	0.000801	
Restaurants	0.001072	0.000358	0.000775	0.000801	0.000801	
Education	0.000147	0.000000	0.000115	0.000073	0.000073	
…			…			

Figure 7: Extract from the normalized Input-Output Table (IOT) utilized for the city of Rhodes.

2.4 Forward and backward propagation of failure

Following the definition of the three performance indices, this section briefly describes the failure propagation procedure in the proposed socioeconomic model. The impact analysis starts at *t* = 0 h where the catastrophic event occurs and leads to several direct losses, such as damages to premises and critical infrastructure. These direct losses and the recovery process are assumed to have already been pre-processed by the user in order to derive the *InfraIdx* diagram of each business sector. Essentially the socioeconomic model uses *InfraIdx* as input in order to calculate the cascading disruptions in the supply (*InputIdx*) and demand (*OutputIdx*), as described in the following paragraphs.

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 Figure 6) in order 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 a CC or non-CC aggravated adverse event is challenging to be quantified, as it is related to socioeconomic factors such as politics, fear, community's 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 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* = 50%, a +10% overproduction can always be activated) and (b) a time-dependent overproduction (e.g., if the "Accommodation" sector has *InfraIdx* = 50%, a +10% overproduction can be activated only during the low season months).

3 Example applications

3.1 A four-node economic system

To illustrate the developed failure propagation methodology, initially a simple economic system is considered and consequently examined. The simplified economic system consists of four nodes (A to D that reflect four business sectors) that are interconnected assuming three different supply/demand connectivities. In the first example (illustrated in Figure 8(a)), the nodes/business sectors A and B are vendors for the node/business sector C, while node/business sector C is vendor for node/business sector D. For simplicity, we assume that the *InputIdx* of a node is instantly affected in case of supply disruptions in any of its vendors, i.e., it downgrades to Condition 5 at the very first time step (*t* = 0 h in the VDT of Figure 6). The same configuration is assumed for the IOT: nodes A and B provide goods/services to node C, which in turn provides goods/services to node D. As illustrated in Figure 8(a), a facility disruption in node B ($\text{Infra}^{B} = 50\%$, i.e. half the businesses in that sector become unfunctional due to “infrastructure damages” as those were defined in section 2.3.1) leads to equivalent supply outages in node C ($\text{Input}^{C} = 50\%$), and this failure further propagates to node D ($\text{Input}^{D} = 50\%$). As a result of the reduced Input^{D}, the consumption of the FDN node D is affected (e.g., the tourists will leave the CH site if the hotels are closed due to a disaster), which consequently reduces the demand of node C ($\text{Output}^{C} = 50\%$), and the failure is ultimately propagated backwards to nodes A ($\text{Output}^{A} = 50\%$) and B ($\text{Output}^{B} = 50\%$).

The second example is similar to the first one with the only difference being that node B directly supplies node D (Figure 8(b)). As a result, the input of node C is not affected by B (i.e., $\text{Input}^{C} = 100\%$), however it still leads to reductions in the node demands ($\text{Output}^{A} = \text{Output}^{B} = \text{Output}^{c} = 50\%$). Finally, in the last simplified example that was considered herein (Figure 8(c)) a circular economic system is assumed (i.e., there are no FDNs) and an infrastructure disruption of 50% in node B leads to both supply and demand disruptions in all nodes. While these simple cases lack important characteristics of a realistic socioeconomic model, they still capable of demonstrating the basic forward and backward propagation of failure and validate the overall methodology.

