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# INDUSTRIAL DISRUPTION INDEX: THE NEW INDICATOR OF INTERDEPENDENCE AND IMPACTS

M.A. Ferreira(1), C.S. Oliveira(2), F. Mota de Sá(3)
(1) *PhD, CERIS, Instituto Superior Técnico, Lisboa, Portugal, monicaf@civil.ist.utl.pt*
(2) *Professor, CERIS, Instituto Superior Técnico, Lisboa, Portugal, csoliv@civil.ist.utl.pt*
(1) *PhD, CERIS, Instituto Superior Técnico, Lisboa, Portugal, mota.sa@ist.utl.pt*

## *Abstract*

In recent works the Disruption index (DI) applied to the urban tissue was developed as a tool to measure earthquake cascade effects.

This indicator can be extrapolated to analyze industrial disruptions caused by the interaction among the various industrial stakeholders acting in a region. The disruption or destruction of a single infrastructural component can rapidly evolve into damage to the surrounding components, in a cascading effect with consequences in health, safety, security, economic or social well-being of people.

During EU REAKT project, the DI methodology was applied to the Sines industrial complex.

In Sines, raw materials, suppliers, packaging, and shipping services are located in the same region damaged by a certain earthquake. Thus, the operation of modern industrial societies is highly interdependent and the success of a region in carrying out business and industrial operations can be rapidly eroded by the failure of a few key services or lifelines.

A review of the relevant literature and the contact with the Sines stakeholders enabled to draw the industrial disruption index, identifying the main infrastructures that influence the global impact in an industrial complex

*Keywords: Industrial disruption, cascade effects, mitigation.*

## 1. Introduction

The Disruption index (DI) [1, 2, 3], can be used to estimate the potential impacts from earthquakes or other hazardous events, integrating physical, human, social, environmental and economic damage.

The analysis proceeds by determining how the top failures can be caused by individual or combined lower level failures or events. It is a useful tool to evaluate the costs and benefits of risk reduction measures, as well as preparedness and response. It is also desirable for other purposes such as risk financing purposes.

In this paper we extend the concept of DI applied to Urban Areas to a DI applied to an Industrial Complex. The methodology follow similar developments but the objects under analysis and the functionalities to be preserved are different, and so there are some changes worth presenting.

## 2. The Industrial Complex of Sines

The Industrial Complex of Sines (Portugal) with more than 13 $km^2$, is one of the largest in Europe, housing a significant number of National (Portuguese) and European Critical Infrastructures. Located next to the Atlantic Coast, at about 180 km from two major seismogenic sources (the Gorringe Bank and the Marquês de Pombal Fault) both able to generate a 8.5 to 9 magnitude earthquake, leading to Peak Ground Accelerations of about 0.20 g to 0.24 g in stiff rock soils, with the possibility of 0.4 g to 0.5 g in soft soils. In this area, several major industries and services are present, namely a thermal power generation plant, concrete, chemical and cement production plants, fuel refinery, dangerous materials and fuel parks, mobile communications, pipelines and many other critical infrastructures, interacting in a complex physical and functional dependency so, prone to trigger chain reactions amplifying and propagating disastrous effects. Within a 5 km distance, a population of about 50,000 persons is present, with schools, hospitals, and many other sensible targets.

Already identified as a risky zone, during the establishment of the National and European Critical Infrastructures Protection Projects, the Sines Industrial Complex constitutes an optimum feasibility case study in the field of cascade effects.

### 2.1 The ZILS (ZONA INDUSTRIAL E LOGÍSTICA DE SINES). Industrial & Logistics Platform

In which concerns for Sines in terms of Industrial and logistic platform provided the integrated development of the entire region and emerged on the concentration of diversified industries and industrial facilities.

Some of the main infrastructures of the harbour are listed and briefly described below:

Sines container terminal “Terminal XX” - the Sines container terminal, called Terminal XXI, started its operations in 2004 and is the largest container terminal in Portugal.

Sines Petrochemical Complex (REPSOL) - mainly destined for export olefins and polyolefins. The Port of Sines has a terminal dedicated to petrochemical products.

Sines Refinery (GALP) - diesel production. It is constituted by a number of processing units spread across two plants, known as Manufacturing I and Manufacturing II. It has a large storage area with a capacity of approximately 3 million cubic meters for crude oil, fuels and other final products and intermediate product.

