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RESILIENCE CALCULATION OF PROCESS PLANTS UNDER SEISMIC LOADING: A CASE STUDY

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ABSTRACT

Earthquakes causes approximately 8% of total accidents in industrial facilities. Although there are several researches in literature pertaining to industrial resilience, none of them provides a modelling framework to quantify the seismic resilience of process plants. This paper presents a methodology for providing a quantitative measure of resilience and business economic losses for the process plants in case of a seismic event. The two main parameters which have utmost influence on the resilience of a process plant are operational capacity and recovery time, so they must be evaluated in proper way. Plant mapping and components vulnerability are the key modelling parameters of plant operational capacity. Exact recovery step functions are introduced based on General Reconstruction Activity Network (GRAN), considering interdependencies between plant components. In order to illustrate the discussed method, a nitric acid plant is set up as a case study. "PRIAMUS" software is used to generate the most probable damage scenarios, assuming the plant is located in seismic region of South Italy, Sicily. Ultimately, recovery curves are constructed for each damaged scenario, and business economic losses are calculated according to direct cost and business interruption. In short, this methodology provides a good estimation of the most critical components and economic losses of a process plant in case of a seismic event.

INTRODUCTION

Resilience is a concept which first was introduced in psychology [1], but nowadays has attracted a lot of research interest in many fields including engineering, process industry, public management etc. Seismic resilience can be defined as ability of the system to withstand and rapidly recover from a low frequency, high impact disruptive event.

In industrial plants, natural hazards such as floods, tsunamis, earthquakes etc., can rise Natural-Technological (Na-Tech) events which can have devastating consequences such as release of hazardous materials, disruption of utilities, damage of infrastructure, economic losses, environmental pollution etc. A recent example is Tohoku earthquake in 2011, which led the Fukushima Na-Tech accident in Japan, a devastating disaster from which Fukushima is not yet recovered. For this reason, it is important to assess resilience of industrial plants, as they are second most dangerous plants after nuclear power plants, due to containment of hazardous material.

While in the field of civil engineering and build transportation infrastructures there are several resilience models proposed in literature [2], [3], [4], [5], [6], [7], [8], the research applied to industrial plants is comparatively scarce.

In this sector, research has been mainly oriented towards the organizational and operational issues including human factors [9], [10], [11] and more recently to applications in safety analysis and risk assessment of process plants [12], [13]. In [14] author deals with process plants but focuses specifically on resilience of single process equipment under natural hazards thus neglecting the overall process flows. Finally, research is scarce too in the domain of manufacturing plants, although some general-purpose modeling approaches have been suggested [15], [16].

In this paper, a resilience model for process plants is presented. The proposed model includes definition of production capacity functions, based on plant configuration and exact recovery models. Economic losses such as business interruption and direct costs are integrated in the model in order to provide decision making support to plant owners, decision makers and

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emergency mangers. A nitric acid plant is selected as case study in order to illustrate the proposed model.

METHODOLOGY FRAMEWORK

The methodology presented in this paper is based on the resilience model firstly presented in PVP2017 [17]. The model for resilience assessment is amenable to both a deterministic and probabilistic analysis. Deterministic resilience analysis implies that the user is interested in analyzing a specific damage scenario, meaning that the set of plant equipment damaged by the natural event, i.e. assigned to an out of service state, is predefined by the user. Any different damage scenario of interest can be separately analyzed. Probabilistic analysis implies that either the initial damage scenario is randomly generated, or that multiple possible damage scenarios are analyzed accounting for their probability of occurrence so that a probability distribution of the parameters of interest can be obtained. Finally, randomness can be included not only in the scenario generation but even in computing the duration of the recovery process. In this paper, resilience due to seismic events will be discussed, but the methodology can be used for any Na-Tech event.

The method aims computing the time trend of system capacity C(t) from the time $\mathbf{t_0}$ time when disruption event occurs, until the plant is totally recovered at a time $\mathbf{t_r}$ as shown in Figure 1. In case that the damage propagation is not considered, the time $\mathbf{t_0}$ is equal to the time when disruptive event stops $\mathbf{t_d}$,whilst for the cases in which damage propagation will be considered the $\mathbf{t_d}$ will be bigger than $\mathbf{t_0}$. Time $\mathbf{t_i}$ corresponds to initiation of recovery of plant operational capacity. Capacity is considered as capability of the system to generate physical output. Step recovery functions are the ones which better represent process plants operational capacity, and they are computed based on plant configuration, damaged equipment and restoration activities, e.g. when an equipment gets damaged, the capacity drops by a percentage, it can be restored back to its initial value only when all repairs work are finished and the equipment is set back to work.

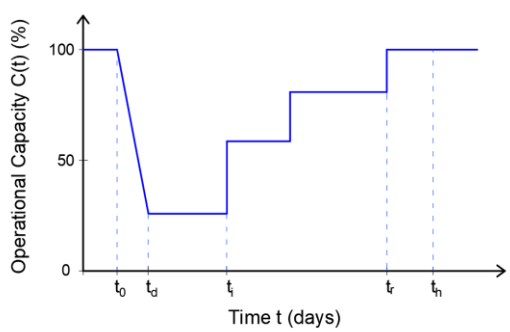

Figure 1. Plant operational capacity curve.

In literature there are several expressions used to calculate resilience index (R). The one according to [18], [19] will be used in this model and it will be given in percentage.

$$R = \frac{100}{t_h - t_0} \int_{t_0}^{t_h} C(t)dt \quad (1)$$

Another index will be resilience loss (RL) [20], which will be calculated until a time $\mathbf{t_h}$, usually defined bigger than $\mathbf{t_r}$ in order to have higher values of R for faster recovery.

$$RL = \int_{t_0}^{t_h} [100 - C(t)dt] \quad (2)$$

Moreover, economic losses (EL) will be integrated in this model including equipment reconstruction cost (ER) and business interruption loss (BI).