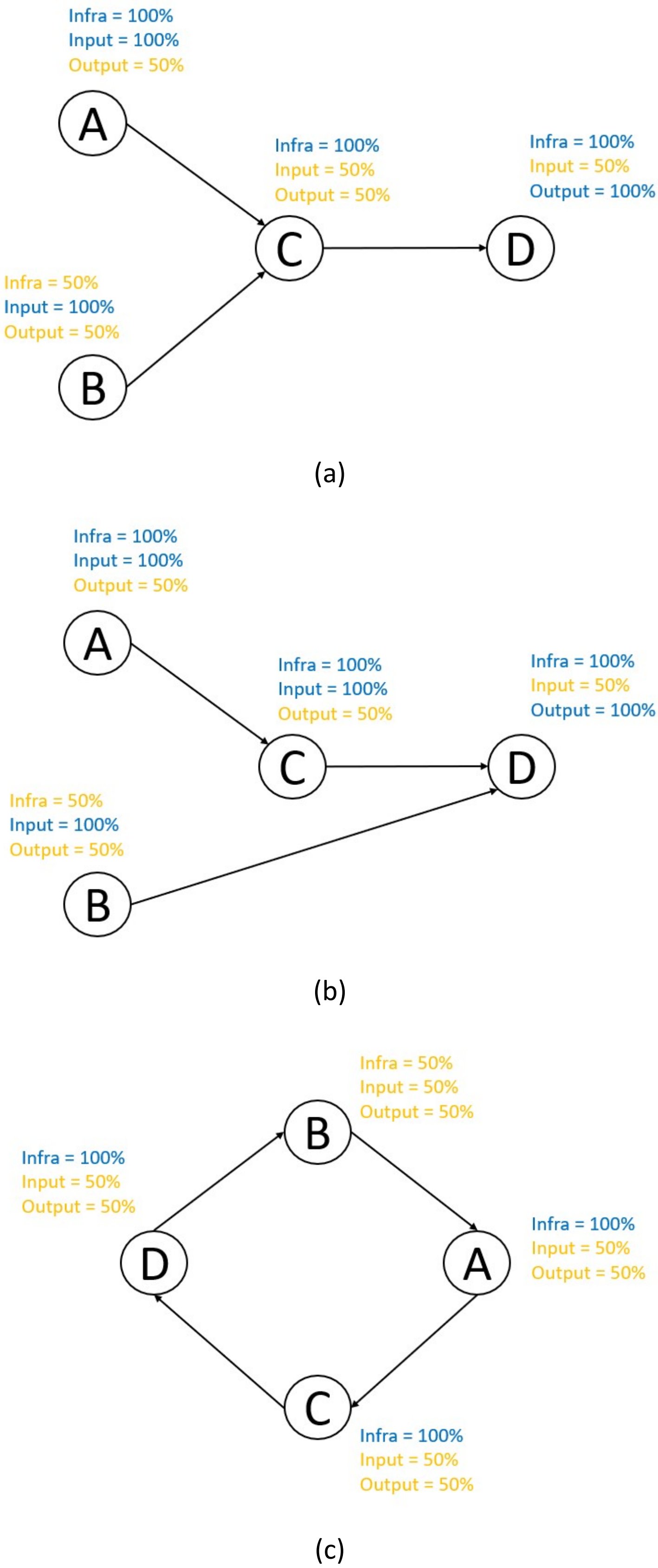


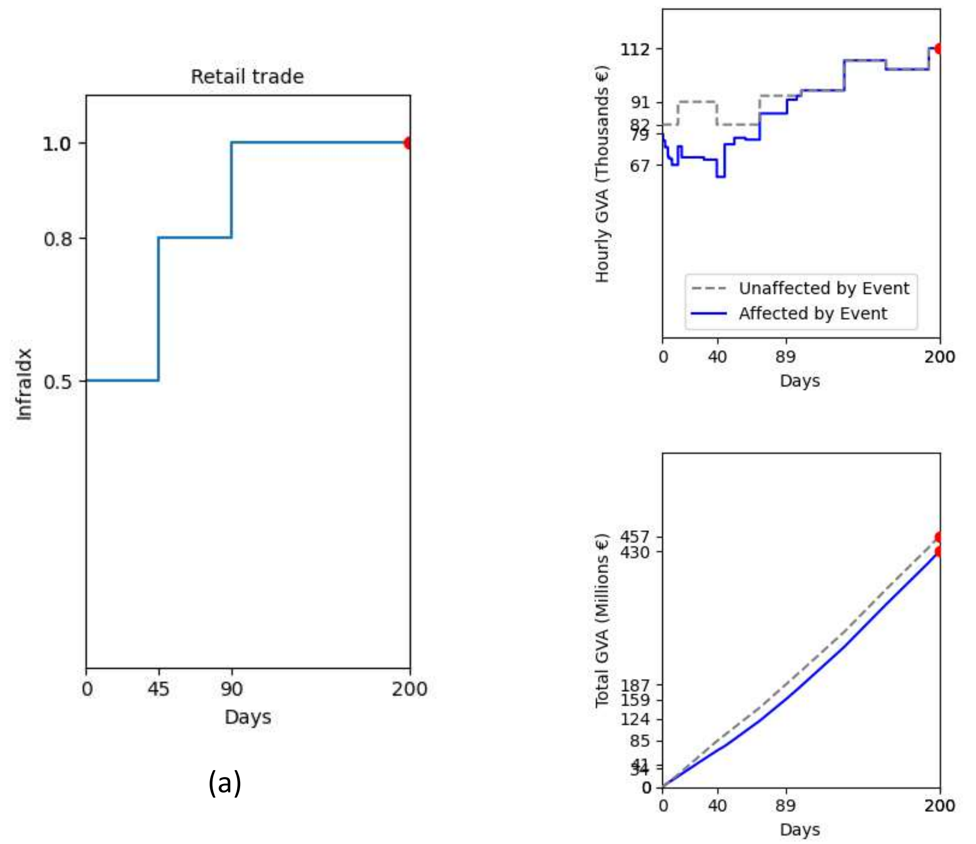
Figure 8: Failure propagation on a four-node economy using three different supply/demand connectivities.

3.2 Socioeconomic model for the city of Rhodes

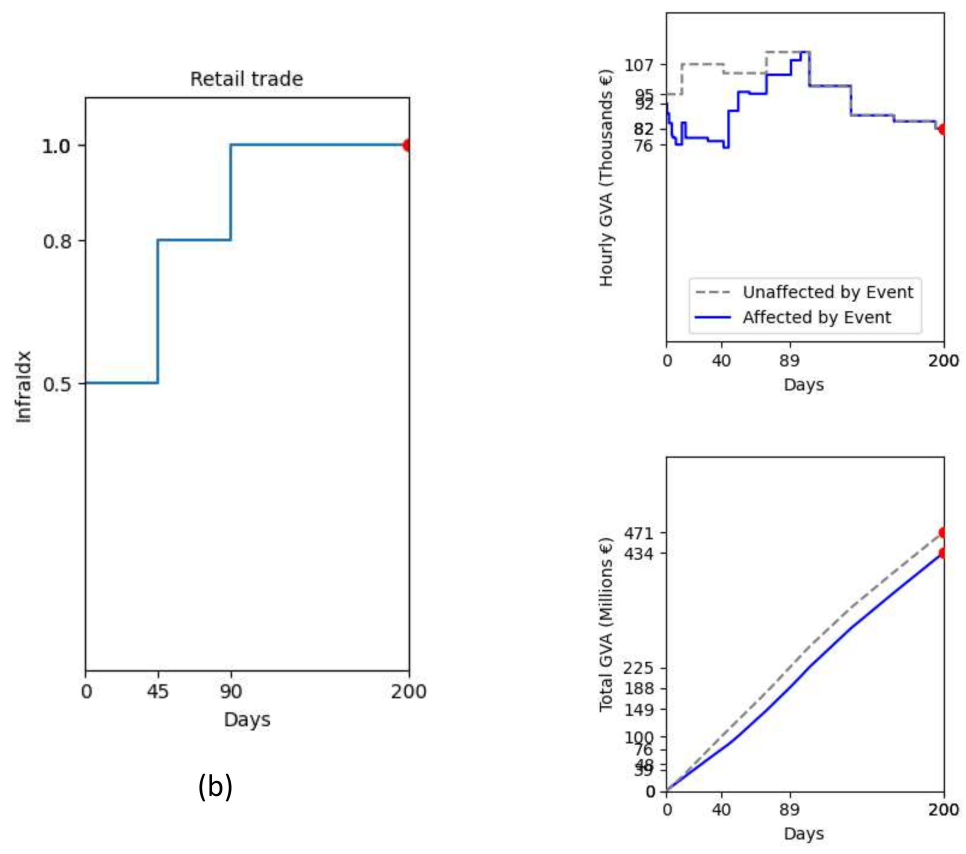
The proposed socioeconomic model is used to simulate the socioeconomic impacts of three disaster scenarios that were considered for the historical city of Rhodes. The business taxonomy previously presented in Table 1 was employed. The taxonomy comprises 23 business sectors with the greatest annual GVAs for the Rhodes island. The annual GVA of each business sector was distributed across twelve intervals using a monthly diagram, to account for the fluctuations between low and high seasons (e.g., the monthly GVA share of the “Accommodation” sector is far greater during June, July, and August compared to December or January). A series of preliminary VDTs were constructed on account of our judgement, yet more refined ones can be obtained in the future by utilizing expert elicitation methods. Finally, the normalized IOT of Greece (Timmer et al., 2015) was used to propagate backwards the demand disruptions, assuming that Rhodes follows a similar business-to-business and business-to-consumer economic profile with that of the entire country.