The Sines refined products are: gasoline; diesel; LPG (liquefied petroleum gas); fuel oil; naphtha (used in the petrochemical industry to produce polymers from which plastic, fibers for textiles and even bubble gum is produced); jet fuel (fuel for airplanes); bitumen (for asphalt and insulate) and sulphur (for pharmaceutical products, farming and pulp whitening).

Liquefied Natural Gas (LNG) (REN Atlântico) - The LNG terminal consists of a docking station with a discharge capacity of 40,000 cubic meters to 165,000 cubic meters with an average discharge time of 20 hours, two storage tanks each having a capacity of 115,000 cubic meters and five open rack vaporizers for regasification. Storage may reach 390,000 $m^3$ of liquefied gas.

## 3. Risk Assessment

Earthquake simulators developed until now show direct physical damage in terms of victims, buildings, essential facilities and transportation systems, without including estimations of indirect losses or propagated effects (functional interdependencies).

QuakeIST® [4] is an integrated simulator developed by the Instituto Superior Técnico, to obtain disaster scenarios affecting large scale systems and their interdependencies. Simulation can test different sets of decisions for the same disaster scenario to find the optimal solution for restoration without wasting time and money; finally it can help to develop a strategy that can increase the resiliency of the critical infrastructures to an urban area.

The project test area (Industrial Complex of Sines, Fig. 1) with urban and industrial occupation constitutes an optimum feasibility case study in the field of cascade effects and contains infrastructures that represent an actual interdependent system containing enough interconnections for research on multiple infrastructure interdependencies.

In Sines test cases, we considered the following selected buildings, infrastructures and elements:

- Buildings
- Power transformers
- Ng pipelines (ng - natural gas)
- Water pipes
- Port facilities

Each theme (infrastructure and so on) was obtained from the different stakeholders, in different formats and units. An extensive data treatment was performed in order to homogenize the information and introduced in the GIS platform and QuakeIST® simulator. A geometrical and mechanical property of each element of the infrastructure was used to set typologies and corresponding vulnerability functions.

Each type of a structure and infrastructures has its own structural dynamics response characteristics and hence a particular structural analysis is needed. The literature review has addressed the issue of vulnerability or fragility relations for each component subjected to ground shaking.

Fig. 1 – Parts of the Industrial Complex of Sines: a) harbor; b) pipelines; c) refinery.

### 3.1 QuakeIST® seismic simulator. Scenarios

One earthquake scenario (Fig. 2), 1755 earthquake, was used for simulation of damage and serviceability of the main elements under study. As an example, we show the gas and water networks results (Fig. 3). For detailing of the ground motion attenuation (GMPE) used and conversions from/to PGA/PGV/EMS-98 Intensity, soil influence, see reference [4].

The visualization of earthquake impacts which are predicted by such simulation contributes to make recognition of earthquake disaster among population and urban services or functions, but also the improvement of the engineering ability of local government officials who are in charge of promoting earthquake disaster mitigation.

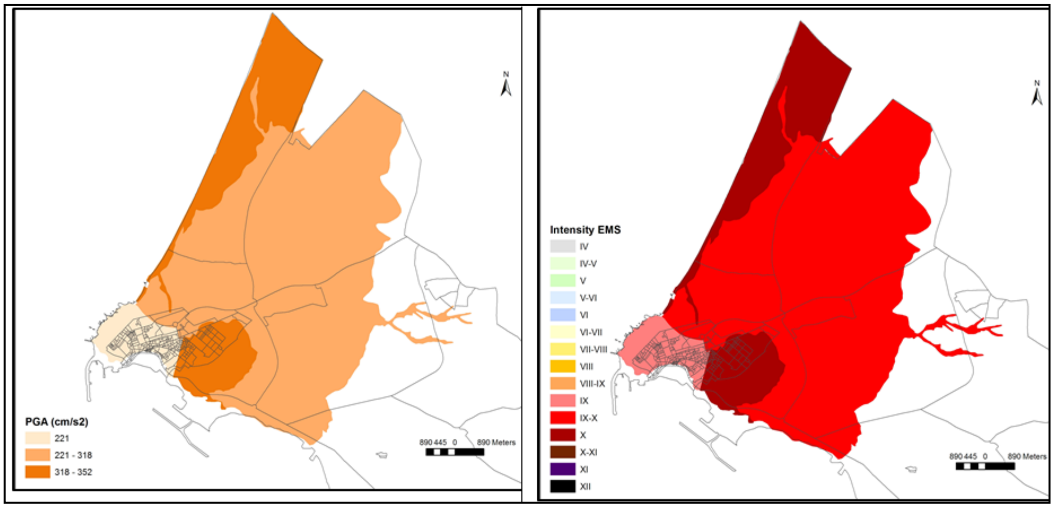


Fig. 2 – Peak ground motion (PGA) obtained for 1755 earthquake scenario, M8.7 (left) and intensities (EMS-98) (right).

