Industrial disruption index. Concepts and applications

Índice de interrupção industrial. Conceitos e aplicações

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Abstract

In recent works the Disruption Index (DI) applied to the urban tissue, was developed as a tool to measure earthquake cascade effects and to quantify the state of disorder induced by the disruption of urban structure and its systemic functions.

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.

The DI methodology was applied to the Sines industrial complex in the framework of REAKT project.

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 / Sines

Resumo

As estimativas de perda de bens e funções auxiliam na prevenção e na escolha de recomendações adequadas. A utilização do Disruption Index em meio urbano permite ter perceção do impacto global de um sismo uma vez que faz a ligação a funções e atividades que definem o tecido urbano.

Este indicador pode ser extrapolado para áreas industriais a fim de analisar as interrupções causadas pela interação entre as várias infra-estruturas. A interrupção ou destruição de um único componente pode evoluir rapidamente em danos aos componentes circundantes, num efeito de cascata, com consequências na saúde, segurança e no bem-estar socioeconómico de uma região.

Assim, a metodologia do Disruption index foi aplicada ao Complexo Industrial de Sines no âmbito do projecto europeu REAKT. Com a ajuda das diferentes empresas e entidades em Sines foi possível "desenhar" o índice de interrupção industrial (Industrial Disruption Index), identificando as principais infraestruturas que influenciam o impacto global de um evento adverso num complexo industrial.

Palavras-chave: Interrupção industrial / Propagação de efeitos / Mitigação / Sines

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1 Introduction

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. The complex accounts for more than 10% of Portuguese critical infrastructures, including many of the most important ones.

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, highly interconnected and mutually dependent in complex ways, 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 other fundamental services and systems that are critical to the economy, environment, security and social well-being.

The REAKT Project [1], "Strategies and Tools for Real-Time Earthquake Risk Reduction" funded by the European Commission, which brings together a large international consortium and is European funded (FP7), consist of the study of seismic risk-mitigating instruments, based on early warning capabilities, allowing in a short time (seconds) the triggering of automatic mechanisms for risk reduction, very focused on critical infrastructures (CI) and their key components.

Within the REAKT Project, very different situations have been analyzed to give a good overall view of what the various problems are that we may encounter in the applications of Earthquake Early Warning Systems (EEWSs) (long bridges, schools, gas mains, harbours, hospitals, industrial facilities, and so on). At the Instituto Superior Tecnico (IST), University of Lisbon, we have been studying the effect of these problems on industrial infrastructures, a group of installations where the EEWS may have a tremendous impact. Lead times, false and missing events are analyzed from the end-user's viewpoint [2].

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.

It is important to notice that the effects of seismic actions on industrial equipment should be given not only in terms of structural damage, but also in terms of content release, which may be activated during or after the shaking (fire, leakage, toxic dispersion and so on [3]. Damages and losses of certain types of containments may be more important than the direct inflicted damages. Also the effect of interdependences may be crucial to the functionality of other equipment and facilities.

The Industrial Disruption Index has been designed to respond to the variety and complexity of damages, loss of production due to supply-chain disruption and to distinguish the interdependent nature of many systems in Sines Industrial Complex.

This article presents a conceptual framework for addressing infrastructure interdependencies that could serve as the basis for further research in this important area.

2 The ZILS (zona industrial e logística de Sines) – Industrial & logistics platform

The port with several terminals and ZILS comprises about 8-10% of the National Critical Infrastructures, which gives it an added importance in strategic terms for the functioning of the country therefore deserving special security concerns. Furthermore, it is a primary area of economic importance, now and projected into the future. An expansion process is taking place at the port of Sines.

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 XXI" – 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.

A railway line ensures the supply of jet fuel to Faro airport (transported by rail) produced by the Refinery. The gas used in the refinery (cogeneration) is supplied by REN Atlantic's pipeline.

The Sines Industrial Complex also includes a cave dug into solid rock that stores propane, with seismic monitoring. Cave SIGÁS belongs to GALP (75%), BP (20%) and Repsol (5%).

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).

The 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) 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 (Table I).

