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A COMPREHENSIVE FRAMEWORK FOR ASSESSMENT AND QUANTIFICATION OF SEISMIC RESILIENCE OF PROCESS PLANTS

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Abstract

Past seismic events have exposed the high vulnerability of process plants, which led to huge economic losses due to production of capacity losses. The magnitude of production capacity loss and economic losses is not only influenced by the magnitude of direct damage that occurs to the facility due to earthquake, but also it is highly related to recovery process. Recovery process in itself is a function of plant preparedness, recovery plan and applicability of the recovery plan. In order to have a clear view of economic losses in process plant in case of seismic event, plant resilience in required. This paper presents a comprehensive framework for quantification of process plant seismic resilience, focusing on plant level. Firstly, resilience definition and process plant resilience metrics are introduced. Then, different methodologies for calculation of seismic resilience of plant as an independent system are presented, furthermore, scenario based analysis for calculation of risk and resilience metrics is explained in details. Finally, case study of a nitric acid plant is used to show the applicability of scenario based analysis for calculation of risk and resilience performance metric. Resilience index, expected annual losses and surface operational capacity curve are used as performance metrics for process plant. The proposed performance metrics and methodology are the first steps toward a risk and resilience targeted design or assessment of process plants under seismic loading.

Keywords: seismic resilience; seismic risk; process plants; comprehensive framework;

1. Introduction

Process plants are high complex systems that contain different typology of equipment such as steel storage tanks, heat exchangers, reactors, pumps, piping systems etc. Hazardous raw material pass through these equipment which makes them highly vulnerable. Moreover, failure of any of the abovementioned equipment with loss of containment can trigger out domino effects that can cause damage of full plant, contamination of nearby areas and high economic losses for plant owners. Past seismic events have shown the devastating consequences that industrial facilities can cause. In 1999, Kocaeli earthquake caused significant damages in 30% of industrial plants of Izmit area, 20% of which got recovered within one month while the remaining 10% was unrepairable, leading to a production loss around 1-1.5 bn US$ every month [1]. In 2011, Tohoku earthquake, which triggered out tsunami and nuclear accident, caused catastrophic damages in many fields including industrial sector. Refinery sector was the one that experienced slowest recovery speed and the biggest drop in industrial production index (5 from 100) [2]. The abovementioned events have demonstrated that it is important not only to assess the seismic risk of industrial facilities but also their resilience.

In literature, there are several developed seismic resilience models and frameworks available regarding community resilience, transportation system, critical infrastructure, civil infrastructure system etc. as they have been studied for many years and research community interest were quite high [3-7]. When it comes to industrial facilities, research about industrial plant resilience is limited and almost all the studies are quite general. Along this line, Mebakri studied resilience of plants under natural hazards in a more quantitative way but focusing in single units (steel storage tanks) and neglecting plant process flow [8]. The first quantitative framework for calculating resilience of process plants considering interconnection between equipment and plant process flow were proposed by [9, 10] and it has been applied to a case study [10, 11] in order to calculate the plant resilience and economic losses under seismic loading. Even more in [12] authors applied the same procedure using probabilistic recovery functions based on Monte Carlo simulation.

In this paper a comprehensive framework for calculation of process plant resilience is introduced. Firstly, plant seismic resilience definition is explained. Then, a general framework with all possible ways for calculating resilience of process plant at plant level is presented. Afterwards, scenario based analysis for calculation of expected seismic resilience and expected annual losses, is explained in more details. Finally, a case study of a nitric acid plant is used in order to calculate the expected resilience, expected annual losses and operational capacity surface, using scenario based analysis.

2. Process plant resilience definition

Seismic resilience is defined as the ability of a system to withstand and rapidly recover if damaged from a low frequency high impact event. In literature, usually, resilience index is defined as area under functionality curve versus time, but for industrial plants operational capacity will be used instead of functionality. Operational capacity is the physical production output of plant and an e.g. of a typical curve is shown in Fig. 1. The operation capacity curve has five important states. First one is the pre-earthquake state in which the plant can experience reduction of capacity due to aging or increase in capacity due to plant upgrade. At time t_0, time of earthquake occurrence, the damage propagation state initiates, which finishes at time t_d. The loss of operational capacity is function of plant robustness, plant topology, and earthquake intensity. Additionally, when the domino effect occurs emergency response and weather conditions are crucial for defining the total capacity loss and the time t_d when damage propagation stops. Post-earthquake steady state corresponds with inspection and planning and its duration is influenced mainly by preparedness of plant emergency managers. In case that there is already foreseen a recovery plan this phase should be much shorter than in cases that the plan has to start from scratch. This phase is also influenced by the availability and resilience of other systems such as community, transportation system, critical infrastructure etc. Impeding factors (post-earthquake inspection, engineering, permitting, financing, contractor mobilization) that might cause delays are also included in this phase, and it ends at time t_a, which is the time when recovery of equipment start.