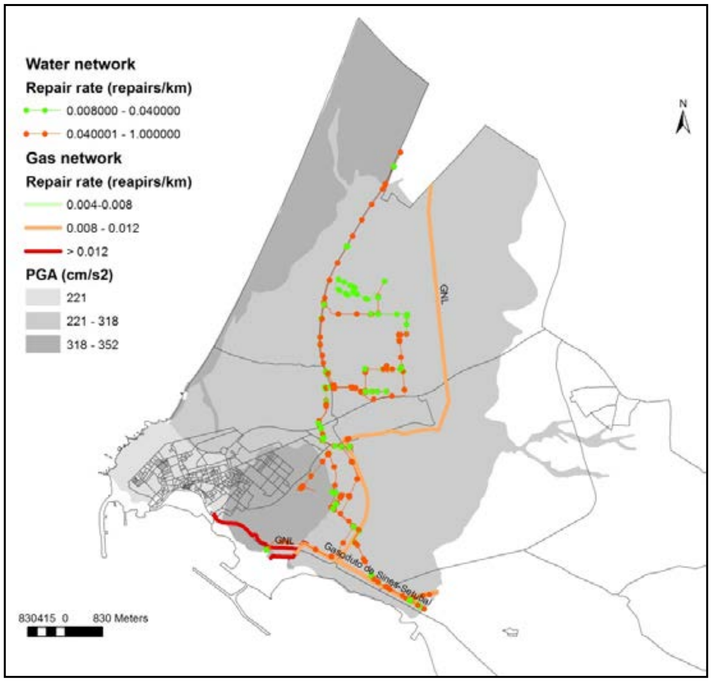


Fig. 3 – Repair rates for gas and water networks under 1755 scenario.

### 3.2 Dependencies and interdependencies

Since ports are indispensable nodes of supply chains involving many strategic stakeholders and activities interacting with each other, the main focus of IST research is to provide a conceptual framework integrating the organizational relationships between supply chain and port stakeholders.

Lifeline systems are interdependent, primarily by virtue of physical proximity and operational interaction. The disruption or destruction to one infrastructural component can rapidly cascade into damage to surrounding components, with system-wide consequences as health, safety, security, economic or social well-being of people.

The earthquake, the aftershocks as well as the tsunami that can be generated can exacerbate disasters. Damage to lifelines and industrial facilities take off line immediately following an earthquake. And many of these remain off line from several months. These outages have a critical effect on region and national businesses and overall quality of life.

In Sines cases, raw materials, suppliers, packaging, and shipping services are located in the same region damaged by an earthquake and also not functioning. Thus, the operation of modern industrial societies is highly interdependent and the success of a region in carrying out business and industrial operations can be rapidly eroded by the failure of a few key services or lifelines.

For a business to operate, it needs to be in a community that is functional following a large earthquake. However, the damage to housing, schools, hospitals, commercial structures, factories and infrastructure systems resulted in a wide spread economic and social disruption.

Part of the overall aim of REAKT [5] is to include in the damage scenarios developed by QuakeIST®, the concept of Disruption Index and apply it to Sines for different levels of seismic action.

To develop the model, it remains essential to identify the system and their components as well as the main dependencies and interdependencies. The Industrial disruption index is based on a methodology developed by ([2], [1] and [3]) which intends to measure the urban disruption, quantifying how a cascade effect contributes to the disruption of urban activities. A review of the relevant literature and the contact with the Sines stakeholders possibly to draw the industrial disruption index, identifying the main sources and infrastructures in an industrial complex.

Figure 4 illustrates the main interdependencies among facilities and their equipments.