Table I Elements at risk and procedure for vulnerability analysis

Element at risk	Methodology	Intensity parameter
Buildings	Giovinazzi & Lagomarsino Macroseismic method	EMS98
Power transformers	REAKT WP5	PGA
Gas pipelines	HAZUS, ALA [5]	PGV
Water pipes	HAZUS, ALA	PGV

In this earthquake loss estimation study, the simplified method for water system network performance evaluation applies to a distribution pipe network (HAZUS, 2007) [6].

3.1 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 occurred 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 is to include in the damage scenarios produced by QuakeIST® [4], the concept of Disruption Index ([7] [8] [9]) 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 the urban DI methodology developed [8] 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 enable the development of the industrial disruption index, identifying the main sources and infrastructures in an industrial complex.

Figure 1 illustrates the main interdependencies among facilities and their equipments.

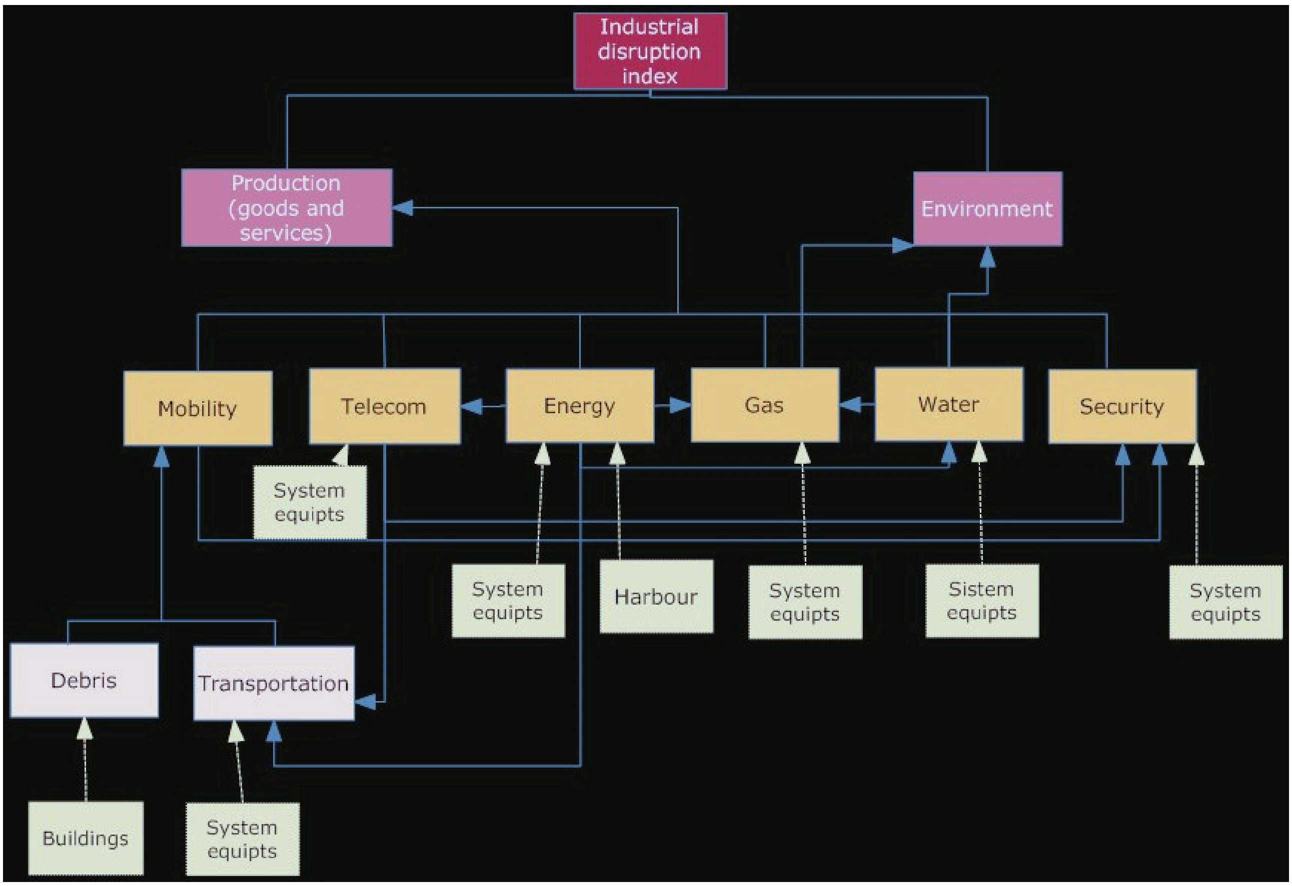

Figure 1 Industrial disruption index

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

Figure 2 Industrial Disruption Index seen from the adjacency matrix G

Figures 1 and 2 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.

3.2 QuakeIST® seismic simulator. Scenarios and impacts