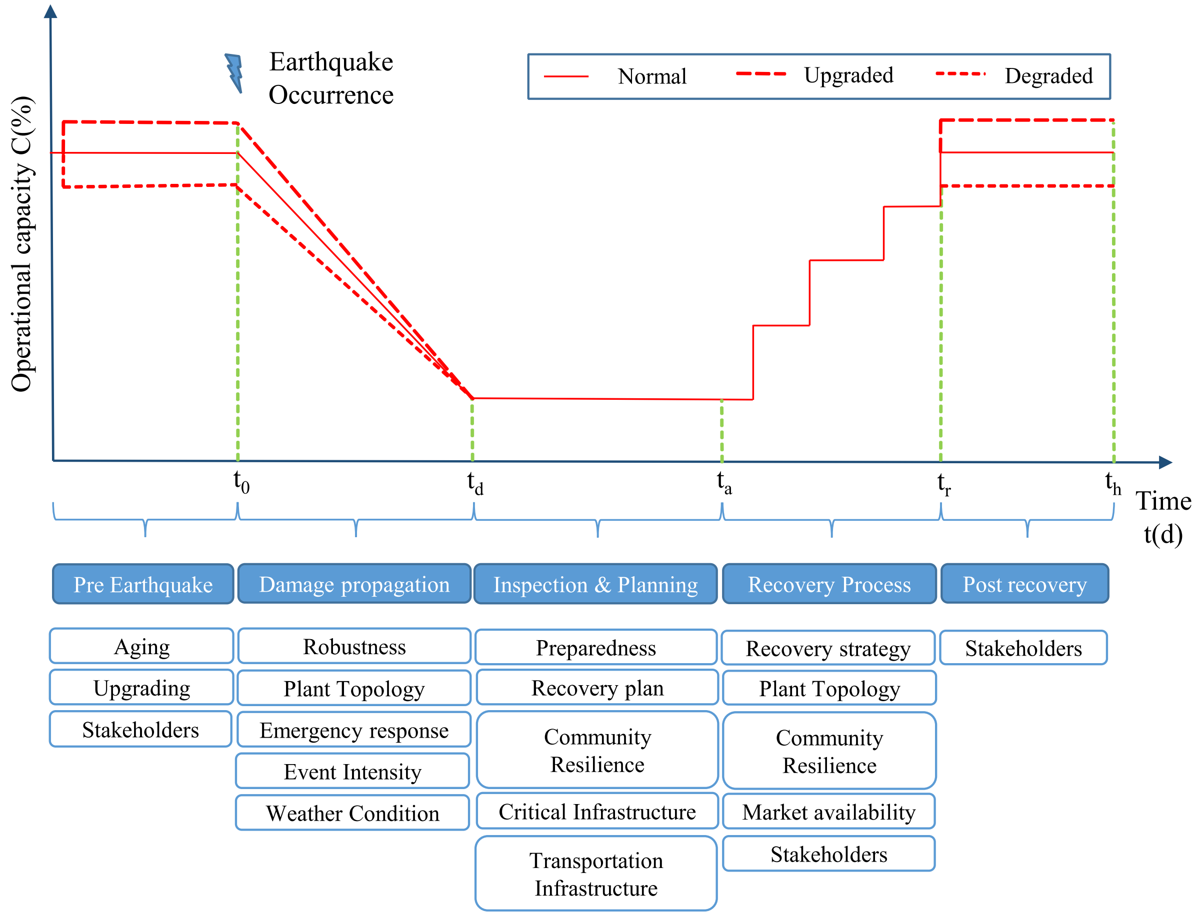


Fig. 1 - Plant operational capacity curve vs time.

The phase of recovery process in plants is a step function as the increase in capacity is immediately when an equipment is repaired. This phase is influenced by the selected recovery strategy, plant topology, community resilience, and market availability for requested equipment. Based on costs, stakeholders, in this case plant owners are the one who have to decide whether the plant will be repaired up to existing operational capacity, will be upgraded or if it will be repaired up to a lower capacity. Time t_r is the time when recovery process finish. Finally, the post recovery phase has a duration up to control time t_h usually bigger that t_r and it decided by stakeholders [6].