Figure 9(a)-(c) show the downtime (*InfraIdx*) diagrams and the corresponding loss of hourly and total city GVA for three “what-if” scenarios. In the first considered disaster scenario (Scenario A), the hazard event, that is assumed to occur during winter (low season), is damaging solely the “Retail trade” business sector (supermarkets, clothing stores, gift shops, etc.). This damage scenario was considered only for illustration purposes, since, apparently, it is highly unlikely the occurrence of a hazard event to directly damage the infrastructure of only one business sector. The hypothetical disaster impacted 50% of the retail shops (i.e., *InfraIdx* = 50%) and a total of 90 days were needed to repair all facility/infrastructure damages and return to *InfraIdx* = 100%. Moreover, it was assumed that the non-disrupted businesses are capable to overproduce by a total of 10%. This condition essentially results in a 10% increase of the initial *InfraIdx*, which becomes equal to 60%. Figure 10 shows snapshots of the socioeconomic model, illustrating the infrastructure, input, and output indices of each sector, as well as the supply bottlenecks (the grey/blue/green/red colors correspond to the Conditions 1/2/3/4/5 of the VDTs, respectively). The total indirect losses of the assumed hazard event due to supply and demand outages amounted to €27.47 millions (3.4% of city’s annual GVA).

Now, if the same event with the same infrastructure consequences on the “Retail trade” sector occurs during the summer period (Scenario B), the total indirect cost would have been €37.40 millions (i.e., 4.6% of annual GVA), as illustrated in Figure 9(b). This outcome essentially highlights the vulnerability of the Rhodes’ economy, and maybe the economy of other CH sites in general, to hazard event occurrences during their high season. If Scenario B impacted the “Manufacturing” instead of the “Retail trade”sector (Scenario C), the economic losses would have been way lower (Figure 9(c)), approximately being equal to €16.47 millions (i.e., 2% of annual GVA). This was an expected finding, as CH sites typically have limited manufacturing activities, due to the fact that extended industrialization is usually prohibited to protect their natural beauty and significant historical value.


Retail trade
InfraIdx
1.0
0.8
0.5
0
45
90
200
Days
Hourly GVA (Thousands €)
112
91
82
79
67
Unaffected by Event
Affected by Event
0
40
89
200
Days
Total GVA (Millions €)
457
430
187
159
124
85
41
34
0
0
40
89
200
Days

(a)


Retail trade
InfraIdx
1.0
0.8
0.5
0
45
90
200
Days
Hourly GVA (Thousands €)
107
95
92
82
76
Unaffected by Event
Affected by Event
0
40
89
200
Days
Total GVA (Millions €)
471
434
225
188
149
100
76
48
39
0
0
40
89
200
Days

(b)