One earthquake scenario (Figure 3), the 1755 earthquake, was used for simulation of damage and serviceability of the main elements under study. The detailing of the ground motion prediction equations (GMPE) – attenuation used, and conversions from/to PGA/PGV/ /EMS-98 Intensity and soil influence are described in [1]. In relation to the soil classification, some studies are being done to update the present results.

QuakeIST® [1] is a software that, besides the ground motion definition, can deal with vulnerability of a building stock, of lifeline networks and of some critical infrastructures. Damage scenarios are then constructed. Everything is assembled in a GIS platform where the operator can do almost everything he needs once he was provided with the necessary data.

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.

For this particular event we present the network impacts for gas and water (Figure 4).

According to level of damage/repair rates, the quality and service availability of gas network will be: Service interruption for a long period; full loss of function and potential ignition. For the water service the result is an interruption for a long period (half or more of the water supply across the entire city was out of action), affecting service continuity in critical facilities.

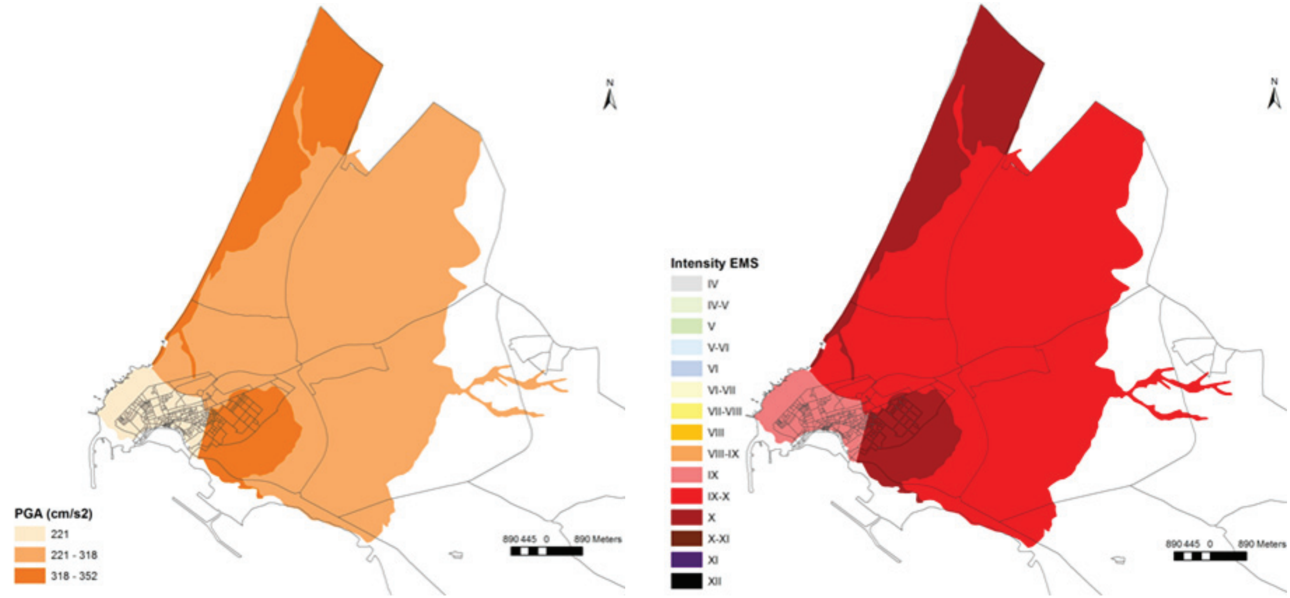

Figure 3 Peak ground motion (PGA) obtained for 1755 earthquake scenario, M8.7 (left) and intensities (EMS-98) (right)