The proposed methodology includes eight steps as shown in Figure 2, which will be described in more details together with the case study.

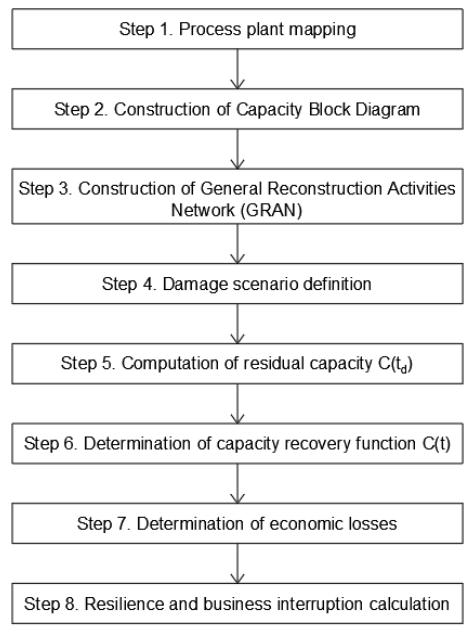

Figure 2. Operational steps of the proposed methodology.

CASE STUDY

The proposed methodology is applied to a nitric acid plant described in [21], properly modified in order to include more complex conditions. The plant is assumed to be placed in Priolo Gargallo, one of the most seismic zones in south Italy (Sicily).

Description of case study

Nitric acid plant delivers 195 tons/day of nitric acid (60% concentration) and 130 tons/day of nitric acid (40% concentration), based on 8000 hours of operation per year. Simplified process flow diagram of the plant is shown in Figure 3.

The major equipment are ammonia storage tanks, ammonia vaporizer, ammonia filter, ammonia super-heater, two-stage air compressor, mixer, reactors, steam super-heater, waste-heat boiler, tail gas pre-heater, cooler/condenser, oxidation vessel, secondary cooler, liquid vapor separator, tail gas warmer, refrigeration unit, absorption column, pumps, bleaching columns, nitric steel storage tanks, electric unit and piping systems.

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Purchase cost of equipment are based on the work of Ray and Johnston [21], which refers to 1986. In order to calculate current cost of equipment the Chemical Engineering Plant Cost Index (CEPCI) is used. The base index is 100 corresponding to 1957-59, while in 1986 it was 318.4 [22]. Consequently, the current cost of equipment's is calculated by using the index of 2018, which increased, from 1989, of around 88% [23]. Accounting for the September 2018 exchange ratio of one A$ to Euro (0.62), the current replacement costs of each equipment are indicated in Table 1.

The total variable unit production cost of 1 ton of 100% nitric acid in 1986 was 97.07 A$, which corresponds to 59.30 A$ (36.8€) for 1 ton of 60% nitric acid and 38.8 A$ (24.0€) for 1 ton of 40% nitric acid [21]. Taking into account inflation, a variable unit production cost of 60€ and 40€ we will be adopted respectively. The selling price of 100% nitric acid in the world market in 1986 varied between 339 and 487 A$ /ton [21]. For our purpose, a value of 400 €/ton, including inflation will be considered, which corresponds to a price of 240 €/ton and 160€/ton for 60% and 40% nitric acid, respectively.

Step 1. Process plant mapping.

Plant contains 32 equipment and 7 groups of pipes which make a total of 39 elements to be considered in calculation as per Table 1. The pant has two Process Flows (PF) as shown in Figure 3, with 60% of total plant capacity allocated in PF1 and 40% of total plant capacity allocated in PF2.

A unique set of equipment **S[f]** corresponds to each PF, for this case **S[1]** = {E-1, E-2, E-3, E-4, E-5, E-6, E-7, E-8, E-9, E-10, E-11, E-12, E-13, E-14, E-15, E-16, E-17, E-18, E-19, E-20, E-21, E-25, E-26, E-27, E-28, E-29, E-30, E-31, E-32, E-33, E-34, E-35, E-36, E-37, E-38} and **S[2]** = {E-1, E-2, E-3, E-4, E-5, E-6, E-7, E-8, E-9, E-10, E-11, E-12, E-13, E-14, E-15, E-16, E-22, E-23, E-23, E-24, E-25, E-26, E-30, E-31, E-32, E-33, E-34, E-35, E-36, E-37, E-39}.

Step 2. Construction of Capacity Block Diagram.

For each PF a Capacity Block Diagram (CBD) should be drawn. Equipment of each **S[f]** should be grouped into process stages (PS) strictly connected in series [17]. In other words, a PF can be represented as a series of PS. The PS with the lowest capacity is the one controlling the entire capacity of the process flow to which is belonging. Units in a PF can be either in series or in parallel, but not a mix.

Figure 4 shows the CBDs of nitric acid plant. Each PF is presented by a CBD with three PS, two PS with fractionated parallel units and one PS which contains all units in series including here the piping systems.

Step 3. Construction of General Reconstruction Activities Network.

In this step, all the activities and logical relationship between them should be defined, in order to have the General Reconstruction Activities Network (GRAN) of the plant. GRAN is similar to the one used in project management and it will include all the activities needed to reconstruct the plant assuming it fully damaged. In Figure 5 is shown an example of a GRAN where arrows represent the reconstruction activities while nodes represent starting and finishing date of activities [17].