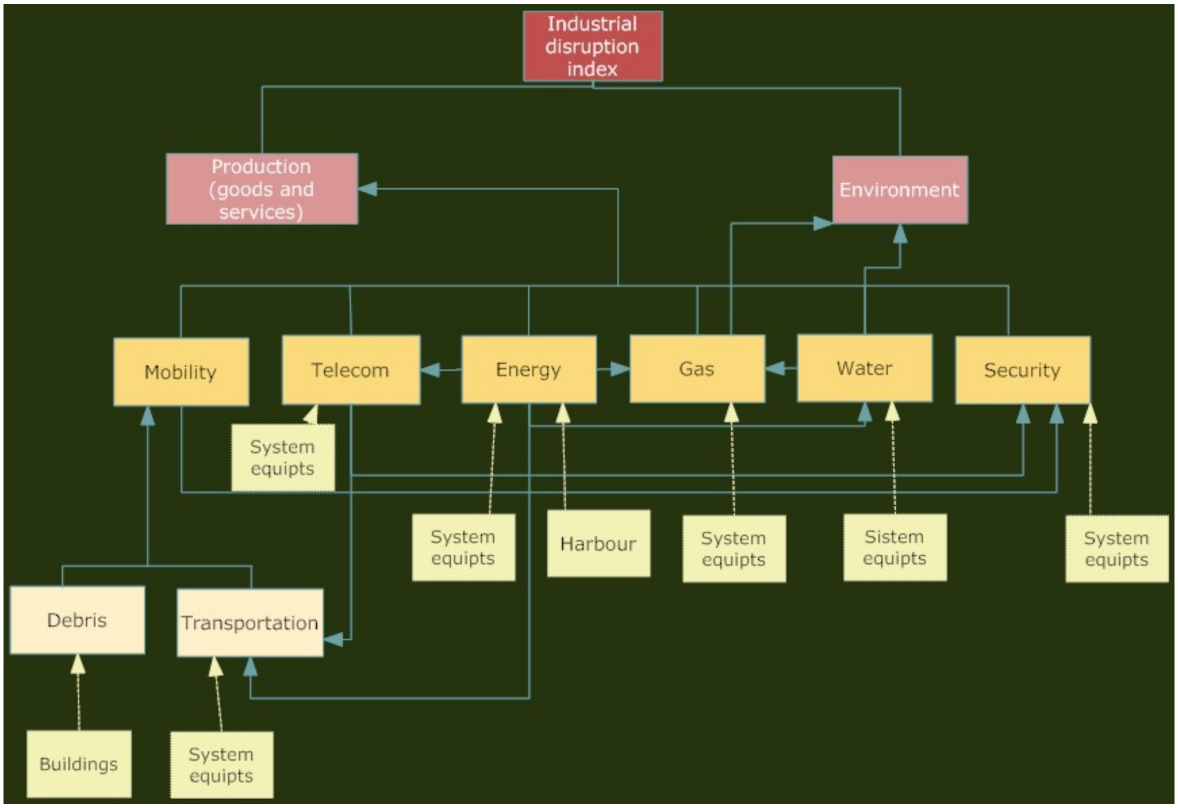
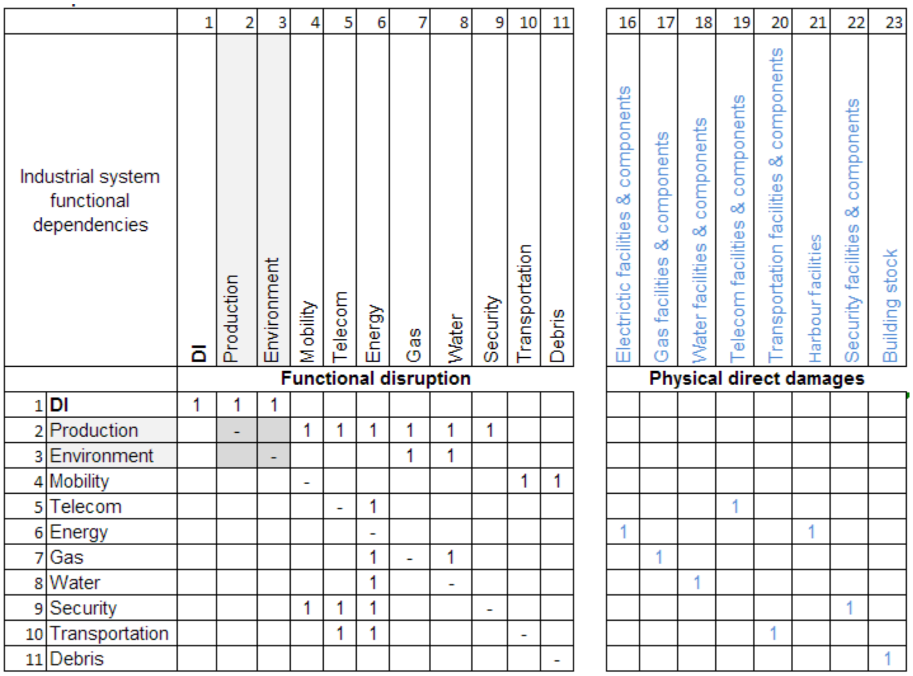