Other essential lifeline in post-disaster situation is electricity. Electric power systems are extreme vulnerable since they contain a large number of vulnerable pieces of equipment usually not well designed for the seismic action. In Figure 5 we can see the performance of the power network for power transformers and PT´s. Damage 3 (D#) means moderate damages such as weaknesses in the connecting structure, originating leaks, and is enough to put the transformers out-of-service during reparations.

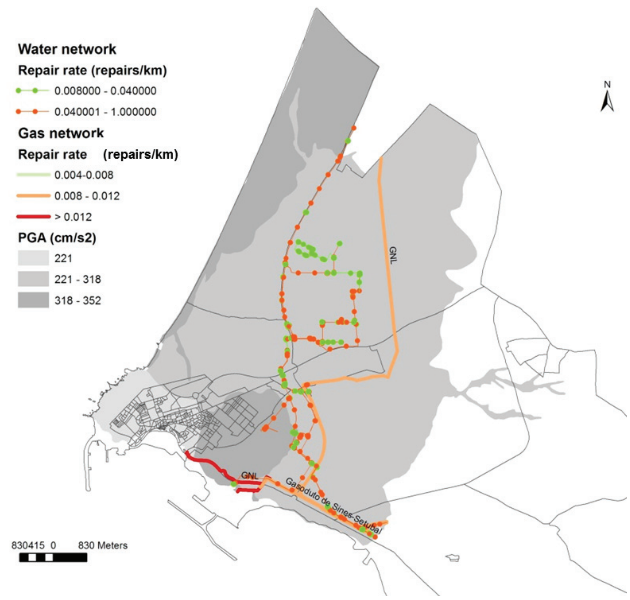

Figure 4 Repair rates for gas and water networks under 1755 scenario

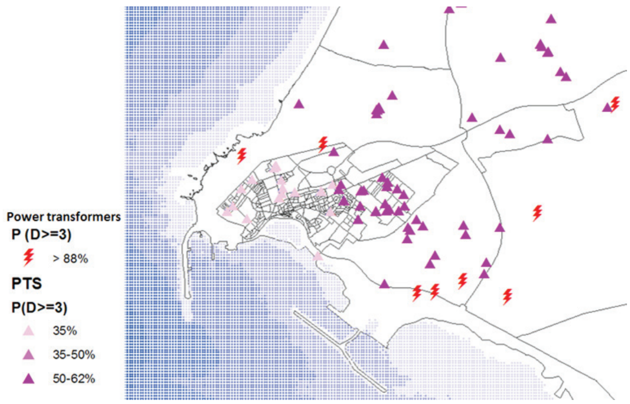

Figure 5 The performance of the power network under 1755 scenario

As the lifelines are interdependent and, for example, (i) the failure of gas and water supply stations caused by damage to the power station (Figure 1); or (2) the collapsed buildings that will block the road, causing mobility problems; or (3) the failure of the telecom system, all of this will create an overall earthquake impact which can be expressed as shown in Figure 6.

The Industrial disruption index is assembled in a scale with five impact levels as described in Figure 7.

Figure 6 indicates that in presence of a seismic scenario as 1755 the industrial area of Sines and altogether the Sines municipality would be particularly affected by: a) losses in industrial production – most industries becomes inoperative; the failure may result in complete unsafe operations, b) danger of explosion and great environmental concerns (pollution and contamination), and c) possible multiple deaths may result.