Resilience index R will be calculated as area under operational capacity curve. The most commonly used expression of the literature [6, 10] is given in Eq.1:

$$R = \frac{1}{t_h - t_0} \int_{t_0}^{t_h} C(t)dt \qquad (1)$$

3. Resilience framework at plant level

In this section resilience of process plants is described focusing only at plant level, neglecting the interdependency with other systems. A general framework with different possibilities of calculation of seismic resilience of process plants at plant level is shown in Fig. 2. The framework consists of four main modules. The first one, plant mapping consists in identification of all plant equipment and plant process flows (PFs). PFs are the physical production output lines and they should be clearly assigned. For each PF the equipment which are connected to it should be defined and also the production capacity that the flow produces. The second module, plant topology, consists on construction of capacity block diagram (CBD) and definition of plant production capacity function. For each PF, equipment, based on their function typology have to be grouped in blocks with units in series, blocks with units in parallel or blocks with redundant units, and these blocks will be connected in series with each other forming CBD. The production capacity of each PF is based on CBD of that flow and it will be equal to the minimum value of capacity of all blocks. In more detail the steps of this module are explained in [9, 10].

The third module is the equipment vulnerability. For each equipment of plant, possible damage states should be defined and they should be expressed in terms of fragility curves. Fragility curves can be derived in different ways: a) based on engineering judgement; b) based on codes; c) analytically based on numerical models; d) using empirical models.

The last module is the risk and resilience module. In this module analysis can be conducted in two different ways, using risk based analysis or using scenario based analysis. In risk based analysis, initially, the quantitative risk analysis is conducted, and all possible damage scenarios with their annual probability of occurrence are defined. After that, there are two approaches to precede with resilience and other performance metrics. First approach is to analyze resilience of a single scenario while, the other is to analyze resilience of a risk threshold. The recovery process in calculating resilience of a single scenario or of a risk threshold can either be deterministic using Overall Reconstruction Activity Network (ORAN), or probabilistic, using ORAN or simplified recovery functions based on recovery times distributions for each equipment which will be explained later on. In more details, the procedure for calculation resilience of single scenario using ORAN is described in [10, 12]. In this paper, calculation of resilience and performance metrics of plant using scenario based analysis, are explained in details.

Fig. 2 - General framework for calculating seismic resilience at plant level.

Scenario based analysis contains seven steps which are shown in Fig. 3. The first step corresponds with probabilistic seismic hazard analysis (PSHA), in which the seismic hazard curve of the site should be defined. Based on hazard curve the minimum and maximum peak ground acceleration (PGA) and their corresponding mean annual frequency off occurrence are defined. In between this interval will be defined the *j-th* seismic scenarios (different PGA integration point) that will be used in analysis. The more points selected, higher the accuracy in final results can be achieved, but the computation time will increase significantly because at each selected PGA a Monte Carlo simulation (MCS) will be conducted, so the number of integration points *n* should be defined in a reasonable and efficient way.