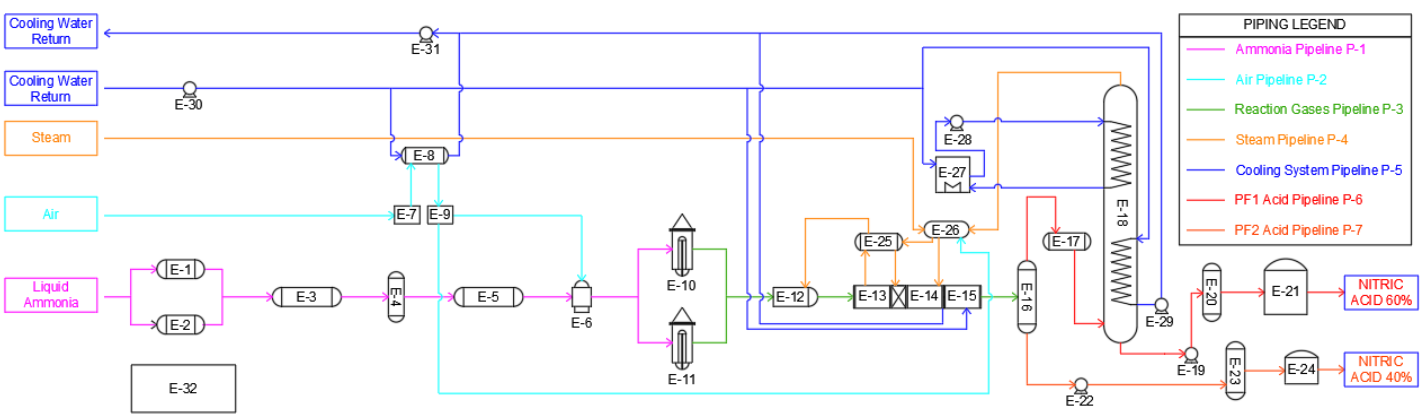

Figure 3. Process Flow Diagram of nitric acid plant.

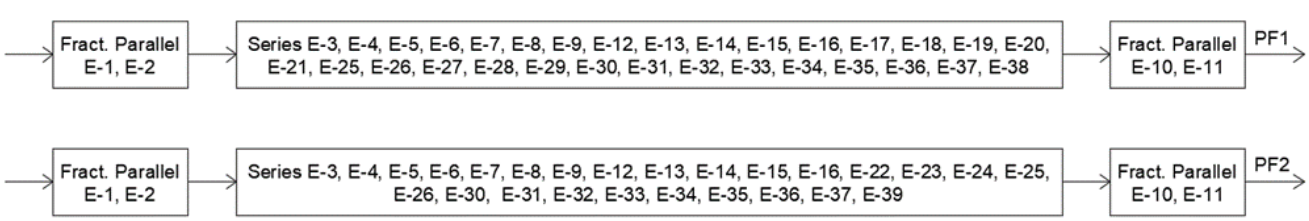

Figure 4. Capacity Block Diagram of nitric acid plant.

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Table 1. Equipment replacement cost and seismic fragility parameters.

Eq. Label	Process Equipment	Replacement cost (€)	PGA_m (g)	β	Damage state	Reference
E-1	Ammonia storage vessel	646,000	0.54	0.46	PL2	Horizontal Vessel [27]
E-2	Ammonia storage vessel	646,000	0.54	0.46	PL2	Horizontal Vessel [27]
E-3	Ammonia Vaporizer	70,000	0.54	0.46	PL2	Horizontal Vessel [27]
E-4	Filter	30,000	1.00	0.60	DS3	Mechanical Equipment [28]
E-5	Ammonia Superheater	34,000	0.54	0.46	PL2	Horizontal Vessel [27]
E-6	Mixer	30,000	1.00	0.60	DS3	Mechanical Equipment [28]
E-7	1-st Stage Air Compressor	1,458,000	0.77	0.65	DS4	Compressor Station [28]
E-8	Compressor intercooler	61,000	0.54	0.46	DS4	Horizontal Vessel [27]
E-9	2-nd Stage Air Compressor	2,722,000	0.77	0.65	DS4	Compressor Station [28]
E-10	Reactor	139,000	0.51	0.45	PL2	Vertical Vessel CL1 [27]
E-11	Reactor	139,000	0.51	0.45	PL2	Vertical Vessel CL1 [27]
E-12	Steam Super-Heater	74,000	0.54	0.46	PL2	Horizontal Vessel [27]
E-13	Waste Heat Boiler	86,000	0.54	0.46	PL2	Horizontal Vessel [27]
E-14	Tail Gas Pre-heater	72,000	0.54	0.46	PL2	Horizontal Vessel [27]
E-15	Cooler/Condenser	186,000	0.54	0.46	PL2	Vertical Vessel CL1 [27]
E-16	Oxidation Vessel	101,000	0.59	0.41	PL2	Vertical Vessel CL2 [27]
E-17	Secondary Cooler	250,000	0.54	0.46	PL2	Horizontal Vessel [27]
E-18	Absorption Column	2,261,000	0.67	0.37	PL2	Extrapolation [27]
E-19	Acid Pump	10,000	1.60	0.60	DS4	Horizontal Pump [28]
E-20	Bleaching Column	74,000	0.59	0.41	PL2	Vertical Vessel CL2 [27]
E-21	Nitric Acid (60%) Tank	1,160,000	0.68	0.75	DS4	Unanchored Tank [28]
E-22	Acid Pump	10,000	1.60	0.60	DS4	Horizontal Pump [28]
E-23	Bleaching Column	74,000	0.59	0.41	PL2	Vertical Vessel CL2 [27]
E-24	Nitric Acid (40%) Tank	696,000	0.68	0.75	DS4	Unanchored Tank [28]
E-25	Liquid Vapor Separator	70,000	0.54	0.46	PL2	Horizontal Vessel [27]
E-26	Tail Gas Warmer	124,000	0.54	0.46	PL2	Horizontal Vessel [27]
E-27	Refrigeration Unit	164,000	1.00	0.60	DS3	Mechanical Equipment [28]
E-28	Water pump	3,000	1.25	0.60	DS4	Vertical Pump [28]
E-29	Water pump	3,000	1.25	0.60	DS4	Vertical Pump [28]
E-30	Water pump	3,000	1.25	0.60	DS4	Vertical Pump [28]
E-31	Water pump	3,000	1.25	0.60	DS4	Vertical Pump [28]
E-32	Electric Unit	811,000	1.00	0.80	DS3	Electric Power [28]
E-33	Ammonia Pipeline	541,000	1.00	0.60	DS5	Elevated Pipes [28]
E-34	Air Pipeline	541,000	1.00	0.60	DS5	Elevated Pipes [28]
E-35	Reaction Gas Pipeline	541,000	1.00	0.60	DS5	Elevated Pipes [28]
E-36	Steam Pipeline	541,000	1.00	0.60	DS5	Elevated Pipes [28]
E-37	Cooling System Pipeline	55,000	1.00	0.60	DS5	Elevated Pipes [28]
E-38	PF1 Acid Pipeline	541,000	1.00	0.60	DS5	Elevated Pipes [28]
E-39	PF2 Acid Pipeline	541,000	1.00	0.60	DS5	Elevated Pipes [28]

