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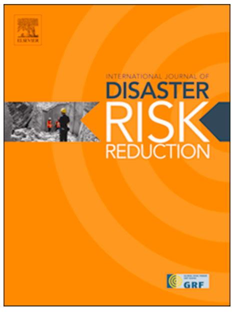

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Operational Status Effect on the Seismic Risk Assessment of Oil Refineries

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Abstract: The operational status of an oil refinery (type and scale of operations that take place at any time instance) largely determines the amount of fuel that is produced, circulated within the facility, and stored in tanks. This status is affected by seasonality, periods of peak or low demand, as well as periods of routine maintenance. However, it is an aspect that is typically neglected even though it stands out among the factors that determine the seismic performance of several critical industrial assets, such as the storage tanks, as well as the consequences of any potential failure. An open-data refinery testbed is employed herein to demonstrate the effect of the refinery's operational status on the seismic risk estimates. Alternative realistic operational scenarios are developed following typical industry practices and are arranged over a time period between two refinery major maintenance shutdown events. The most probable damage state is selected for each asset to identify the most vulnerable ones. Based on the type and importance of the impacted assets, the potential consequences are determined at the facility level. Resulting estimates are very different if an earthquake strikes during a regular/high/low-demand period, or during a maintenance period. The framework can be utilized to identify the locations within the refinery that may trigger cascading failures and secondary damages, should their assets be damaged by a seismic event. The outcomes can be exploited by stakeholders, risk engineers, and emergency action planners for developing customized and businesslike procedures to enhance the seismic resilience of the facility.

Keywords: oil refinery, earthquake, risk assessment, operational status

1. Introduction

Crude oil refineries are critical energy infrastructures that play a determinant role in the economy, both at a regional and national scale. Large amounts of flammable, toxic, and explosive materials are produced, circulated, and stored within the refineries. In case of earthquake-induced damages, the consequences may be disastrous, spanning from injuries and fatalities to environmental pollution, direct and long-term monetary losses, as well as downtime [1]. Refineries are designed, constructed, operated, and maintained through a grid of strict regulations aiming to ensure their structural and operational integrity even when they are affected by large earthquake events since they are classified as major-risk facilities according to the Seveso-III Directive [2]. Nevertheless, seismically-triggered Natural-Technological (NaTech) accidents still occur. For example, after the 1991 Costa Rica [3], the 1999 Kocaeli, Türkiye [4] and the 2011 Great East Japan [5] earthquakes, several oil storage facilities, and power plants were heavily damaged [6,7], resulting in the contamination of huge farmlands. The disastrous results of seismically-triggered failures of refineries and industrial facilities in the 2000s (e.g., the 2003 Bam, Iran [8], the 2006 Silakhor, Iran [9], the 2008 Wenchuan, PRC [10], the 2010 Chile [11], the 2012 Emilia Romagna, Italy [12], and 2023 Türkiye [13] earthquakes) and in particular the 2011 accident at the Fukushima Nuclear Power Plant [14,15] forced the international community to take action. This resulted in the Sendai Framework for Disaster Risk Reduction [16] that sets up guidelines for risk reduction in critical infrastructure, such as oil refineries [17]. Refinery designers, operators, and stakeholders are cooperating with regulatory authorities to develop and update a comprehensive framework for risk assessment of industrial facilities in case of NaTech events [18]. This framework includes risk identification and analysis [19], risk evaluation [20], and risk rating [21,22]. However, these analysis tools and procedures are generally qualitative and do not offer the necessary information to compute seismic losses and resilience. Still, they are useful to develop a preliminary mitigation strategy using, for instance, accident analysis and risk analysis tools [19].

Taking a step towards the quantification of seismic risk for community-critical infrastructure, research efforts are shifting towards a performance-based methodology [23]. The latter is systematically adopted for individual refinery assets, such as tanks [24–32], high-rise stacks [33–36], buildings supporting equipment [37–42], and pipe racks [43–49] among others. Regarding industrial facilities, research efforts have recently intensified, starting from the integration of seismic hazard into typical Quantitative Risk Analysis (QRA) [22,50]. Girgin and Krausmann [51] developed an online tool for the rapid risk assessment of NaTech events at local and regional scales. Bursi et al. [52] presented a probabilistic seismic analysis of an LNG subplant, employing detailed finite element modeling for the critical assets. Alessandri et al. [53] developed a detailed framework for the probabilistic analysis of process plants based on Monte Carlo simulations. Their analysis includes multiple accident chains, consequences analysis, and risk computation, all of which were tested on a tank farm. Caputo et al. [54] systematically reviewed the seismic QRA of chemical process plants. They concluded that the next required steps in the pertinent scientific field are the consistent handling of uncertainties, the introduction of temporal event sequence, the reliable estimation of loss functions, and the quantification of resilience. On account of the above, Caputo et al. [55] developed a methodology to estimate the seismic resilience of process plants, assessing the capacity and economic losses, as well as the time needed for recovery following earthquake events. Furthermore, Huang et al. [56] employed Monte Carlo simulation within QRA, accounting for alternative stress scenarios in a chemical tank farm, incorporating the equipment's importance level and the event trees of failures to eventually compute the probability of failures caused by domino effects. Corritore et al. [57] focused their research on identifying the most vulnerable (and critical) assets in major-hazard facilities in case of an earthquake to improve existing QRAs. Kalemi et al. [58] developed a framework for the probabilistic seismic resilience analysis of process plants that includes the process mapping, the definition of the initial plant capacity, the formulation of the plant recovery model, and the definition of a resilience index and economic loss model. Wang et al. [59] developed a quantitative assessment framework for the seismic resilience of petroleum depots by explicitly considering the interactions between the components and the subsystems with the overall system/facility. O'Reilly et al. [60] presented their work on a risk-aware navigation system within industrial plants subjected to earthquake-triggered NaTech events by incorporating the input from a grid of sensors (accelerometers, fiber optic sensors, and weather stations). Finally, Karastathis et al. [61] presented an early warning system for protecting oil refineries in case of an earthquake, using a network of accelerometers to detect earthquake events in the surrounding area and provide visual rapid assessment of the expected damages.