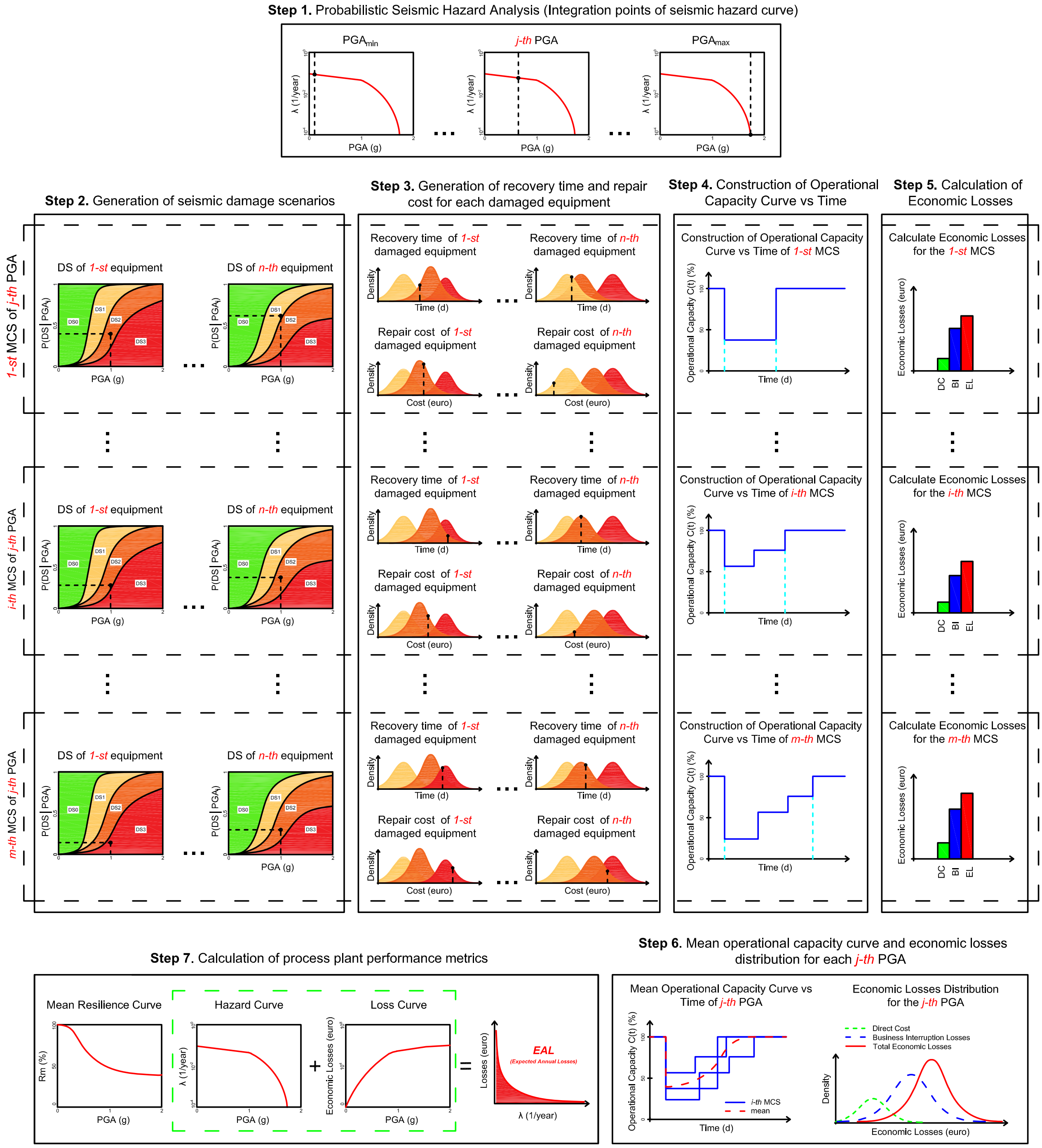
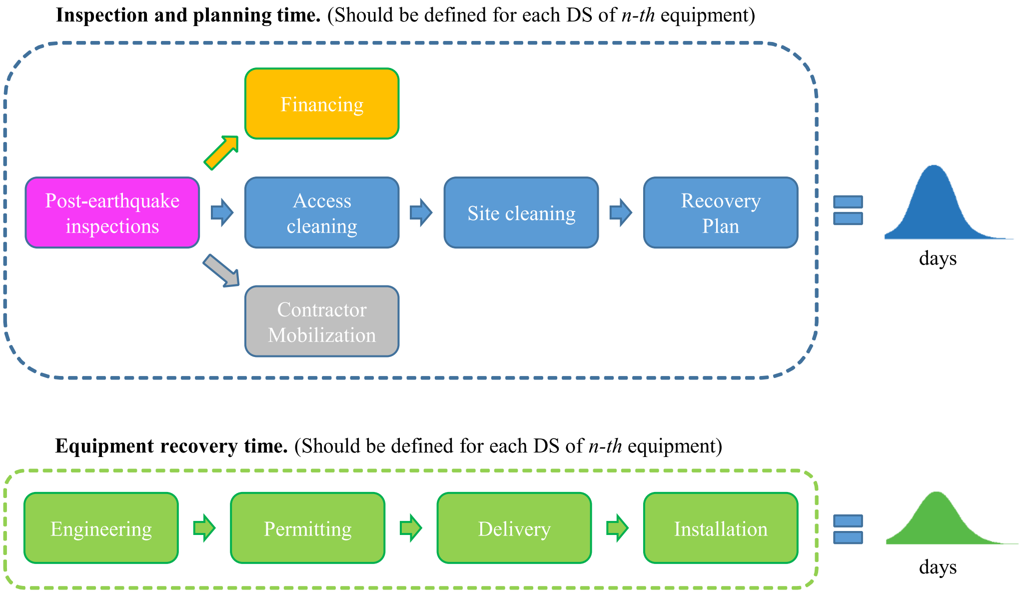


Fig. 3 - Steps for calculation seismic resilience of plant using scenario based analysis.

The steps from 2 up to 5 include MCS, and the total number *m* of simulations has to be defined by stakeholders or based on convergence criteria. For each *i-th* MCS at *j-th* level of PGA, firstly a random seismic damage scenario should be defined based on fragility curves. A random number between 0 and 1 will be generated simultaneously for each equipment, and by checking their fragility curves the damage state of equipment will be considered to be the worst one, as showed in step 2 of Fig. 3.