Fig. 4 – Industrial disruption index.

Figure 4 and 5 show how propagation and cascading effects can be calculated in a bottom-up sequence, starting with the physical damages directly suffered by the exposed assets, proceeding with the impacts that each node has in the functional performance of nodes that depends on them, until reaching the top node, DI. Mathematically, the DI can be represented by its Adjacency Matrix of a Directed Graph [G], in which the element Gij equals 1 if row i depends on column j and is zero otherwise.



| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Industrial system functional dependencies | DI | Production | Environment | Mobility | Telecom | Energy | Gas | Water | Security | Transportation | Debris | Electrictic facilities & components | Gas facilities & components | Water facilities & components | Telecom facilities & components | Transportation facilities & components | Harbour facilities | Security facilities & components | Building stock |
| | | **Functional disruption** | | | | | | | | | | | **Physical direct damages** | | | | | | | |
| 1 | **DI** | 1 | 1 | 1 | | | | | | | | | | | | | | | | |
| 2 | Production | | - | | 1 | 1 | 1 | 1 | 1 | 1 | | | | | | | | | | |
| 3 | Environment | | | - | | | | 1 | 1 | | | | | | | | | | | |
| 4 | Mobility | | | | - | | | | | | 1 | 1 | | | | | | | | |
| 5 | Telecom | | | | | - | 1 | | | | | | | | | 1 | | | | |
| 6 | Energy | | | | | | - | | | | | | 1 | | | | | 1 | | |
| 7 | Gas | | | | | | 1 | - | 1 | | | | | 1 | | | | | | |
| 8 | Water | | | | | | 1 | | - | | | | | | 1 | | | | | |
| 9 | Security | | | | 1 | 1 | 1 | | | - | | | | | | | | | 1 | |
| 10 | Transportation | | | | | 1 | 1 | | | | - | | | | | | 1 | | | |
| 11 | Debris | | | | | | | | | | | - | | | | | | | | 1 |

Fig. 5 – Industrial disruption index seen from the Adjacency Matrix G.

Figure 6 illustrates the case of water supply in the Complex of Sines, composed by reservoirs and piping.

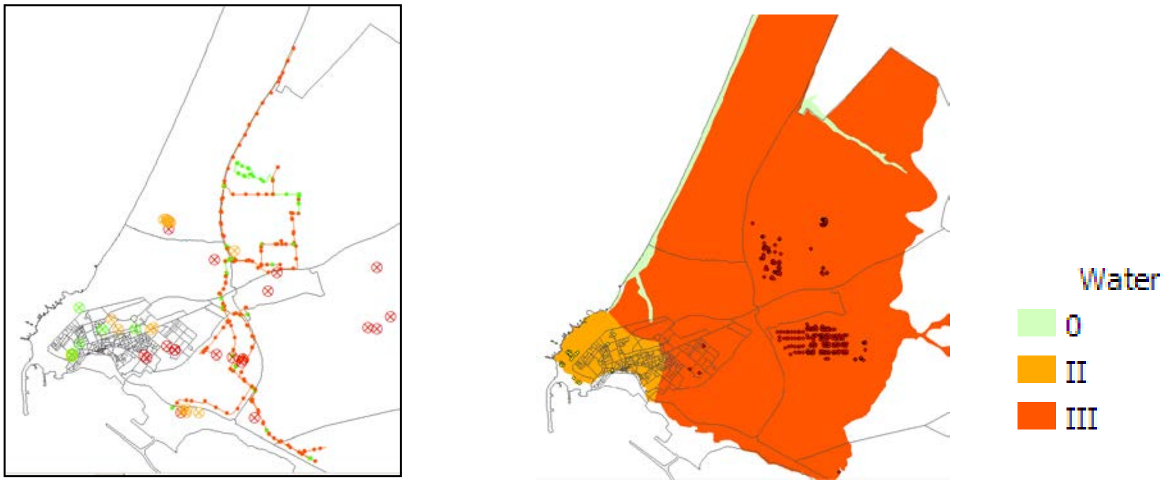


Fig. 6 – Impact of the earthquake in the water supply system: left) direct damage to reservoirs and piping; right) disruption to the whole system.