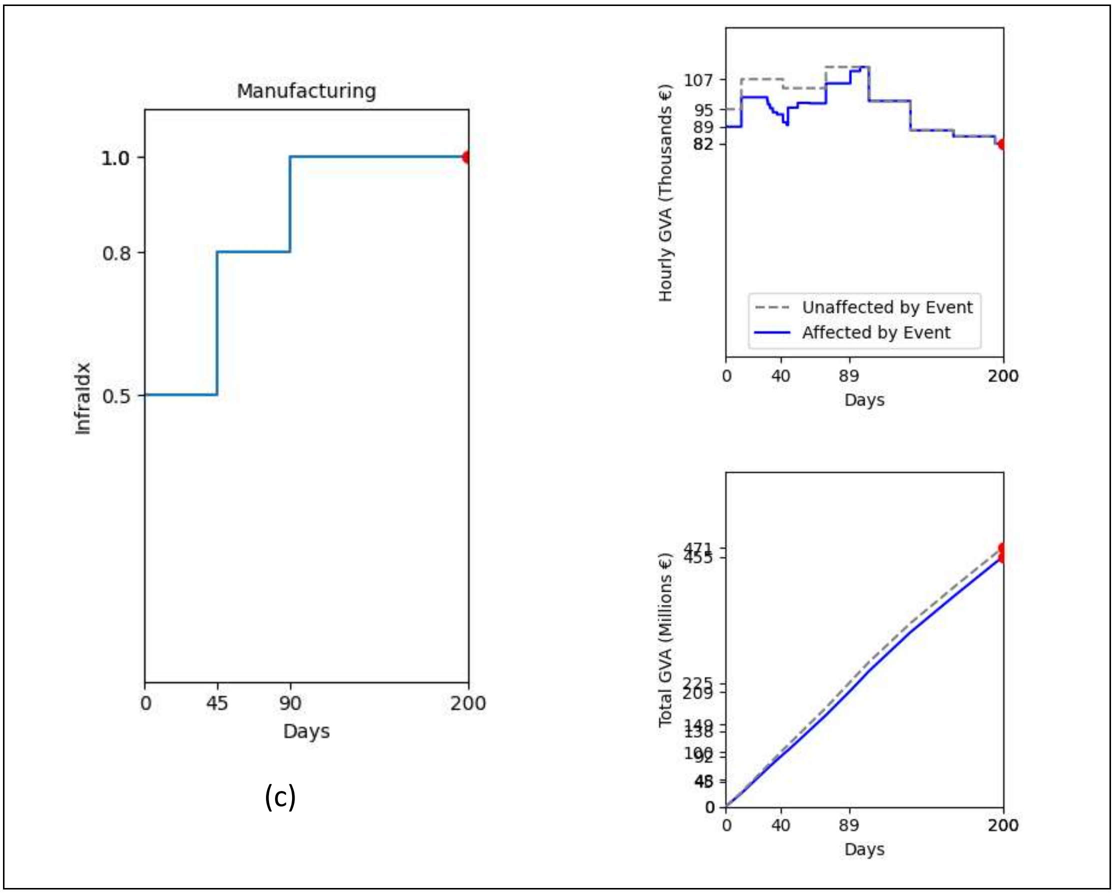
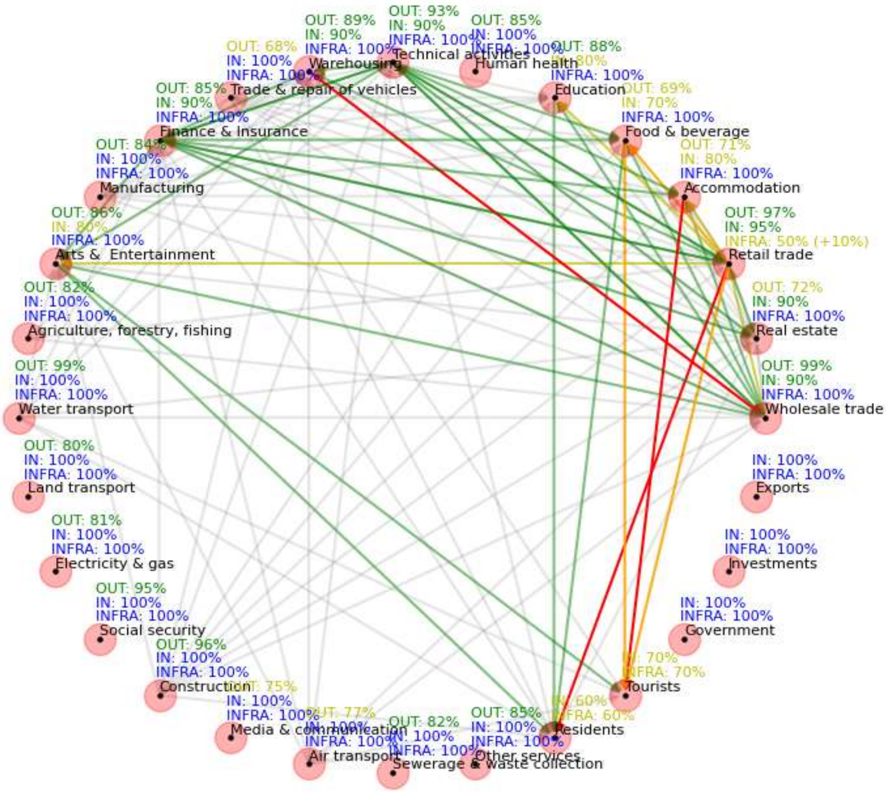