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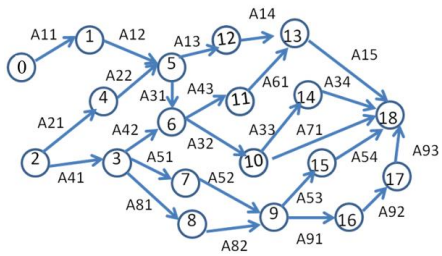

Figure 5. Fictional General Reconstruction Activity Network.

The reconstruction activities will be divided in two groups, common activities and activities related to specific equipment. Common actives can include activities such as emergency response, access cleaning, site cleaning, damage survey and recovery plan, commissioning and production ramp up as shown in Figure 6. Meanwhile, for each *i-th* equipment of plant, the full list of activities needed to be carried out to bring them back into working state from totally damaged state, should be defined. A duration $T_{i,j}$ should be defined for each *j-th* activity associated to *i-th* equipment. Finally, constrains between activities has to be set in empirical correlations such as some activities can start only after the precedent activity is finished, e.g. installation of an equipment cannot start unless the foundation is finished. For this case study Matlab is used to model the GRAN, but any programing language can be used.

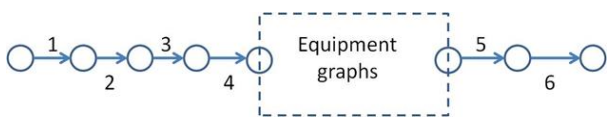

Figure 6. GRAN of nitric acid plant.

Legend: 1 = Emergency response, 2 = Access clearing, 3 = Site cleaning and remediation, 4 = Damage survey and recovery planning, 5 = Commissioning, 6 = Production ramp up.

Novelty of this method is that it can also consider the interdependencies between the restoration activities of different equipment, as shown in Figure 7 with red arrows.

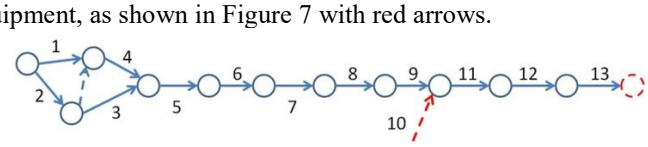

Figure 7. Steel storage tank installation activity network.

Legend: 1 = Removal of damaged equipment and site cleaning, 2 = Tank Design, 3 = Materials order and delivery (tank structure), 4 = Foundation construction, 5 = Base plates assembly, 6 = Walls assembly and internal fittings installation, 7 = Welding inspection, 8 = Roof building and installation, 9 = Ancillaries and fire-fighting equipment installation, 10 = Connecting pipes installation, 11 = Piping connection, 12 = Water filling and foundation settlement, 13 = Cleaning and testing, painting.

Step 4. Damage scenario definition.

In order to define the damage state of *i-th* equipment, a damage state variable δ_i is introduced. A scenario vector SV = $\{\delta_i, \ldots \delta_N\}$, will be used to define the damage state of the plant with N equipment. In this paper only two damage state of equipment are considered:

$$\delta = \begin{cases} 0 & if\ i-th\ equipment\ is\ damaged \\ 1 & if\ i-th\ equipment\ is\ undamaged \end{cases} \quad (3)$$

Damage scenario for case of seismic event will be uncertain, so for each generated SV, the probability of occurrence should be calculated using the procedure described below.

First step would be estimation of seismic hazard curve of the site using Probabilistic Seismic Hazard Analysis (PSHA) [24]. Second step would be vulnerability assessment of equipment by defining fragility curves for each equipment of process plant. Seismic fragility curves can be taken from literature or can be computed using numerical modeling [25], [26], while or this case study fragility curves are selected from literature [27], [28] considering as limit state extensive damage or complete failure of equipment. In Table 1 are given the parameters of fragility curves, median peak ground acceleration (PGA) and the lognormal standard deviation β. Third step will be definition of damaged scenarios using probabilistic seismic analysis, based on Monte Carlo simulation as described in [29].

PRIAMUS [30] software is used to carry out the probabilistic seismic analysis and the most probable damage scenarios of the nitric acid plant are given in Table 2.