Figure 7 shows the global impact to the Industrial Complex of Sines considering the overall system (at a macro level) has presented in Fig. 5.

The main concerns are: explosion risk, environmental concerns with health impacts, product becomes inoperative; the failure may result in complete unsafe operation and possible multiple deaths. High cost for recover.

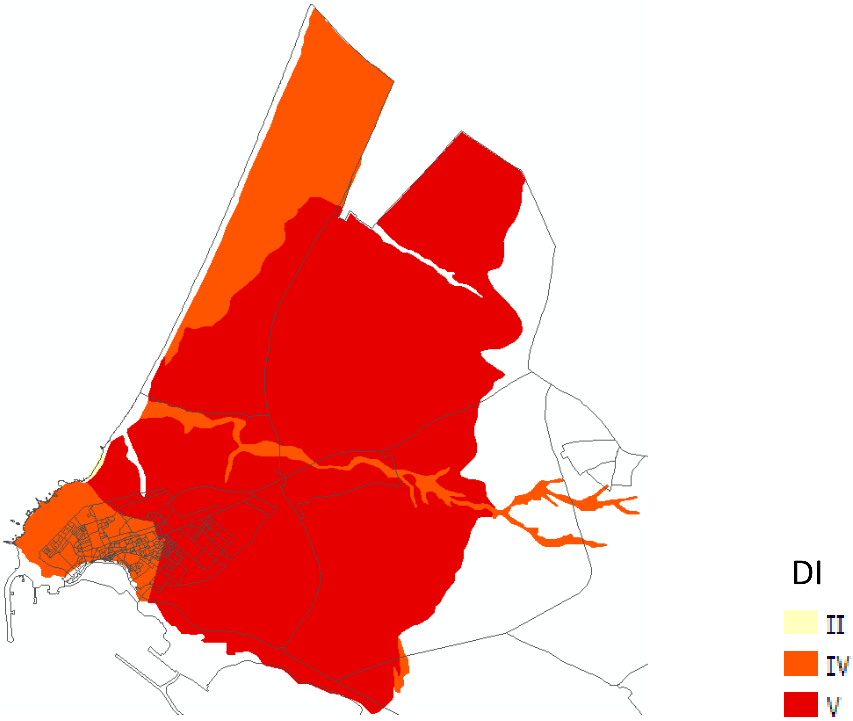
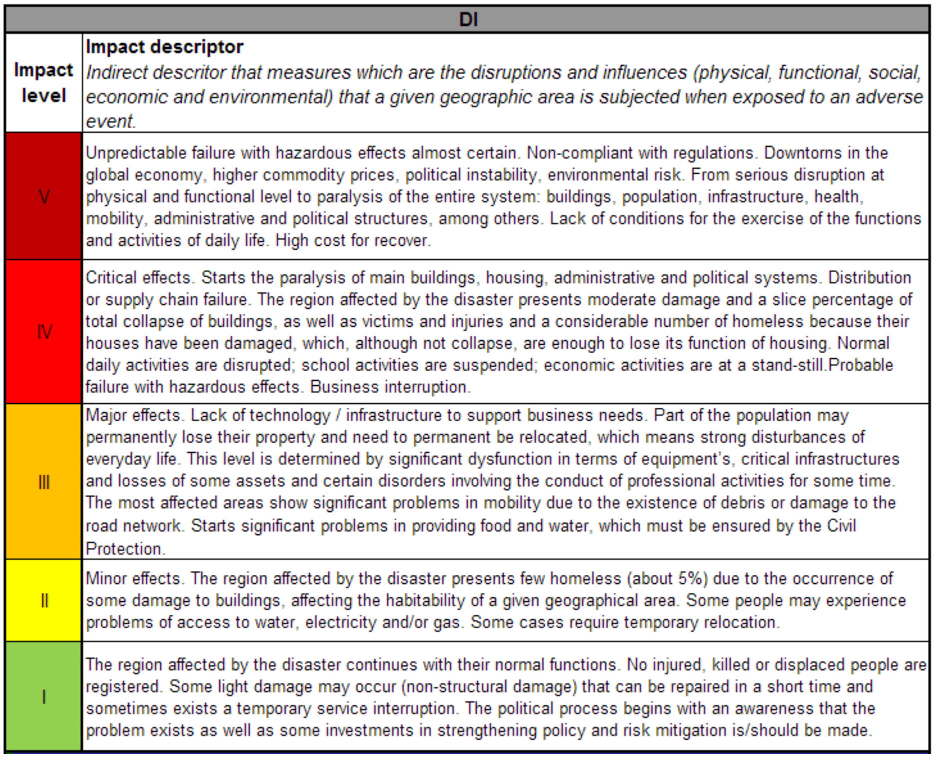