Step 3 deals with assignment of repair time and direct repair cost for each damaged equipment. A simplified recovery function similar to the one of REDi [7] can be used. Basically for each equipment for each damage state two recovery times should be assessed, one which is related to inspection and planning including impending factors and the second one related to equipment recovery process as shown in Fig. 4. Both this recovery times can be given as distributions for each equipment based on activities showed in Fig. 4, and equipment recovery will start after inspection and planning. Furthermore, the direct costs should be assigned as distributions for each damage state for each equipment. Based on damage state of each equipment recovery times and costs are generated randomly as shown in Fig. 3. In step 4, based on CBD and operational capacity function described in [9, 10], operational capacity curve versus time are constructed for each *i-th* MCS of *j-th* PGA. Step 5 includes calculation of economic losses: direct economic loss (*DC*) related to equipment reconstruction costs, business interruption losses (*BI*) and total economic loss (*EL*). Economic losses are calculated for each *i-th* MCS of *j-th* PGA using the procedure described in [9, 10].


Inspection and planning time. (Should be defined for each DS of *n-th* equipment)

Equipment recovery time. (Should be defined for each DS of *n-th* equipment)

Fig. 4 – Simplified recovery process.

In step 6, after MCS of each *j-th* PGA scenario mean operational capacity curve and mean resilience index (R_m) are calculated. Additionally, mean economic losses are also calculated based on distributions generated from MCS. Finally, the last step deals with calculation of performance metric. Firstly, mean resilience curve versus PGA can be calculated. Then based on mean economic losses, the loss curve can be calculated as economic losses versus PGA. By combining the hazard curve and loss curve the seismic loss exceedance curve can be calculated as function of mean economic losses vs mean annual frequency of exceedance. By integrating the seismic loss exceedance curve, the mean Expected Annual Losses (EAL_m) can be calculated, which in other words is the area under the curve and it can be calculated using Eq.2. Finally, operational capacity surface can be plotted as function of PGA and time.

$$EAL_m \cong \sum_{j=2}^{n} \frac{EL_m(j) - EL_m(j-1)}{2} [\lambda(j) - \lambda(j-1)] \tag{2}$$

4. Case study

A nitric acid plant [10] is used as a case study. In order to reduce computational time, pipelines and pumps are neglected from analysis. Different damage states of equipment are considered and fragility curves parameters are given in Table 1 based on recommendation of [13]. For each damage state of equipment a recovery time is defined as one side truncated normal distribution with lower bound 80% of mean and standard deviation 20% of mean. The mean recovery time for each damage state of equipment is based on engineering judgement. The plant is assumed to be located in a high seismic area in south Italy, Priolo Gargallo. For simplicity, resilience will be calculated focusing on plant level using scenario base analysis and neglecting the interdependencies with other systems.

4.1 Plant mapping

The plant contains two PFs and 23 critical equipment as shown in Fig. 5. In PF1 is allocated 60% of total plant capacity, while the remaining 40% is allocated in PF2. Plant operates 24 h/d and it produces 195 t/d of 60% concertation nitric acid in PF1 and 130 t/d of 40% concertation nitric acid in PF2. Variable unit production cost for 1 t of 60% nitric acid is 60 €/t while for 40% nitric acid is 40 €/t. The selling price of 60% nitric acid is 240 €/t while selling price of 40% nitric acid is 160 €/t [10].

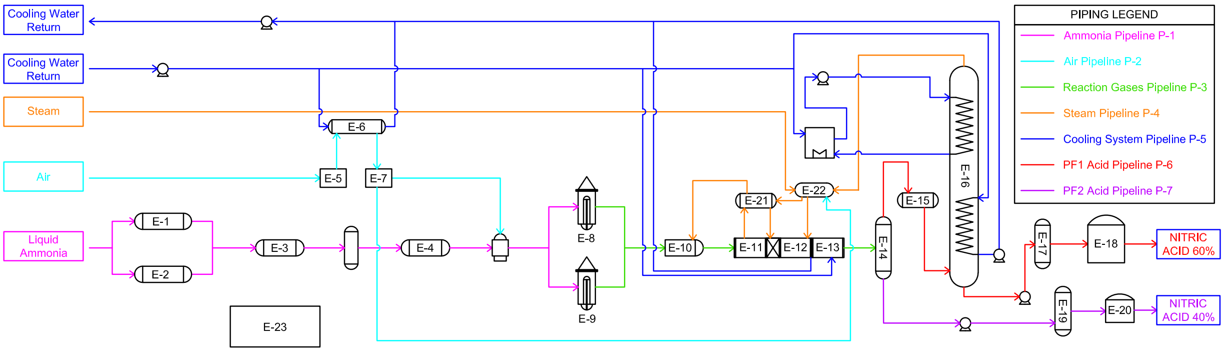


Fig. 5 - Process flow diagram of nitric acid plant.

After defining process flow of the plant, the next step is to define plant topology. Based on their functionality, the capacity block diagram is used to group the equipment as explained in [9, 10]. For this plant, each PF is constructed of two blocks with two equipment each in fractionated parallel and a block with equipment in series as shown in Fig. 6. The equipment in fractionated parallel cover 50% of process flow capacity each, while the ones in series 100%.