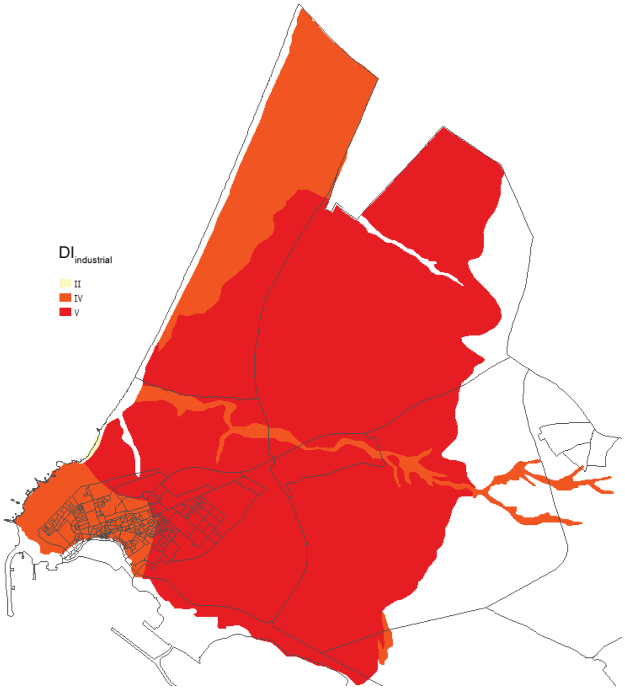

Figure 6 The industrial disruption index to Sines under 1755 earthquake scenario

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.

It is important to add that this study was directed to the great Complex of Sines. It can be easily understandable that interdependences are not restricted to this area. Consequences of lack of production (gas, oil, etc.) will propagate across the country and neighbouring zones with great influence in the financial market. The industrial disruption index can easily take this issue into consideration.

4 Final remarks

Risk emanates from multiple sources and it is virtually impossible to predict and prepare for every type of risk. In that environment, companies should work proactively to identify and address specific vulnerabilities in the supply chain that expose them to risks and at the same time develop the resilience to be able to recover from the risk events that are anticipated to occur.

In this work we propose the use of Industrial Disruption Index as a tool to measure the entire impact of a disruption to an industrial complex, through cascading failure.

DI	
Impact level	**Impact descriptor** *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.

Figure 7 Industrial Disruption Index Impact descriptor

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References

[1] REAKT (2011) – Strategies and tools for Real Time EArthquake RisK ReducTion. FP7-ENV-2011. http://www.reaktproject.eu/

[2] Oliveira, C.S.; Mota de Sá, F.; Lopes, M.; Ferreira, M.A.; Pais, I. (2011) – Early Warning Systems: Feasibility and End-Users' Point of View. Pure Appl. Geophys. (2015) 172: 2353. doi:10.1007/s00024-014-0999-0

[3] Salzano, E; Agreda, A.G.; Di Carluccio, A.; Fabbrocino, G. (2009) – Risk assessment and early warning systems for industrial facilities in seismic zones. Reliability Engineering and System Safety, 94, 10, 1577–1584.

[4] Mota de Sá F.; Ferreira M.A.; Oliveira C.S. (2016) – QuakeIST® Earthquake scenario simulator using Interdependencies. *Bulletin of Earthquake Engineering*. DOI: 10.1007/s10518-016-9884-9

[5] ALA (2001) – Seismic fragility formulations for water systems. American Lifeline Alliance, ASCE.

[6] HAZUS-MH MR4 Technical Manual (2007) – Department of Homeland Security Emergency Preparedness and Response Directorate. FEMA

[7] Oliveira, C.S.; Ferreira, M.A.; Mota de Sá, F. (2012) – The concept of a disruption index: application to the overall impact of the July 9, 1998 Faial earthquake (Azores islands). *Bulletin of Earthquake Engineering* 10(1), 7-25.

[8] Ferreira, M.A. (2012) – *Risco sísmico em sistemas urbanos*. Tese de Doutoramento. Instituto Superior Técnico, Universidade Técnica de Lisboa. 295 pp.

[9] Ferreira, M.A.; Mota de Sá, F.; Oliveira, C.S. (2014) – Disruption Index, DI: an approach for assessing seismic risk in urban systems (theoretical aspects). *Bulletin of Earthquake Engineering* 12(4), 1431-1458.