Fig. 7 – Final plot of the Industrial Disruption Index applied to the Industrial Complex of Sines for a scenario similar to 1755 earthquake.

Finally, Fig. 8 plots the qualitative descriptors of Industrial Disruption index, where the impact levels are numbered in decreasing order of industrial disruption/dysfunction.



| DI | |
|---|---|
| **Impact level** | **Impact descriptor**<br>*Indirect descritor that measures which are the disruptions and influences (physical, functional, social, economic and environmental) that a given geographic area is subjected when exposed to an adverse event.* |
| V | Unpredictable failure with hazardous effects almost certain. Non-compliant with regulations. Downtorns in the global economy, higher commodity prices, political instability, environmental risk. From serious disruption at physical and functional level to paralysis of the entire system: buildings, population, infrastructure, health, mobility, administrative and political structures, among others. Lack of conditions for the exercise of the functions and activities of daily life. High cost for recover. |
| IV | Critical effects. Starts the paralysis of main buildings, housing, administrative and political systems. Distribution or supply chain failure. The region affected by the disaster presents moderate damage and a slice percentage of total collapse of buildings, as well as victims and injuries and a considerable number of homeless because their houses have been damaged, which, although not collapse, are enough to lose its function of housing. Normal daily activities are disrupted; school activities are suspended; economic activities are at a stand-still.Probable failure with hazardous effects. Business interruption. |
| III | Major effects. Lack of technology / infrastructure to support business needs. Part of the population may permanently lose their property and need to permanent be relocated, which means strong disturbances of everyday life. This level is determined by significant dysfunction in terms of equipment's, critical infrastructures and losses of some assets and certain disorders involving the conduct of professional activities for some time. The most affected areas show significant problems in mobility due to the existence of debris or damage to the road network. Starts significant problems in providing food and water, which must be ensured by the Civil Protection. |
| II | Minor effects. The region affected by the disaster presents few homeless (about 5%) due to the occurrence of some damage to buildings, affecting the habitability of a given geographical area. Some people may experience problems of access to water, electricity and/or gas. Some cases require temporary relocation. |
| I | The region affected by the disaster continues with their normal functions. No injured, killed or displaced people are registered. Some light damage may occur (non-structural damage) that can be repaired in a short time and sometimes exists a temporary service interruption. The political process begins with an awareness that the problem exists as well as some investments in strengthening policy and risk mitigation is/should be made. |

Fig. 8 – Industrial Disruption Index impact descriptors.

## 3. Final considerations

This approach, as an extension of the Urban DI, is important in several aspects of the mitigation of the earthquake impact. First of all it will produce a more realistic picture of the effects in a region for a given scenario or for a given occurrence, in a prospective way. But it will contribute to realize which the more important pieces are and links in the chain of performances, such it will be possible to identify the main blockages to be removed for a better overall performance, and the pieces of no importance.

Furthermore, it permits to:

- Assess potential faulty mechanisms and its impacts in the operation of systems, listing them according to gravity of impact.
- Find a long term strategy for avoiding the most susceptible zones, namely, for liquefaction, landslides, and fault traces.
- Implementation of early warning systems for critical facilities.
- Know your industrial risks including interdependencies – what to expect from end-users, either on the offer or the demanding side, including consumers.
- Resilience: be ready on advance to recover fast.

## 4. Acknowledgements

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