Table 2. Probabilistic seismic damage scenarios.

#	Seismic damage scenario (damaged units)	Annual Probability
0	None	0.999
1	E-21 E-24	1.39e-06
2	E-32	9.05e-07
3	E-24	3.22e-07
4	E-21	2.63e-07
5	E-7, E-9	1.90e-07
6	E-10, E-11	9.93e-08
7	E-1 E-2 E-3 E-5 E-8 E-12 E-13 E-14 E-15 E-17 E-25 E-26	7.29e-08
8	E-9	7.05e-08
9	E-10	6.37e-08
10	E-11	4.77e-08
11	E-7	4.08e-08
12	E-1 E-2 E-5 E-12 E-25	2.71e-08
13	E-4 E-6 E-27 E-33 E-34 E-35 E-36 E-37 E-38 E-39	2.68e-08
14	E-16 E-20 E-23	2.02e-08
15	E-21 E-24 E-32	1.64e-08
16	E-2 E-3 E-5 E-8 E-13 E-14 E-15 E-17 E-25 E-26	1.55e-08
17	E-16	1.52e-08
18	E-24 E-32	1.35e-08
19	E-10 E-11 E-32	1.34e-08

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Step 5. Computation of residual capacity.

Definition of PFs and CBD in step 1 and 2 allows user to calculate the residual capacity $\mathbf{C(t_d)}$ of the plant for any damage scenario. Overall plant residual capacity can be calculated as a summation of partial capacities of each PFs as below:

$$C(t_d) = \sum_f O_f C_f(t_d) \tag{4}$$

where, O_f is the fraction of total plant capacity allocated in *f-th* PF, while $C_f(t_d)$ is operation capacity of *f-th* PF when disruption occurs. Having defined the CBD for each *f-th* PF as a series of *s-th* PS, the capacity of process flow can be defined as follow:

$$C_f = Min\{C_{s,f}\} \tag{5}$$

where, $C_{s,f}$ is the capacity of *s-th* process stage, located in *f-th* PF. Capacity of each PS is function of equipment working state and it is given in Table 3 .

Table 3. Process Stage Capacity model.

PS with units in series	$C_{s,f} = \prod_{i \epsilon S[s,f]} \delta_i$
PS with *n* equal units in parallel with capacity $1/n$	$C_{s,f} = \sum_{i \epsilon S[s,f]} \frac{1}{n} \delta_i$

In this case study the fraction of total plant capacity allocated in PF1 and PF2 will be O_1=0.6 and O_2=0.4 respectively.

Step 6. Determination of capacity recovery functions.

In order to automatically model capacity recovery function C(t) based on GRAN, another damage state coefficient $\gamma_{i,j}$ is introduced, a coefficient which multiplies each $T_{i,j}$ recovery task duration in order to calculate the recovery time of *i-th* damaged equipment by completing all *j-th* restoration tasks.

$$Tr_i = f(\gamma_{i,j} T_{i,j}) \tag{6}$$

Initial value of $\gamma_{i,j}$ will be 0, which means that recovery time of each equipment before the event is zero, while for a given SV with *m-th* damaged equipment (δ_i=0, iϵ[1..m]) the all $\gamma_{i,j}$ will be switched to 1. This way the GRAN will include only the recovery activities that are needed to recover *m-th* damaged equipment. By using the critical path method, the recovery time of each damaged equipment can be calculated. After having defined the recovery time of each damaged equipment, the plant operational capacity C(t) can be calculated having the time(*t*) as variable and by switching equipment state to undamaged (δ_i=1) when t=Tr_i.

Step 7. Determination of economic losses.

There are two types of economic losses that a plant experience due to a disruptive event. First ones, direct costs are the equipment reconstruction cost (ER) and include all the costs related to restoration activities such as: site cleaning, removing of damaged equipment, cost of new equipment etc. Second ones, business interruption cost (BI) are the variable losses due to reduction of production capacity leading to reduction of incomes. Total economic losses (EL) are calculated as summation of ER with EL. ER and BI can be calculated as follows

$$ER = \sum_i \sum_j \delta_i Cr_{ij} \tag{7}$$

$$BI = \sum_f \sum_z (p_f - Cvu_f) \left[C_{Nf} - C_f(t)\right] \Delta t_z \tag{8}$$

where Cr_{ij} is the cost of *j-th* restoration activity required to bring back into functional state the *i-th* equipment [17]. In Equation (8), p_f is the unit selling price of the *f-th* process flow, Cvu_f the variable unit production cost of the *f-th* process flow, C_{Nf} is the nominal production output of the *f-th* process flow, $C_f(t)$ is the capacity of *f-th* process flow at time t, and Δt_z is the duration of the *z-th* time interval between functional recovery of two successive units.

For the case study as we are considering severe damage of equipment, the Cr_{ij} will be the value of full replacement cost of *i-th* damaged equipment.

Step 8. Resilience and business interruption calculation.

In this part, resilience calculation and business interruption of plant due to seismic loading are shown. A reference time (t_h=180 days), equal to maximum time needed to reconstruct the completely damaged plant, is used in eq. (1) and (2).

In Figure 8 is shown plant operational capacity for seismic damage scenario #1 and #2. In scenario #1, which has the biggest mean annual frequency of occurrence 1.6 E-6, equipment E-21 and E-24 are damaged so the plant operational capacity at t_d drops to 0. After 170 days E-24 is reconstructed so the operational capacity increases to 40% as the PF2 is functional. The full recovery time for this scenario is 180 days, time needed to reconstruct E-21 and bring the plant to full operational capacity. This is a very low resilience damage scenario as the resilience index is 2.8%, corresponding to a resilience loss of 97.2%. In scenario #2, which is the second most probable seismic damage scenario, E-32 (electric unit) is damaged so the plant operational capacity at t_d drops to 0 as this unit is used by both PFs. The recovery time of this unit takes 95 days, which corresponds also to time when plant is fully recovered. This scenario has a resilience index R=47.8%, corresponding to a resilience loss of 52.2%.