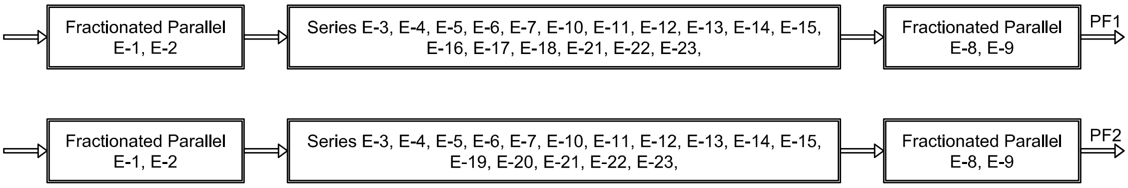


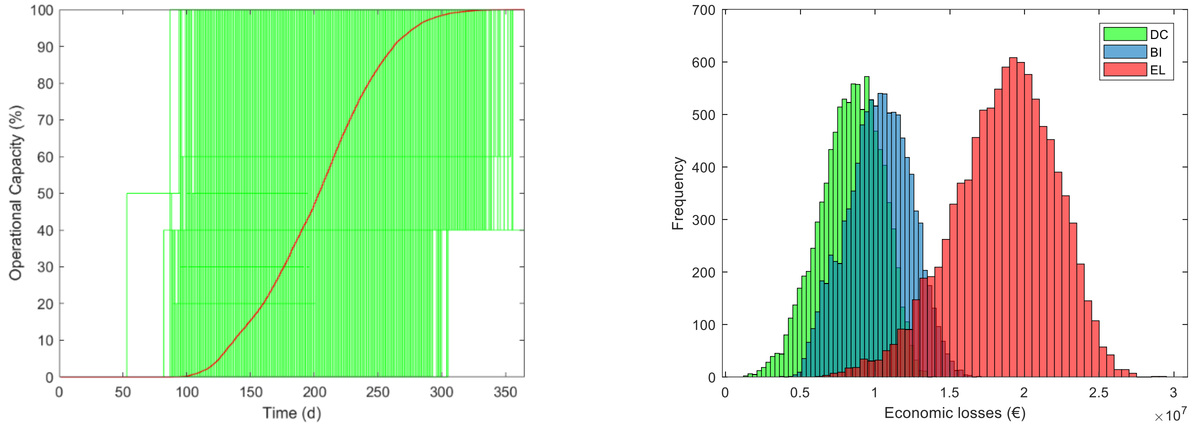
Fig. 6 - Capacity Block Diagram of nitric plant.

4.2 Scenario based analysis

Seismic hazard curve of Priolo Gargallo [14] is used for scenario-based analysis. PGA_{min} is considered to be 0.05g while the PGA_{max} is considered as 1.8g. Several PGA between PGAmin and PGAmax are considered as scenarios. For each of the selected PGA a Monte Carlo Simulation is conducted to generate seismic damage scenarios as shown in Fig. 3. For each PGA, 10000 simulation are generated using PRIAMUS [15]. A random number between 0 and 1 is sampled for each equipment and based on fragility curves the damage state is defined, considering to be the worst one. Along with equipment damage states a random recovery time is generated based on predefined truncated normal distribution for each damaged equipment as described in section 3. A control time of one year (365 days) is selected for resilience calculation.