Figure 9: Hypothetical disaster scenarios for the city of Rhodes for an event that (a) occurs during winter and impacts "Retail trade", (b) occurs during summer and impacts "Retail trade", and (c) occurs during summer and impacts "Manufacturing". The dashed grey curves correspond to the city's hourly and total GVA under normal conditions (i.e., no event occurred), while the solid blue to the considered damage scenario (i.e., the event occurred).



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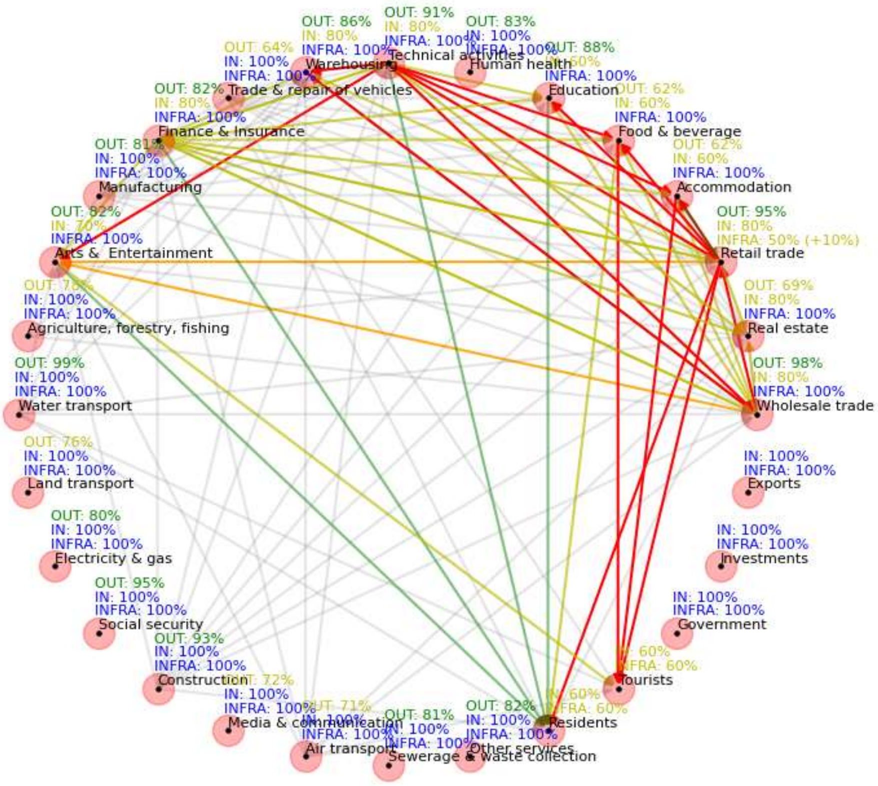