In Figure 9 is shown the resilience index of seismic damage scenarios, where scenario #1 and #15 are the least resilient scenarios (R=2.8%), this related to long recovery time of damaged equipment and also because they are equipment in series used by both PFs. Scenario #9 and #10 are the most resilient ones (R=78.6%), this related to short recovery time and because E-10 and E-11 are elements in parallel, so even when one of them will fail the plant will continue working with 50% capacity.

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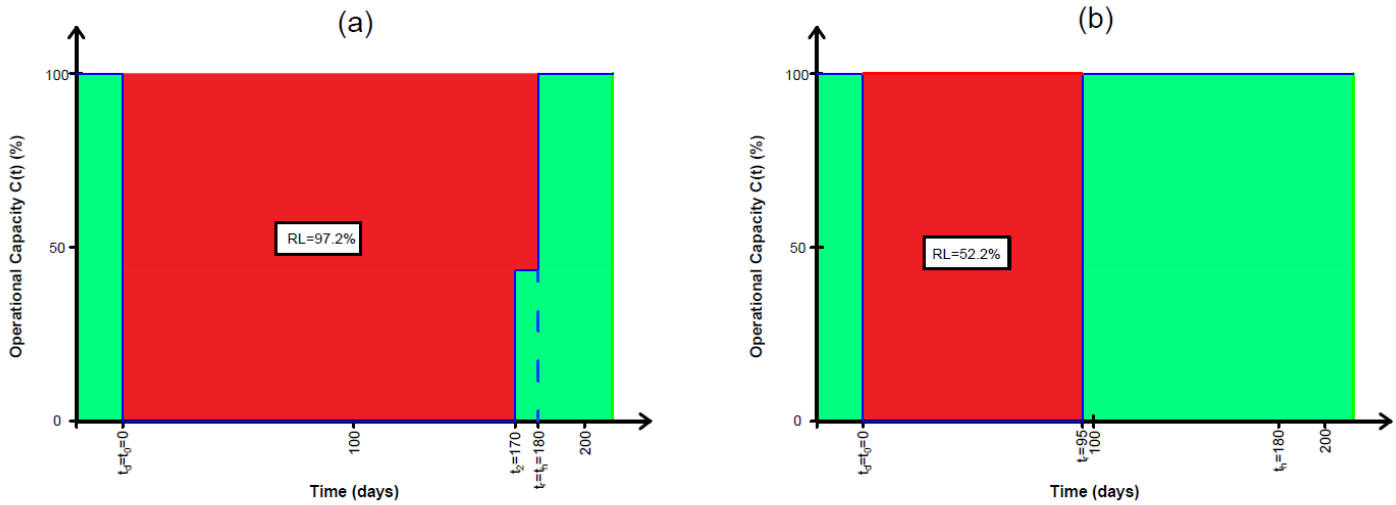

Figure 8. Plant operational capacity curve for seismic damage scenario #1 (a) and scenario #2 (b).

Time when the plant is fully recovered for each damage scenario is shown in Figure 10. Scenario #1, #4 and #15 are the ones with longest duration of 180 days, while scenario #6, #9 and #10 are fastest recovery ones, having a full recovery time of 78 days.

Another very important index is the mean annual frequency of occurrence of seismic damage scenarios, which is shown in Figure 11. Scenario #1 has the highest annual probability of occurrence, around 1.39 E-6, while scenario #19 has lowest probability of occurrence ~1.34E-08.

In Figure 12 economic losses for each seismic damage scenarios are presented. In terms of economic losses scenario #1 has an economic loss of 10.8 million euros due to 1.9 million euros from equipment reconstruction cost and 8.9 million euros from business interruption. Scenario #15 is the one with biggest economic loss of around 11.6 million euros, while scenarios #10 and #11 are the one with the smallest EL of around 2.1 million euros. Scenario #5 is the one which has the biggest direct cost, around 4.2 million, as the air compressors are the most expensive equipment of plant.

It can be extracted from Figure 12 that business interruption has the biggest influence on EL of the plant, around 80% of EL. It is important for plant owners or emergency managers of plant to have a recovery plan and a recovery strategy in case of seismic event in order to minimize the recovery time and reduce the economic losses due to business interruption.

By checking both Figure 11 and Figure 12, it can be noticed that scenario #15, even though generates the biggest EL, equal to 11.6 million euros, the corresponding mean annual frequency of occurrence is rather small ~1.64E-8, while scenario #1 is the most critical one as it has economic losses of 10.8 million euros with the highest annual frequency ~1.394E-6. Therefore, both mean annual probability of occurrence and economic losses are needed by decision makers, emergency managers or plant owners in order to evaluate which are the most critical seismic damaged scenarios that need to be considered. This can be achieved by computing the expected annual value of the economic loss.