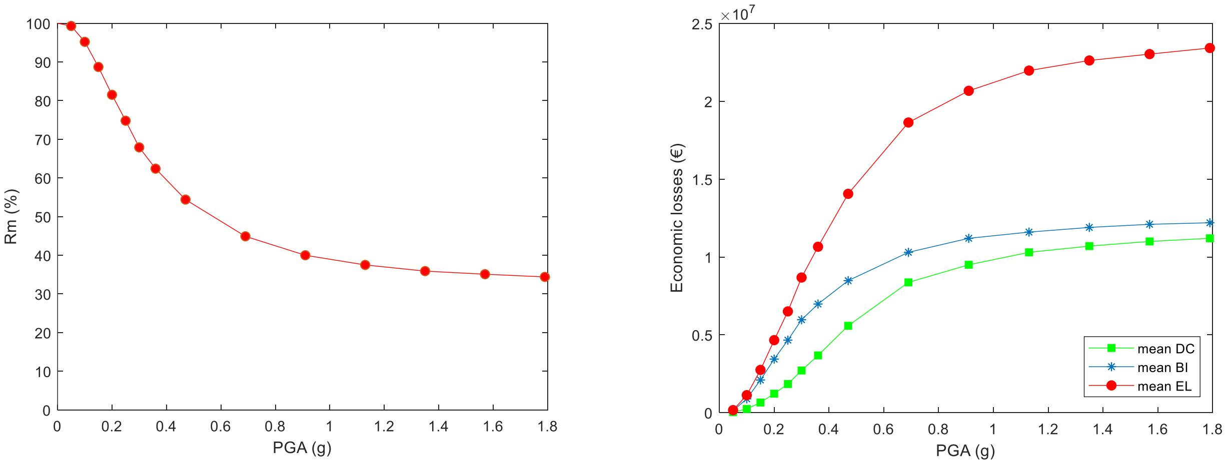
Fig. 7 (a) shows the operational functionality curves for the 10000 MCS corresponding to PGA = 0.69g, and in red is shown the mean curve, which has a mean resilience index of 44.87%. Fig. 8 (a) shows the variation of mean resilience index versus PGA. At lower values of PGA (0.05g to 0.6g), an increase by 0.05g causes a reduction of *Rm* by around 7%, while for PGA bigger than 1.1g the mean resilience index reaches a plateau around 35%, therefore, it is important to have more integration point at lower PGA. Fig. 7(b) shows the distributions of economic losses for all 10000 MSC for scenario of PGA = 0.69g. Direct costs have a mean of 8.37 million euros, *BI* have a mean 10.26 million euros and *EL* have a mean of 18.64 million euros. Fig. 8 (b) shows the variation of mean economic losses for different level of PGA. *BI* are the one which has the higher influence on total economic losses especially for low level of PGA. The *EL* reach a maximum value of around 23.43 million € for a PGA 1.8g.

Mean expected annual losses (*EALm*) for this plant are around 43650€ and they are calculated using Eq.2 and the expected loss curve shown in Fig. 9 (a). *BI* are the one which have the biggest influence on *EALm*, around 31598€, which corresponds to 72.3%. For this reason, it is important to have an efficient recovery plan and to minimize the impedance factors in order to reduce delays in starting of recovery phase and also to reduce



(a) (b)

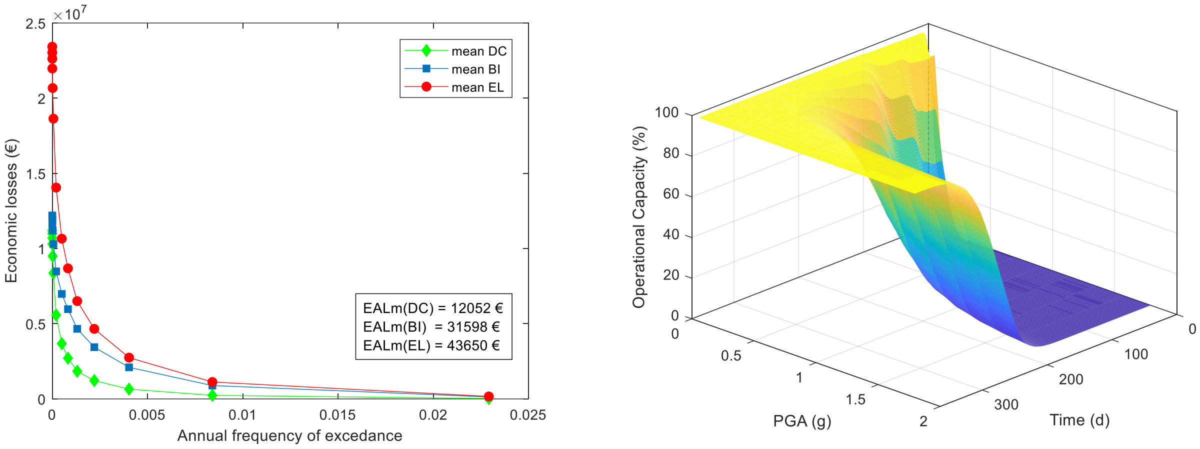
Fig. 7 - (a) Operational Capacity curves for 10000 MCS corresponding to PGA=0.69g (mean curve in red) , (b) Economic losses distribution for 10000 MCS corresponding to PGA=0.69g.



(a) (b)

Fig. 8 - (a) Mean resilience index curve for different PGA; (b) Economic loss curve for different PGA.

the economic losses. Plant owners and decision makers can decide if this *EALm* is acceptable them, otherwise they should try to reduce it by using mitigation strategies to reduce the possibility of damage in equipment, modify the plant topology by adding redundant units or by trying to shorten the recovery time. Moreover, Fig. 9 (b) shows the operational capacity surface, which gives a more general view to stakeholders about the recovery process for different level of PGA.



(a) (b)

Fig. 9 – a) Expected loss exceedance curve; b) Plant operational functionality surface.