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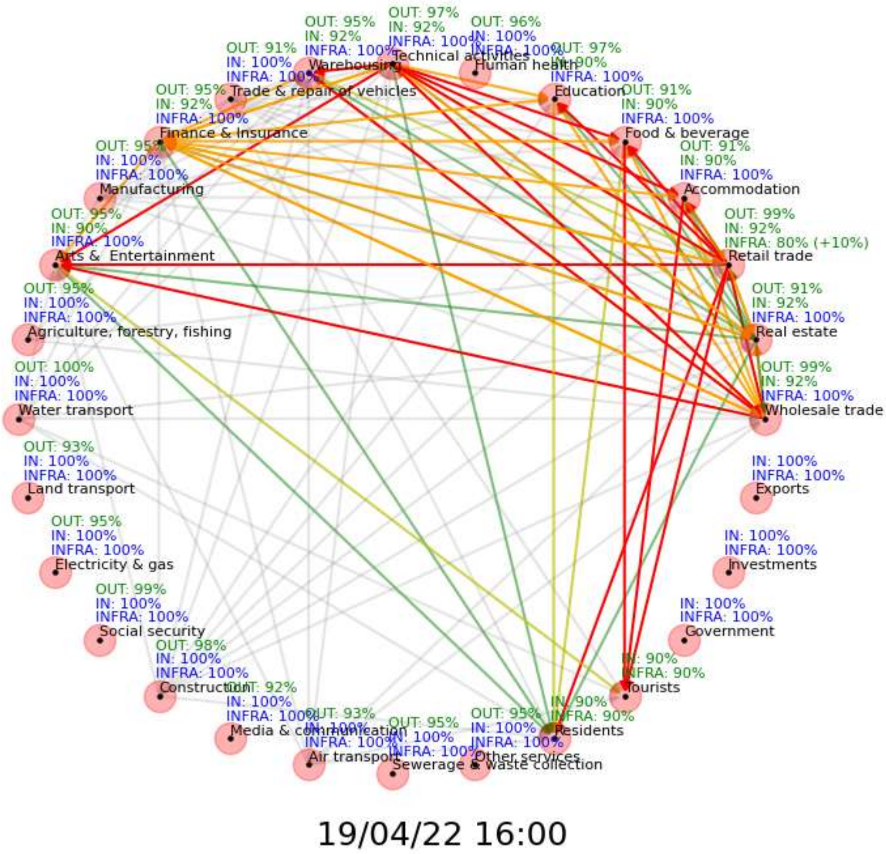

Figure 10: The socioeconomic model of Rhodes for the disaster Scenario A that damages the “Retail trade” sector. The edges of the graph represent the supply connectivity of the business sectors, as defined by the VDTs (gray color correspond to Condition 1, red to Condition 5, etc.)

4 Conclusions

A socioeconomic model for quantifying the impacts of catastrophic events on the community of CH sites was generated in Task 5.5 and summarized in the present Deliverable 5.5 (“HYPERION resilience framework”). The proposed methodology employed a simplified business taxonomy to categorize the individual businesses operating on a CH area and aggregate them into compact business sectors. Three performance indices were defined to assess the post-event performance of a business sector: (a) the infrastructure, (b) the input, and (c) the output index. To capture failures in the supply chain, indices (a) and (b) were propagated using the VDTs of the BC practice (forward propagation of failure), while the cascading demand disruptions were treated by propagating index (c) using an IOT approach (backward propagation of failure).

Consequently, to illustrate and verify the proposed failure propagation methodology, a series of hypothetical disaster scenarios was considered on simple economic systems with different node connectivities. Finally, the report presents three disaster scenarios on the complete socioeconomic model of the city of Rhodes, demonstrating the salient characteristics of the demo site, such as the effect of low/high season, the hierarchical importance of business sectors, etc. Ultimately, the developed failure propagation methodology comprises an effective assessment tool that is planned to be used during Task 7.2, to assess the efficiency of different BC models and adaptation strategies.

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