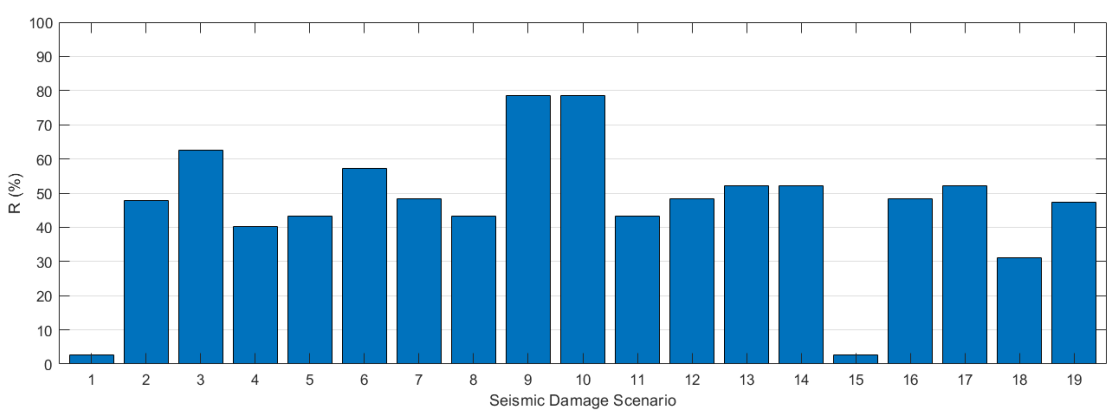

Figure 9. Resilience index for each seismic damage scenario.

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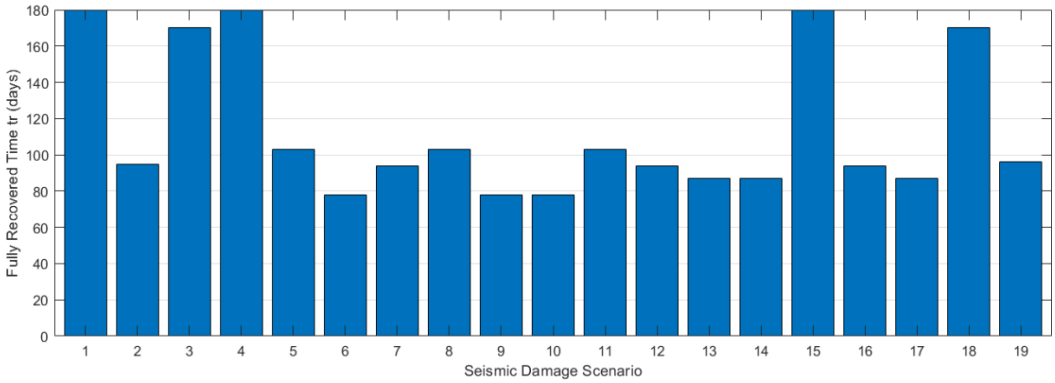

Figure 10. Time when plant is fully recovered.

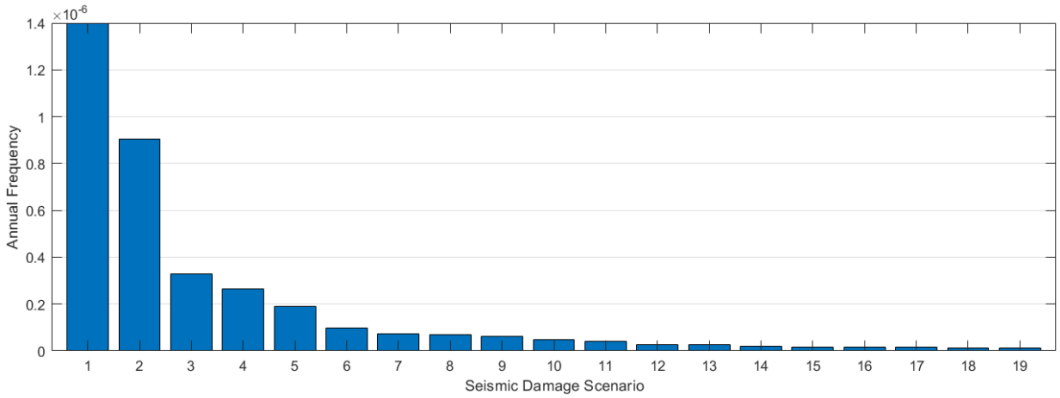

Figure 11. Mean annual frequency of occurrence for the most probable seismic damage scenarios.

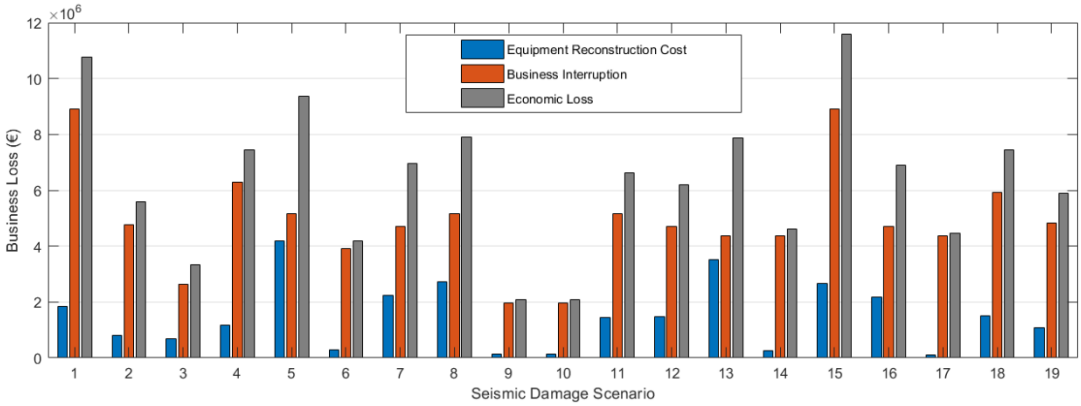

Figure 12. Economic losses for seismic damage scenarios.