5. Conclusions

This paper summarizes possible ways for calculation of seismic resilience of process plants. The framework for resilience calculation at plant level contains four main modules. Starting with the common ones, first module is plant mapping, second is plant topology and third is vulnerability module. Meanwhile the last one, risk and resilience module, has several possibilities for calculating the seismic risk, resilience and economic losses of plant. In this paper probabilistic scenario based analysis using MCS is explained in details, while for risk based analysis references are made. The framework allows to account for different damage states of equipment by using probabilistic recovery. Mean resilience index, mean expected annual losses and operational capacity surface are used as system performance metric. They provide useful information for decision makers, plant owners and emergency managers of process plants.

The proposed methodology is applied to a nitric acid plant, considering different damage states of equipment and probabilistic recovery. Domino effects and interconnection with other system have been neglected. The nitric plant has an *EALm* of around 43650€, from which 72.3% are due to *BI* and 27.7% due to *DC*. Plant mean resilience index is calculated for different level of PGA, having a minimum value of 34.4% at 1.8g. Finally, plant operational capacity surface is constructed as function of time and PGA.

Proposed methodology for defining and quantifying the plant performance metric, is the first step toward a targeted seismic risk and resilience assessment/design of process plants. Mean expected annual losses or operational capacity surface can be used as performance indexes towards targeted resilience assessment/design.

Finally, when calculating the process plant resilience, it is important to consider the connection of plant with other systems such as community, transportation infrastructure or critical infrastructure as they might influence resilience of each other. Community influences directly the plant resilience, e.g. if the plant workers are affected from earthquake, they are not mentally or physically able to work due to earthquake shock or if they have to relocate due to damages in the houses, the plant might run out of workers. Accessibility of plant after earthquake is also a very important issue which directly affects the plant functionality and recovery phase, therefore transportation infrastructure should be also taken into consideration. Critical infrastructure, such as electricity, internet, gas line etc. directly influence the functionality of process plant, therfore they need to be taken into consideration. Moreover, process plant can also influence the resilience of other systems, in case of release of toxic material due to equipment failure with loss of containment LOC. All these interconnections will be taken into account in future research.

Table 1 - Fragility curves parameters for different damage state of equipment.

Eq. Label	**Process Equipment**	**DS2**		**DS3**		**DS4**		**DS5**	
		PGA_m (g)	β	PGA_m (g)	β	PGA_m (g)	β	PGA_m (g)	β
E-1	Ammonia storage vessel	-	-	0.52	0.7	-	-	1.56	0.61
E-2	Ammonia storage vessel	-	-	0.52	0.7	-	-	1.56	0.61
E-3	Ammonia Vaporizer	-	-	0.52	0.7	-	-	1.56	0.61
E-4	Ammonia Super heater	-	-	0.52	0.7	-	-	1.56	0.61
E-5	1-st Stage Air Compressor	0.15	0.75	0.34	0.65	0.77	0.65	1.5	0.8
E-6	Compressor intercooler	-	-	0.52	0.7	-	-	1.56	0.61
E-7	2-nd Stage Air Compressor	0.15	0.75	0.34	0.65	0.77	0.65	1.5	0.8
E-8	Reactor	-	-	0.6	0.4	0.88	0.39	-	-
E-9	Reactor	-	-	0.6	0.4	0.88	0.39	-	-
E-10	Steam Super-Heater	-	-	0.52	0.7	-	-	1.56	0.61
E-11	Waste Heat Boiler	-	-	0.52	0.7	-	-	1.56	0.61
E-12	Tail Gas Pre-heater	-	-	0.52	0.7	-	-	1.56	0.61
E-13	Cooler/Condenser	-	-	0.6	0.4	0.88	0.39	-	-
E-14	Oxidation Vessel	-	-	0.6	0.4	0.88	0.39	-	-
E-15	Secondary Cooler	-	-	0.52	0.7	-	-	1.56	0.61
E-16	Absorption Column	-	-	0.6	0.4	0.88	0.39	-	-
E-17	Bleaching Column	-	-	0.6	0.4	0.88	0.39	-	-
E-18	Nitric Acid (60%) Tank	0.15	0.7	0.35	0.75	0.68	0.75	0.95	0.7
E-19	Bleaching Column	-	-	0.6	0.4	0.88	0.39	-	-
E-20	Nitric Acid (40%) Tank	0.15	0.7	0.35	0.75	0.68	0.75	0.95	0.7
E-21	Liquid Vapour Separator	-	-	0.52	0.7	-	-	1.56	0.61
E-22	Tail Gas Warmer	-	-	0.52	0.7	-	-	1.56	0.61
E-23	Electric Unit	0.8	0.6	1.0	0.8	-	-	-	-

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