Having the annual frequency of occurrence and the time when plant is fully recovered for each scenario vector, the distribution of time when plant is fully recovered can be estimated. In Figure 13 is shown the distribution of time to full recovery of nitric acid plant for case of seismic loading, having a mean of ~140.9 days and a standard deviation of ~42.3 days.

In Figure 14 is shown the probably that plant will be fully operational over time t, in case of a seismic damage. The plant has a probability of 50% chance of being fully operational after 100-150 days, while it is most likely to be fully operational after 180 days.

In Figure 15 are shown the distribution of business losses for: (a) equipment reconstruction costs, (b) business interruption and (c) economic loss.

CONCLUSIONS

In this paper a case study describing the application of the resilience estimation method developed by Caputo and Paolacci [17] is presented.

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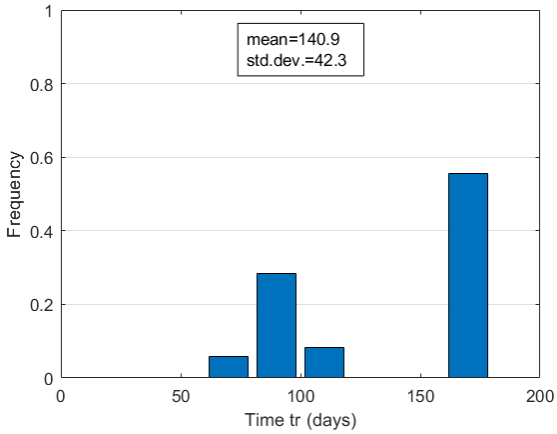

Figure 13. Distribution of time when plant is totally recovered.

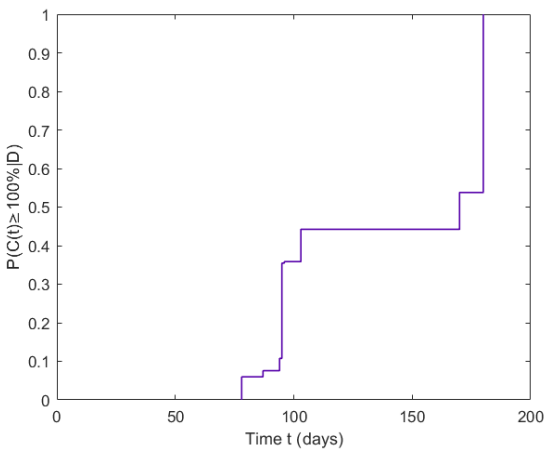

Figure 14. Probabilistic restoration function.

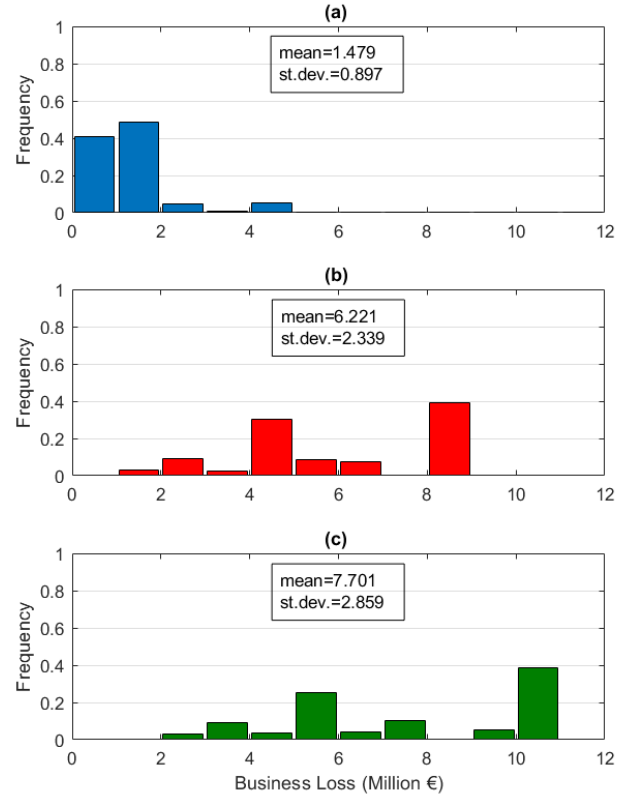

Figure 15. Distribution of business losses: (a) Equipment Reconstruction Cost, (b) Business Interruption and (c) Economic Loss.

The method, which is based on plant structure and process flows, provides an estimate of the economic losses and operational capacity trend during recovery phase for a given damage scenario.

Exact recovery functions based on General Reconstruction Activity Network are used, in order to have an accurate assessment of plant recovery function, which will allow to quantify equipment reconstruction costs and business interruption economic losses. In order to show its potentiality, the proposed method is applied to a case study, a Nitric Acid plant under seismic loading conditions.

Only units directly damaged by earthquake have been considered in seismic damage scenarios. A damaged component is considered to be unrepairable, so it will need to be entirely dismounted and reconstructed. Moreover, the recovery capacity and time of each recovery activity have been considered as deterministic.

Results showed that steel storage tanks are the most critical components of the Nitric Acid plant due to their high vulnerability, high mean annual frequency of occurrence of seismic damage and long reconstruction times. Indirect economic losses due to business interruption causes around 80% of total economic losses, so it is very important to measure them in an accurate way. Results provided from this methodology are extremely useful for decision makers, facility planners, emergency managers or plant owners, to support their decision-making process in case of Na-Tech events.

To the best of the author's knowledge, this is the first attempt to rationalize and quantify the concept of resilience for process plants, relying on detailed plant structure and process flows.

Further studies will be focused in full probabilistic formulation of methodology and accounting for domino effects when defining the seismic damage scenarios.

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