Owing to the above, it is evident that the research community has made decisive steps toward establishing a framework to compute the seismic resilience of process plants. Still, the following gaps in the existing literature can be identified: (1) lack of a framework that is suitable for examining an entire crude oil refinery as an integrated system, (2) lack of a transparent methodology for considering the impact that the failure of a particular asset could have on the functionality of the entire system, and (3) lack of a framework for assessing the operational status of the refinery.

To help foster further research in the field, the authors have recently formulated an open-data virtual crude oil refinery testbed, located in a high-seismicity region of Greece, to consequently develop and test system-level assessment methods [62]. The testbed includes the following: (a) all critical assets, the potential failure of which is prioritized according to their impact on plant functionality; (b) the overall layout of the refinery since the location of the individual assets is critical when examining cascading failures (currently out-of-scope of this study), i.e., the initiation of a fire and its propagation to other assets that may or may have not been damaged by the earthquake; and (c) the parameters that govern the response of tanks (e.g., size, fill ratio, and content density), as they largely determine the direct consequences and their cascading effects; for example, the approach to extinguishing a fire in a crude oil tank differs dramatically from that of a fire in a naphtha tank.

In partially addressing the aforementioned issues, the present study focuses on the operational status of the refinery to demonstrate its effect on seismic performance estimates. A series of realistic operation scenarios are developed per typical industrial practices and are analyzed to demonstrate the status of each asset. Moreover, preliminary seismic performance estimates are presented to demonstrate the effect of operational status and identify the most vulnerable asset in each case. The overall goal is to enhance the seismic resilience of refineries by setting the pathway for planning customized and business-like procedures for emergency response actions, as well as preventive measures that account for the actual operation status of the refinery. At the same time, the presented framework sheds light into the refinery sectors where it is more likely to be the onset of cascading failures due to a fire or an explosion as a result of the damages sustained by their most vulnerable assets per scenario.

2. Refinery testbed outline

As a basis, we employ the open-data testbed developed by the authors [62] to represent a typical mid-sized crude oil refinery. The process plant covers an area of $1850\text{m} \times 1250\text{m}$ and its plan view is illustrated in Figure 1. The core of the process plant is the refining unit areas, where all chemical and physical processes take place. In the remaining area, atmospheric liquid-storage tanks, spherical pressure vessels for storing gaseous fuel, such as butane and propane, and the main refinery flare are located. The complete catalog of the assets considered in the exposure model is shown in Table 1. The geometry, the dynamic characteristics, the numerical analysis results, and the fragility curves for all the considered assets are offered in a dedicated repository [63]. The development of the exposure model, which includes the most seismically vulnerable assets, was carried out using a spectrum of approaches, namely, numerical analysis results of assets, literature, and engineering judgment [62]. It should be noted that piping was not considered in the exposure model based on the following considerations: (a) buried steel piping primarily consists of straight segments that can be damaged by transient ground displacements caused by seismic wave propagation under certain conditions related to soil stratigraphy [64]. Uniform soil conditions have been assumed, and therefore, the potential failure of buried pipes due to seismic wave propagation has been excluded. It is important to note that the buried piping network of the refinery is not directly comparable to an urban gas distribution network, which covers a larger (city-level) area with varying geological conditions and is, therefore, more susceptible to seismic-induced permanent and transient ground displacements [65,66]. (b) Above-ground piping is typically supported by sleepers, with or without pendulum-type connectors, while expansion joints, U-type pipe loops, elbows, and bends provide the necessary flexibility for thermal expansion and contraction of the piping. The latter two conditions are more commonly associated with pipe damage. These configurations, along with the inherent flexibility of the piping, enable the system to undergo slight transverse and longitudinal displacements, usually allowing it to safely accommodate the displacements imposed by ground shaking.

The refinery is assumed to be located west of Athens, Greece, in a major industrial area. This area is within a high-seismicity region of Greece due to many active faults identified in the Corinth Gulf [67]. Using the 2013 European Seismic Hazard Model [68], the obtained seismic hazard curve for the site of interest is shown in Figure 2, having a 10% in 50yrs value of 0.36g. Uniform soil conditions have been assumed throughout the facility for the purpose of the test, allowing neglect the ground motion spatial variability, thus applying each ground motion as is to all refinery assets.

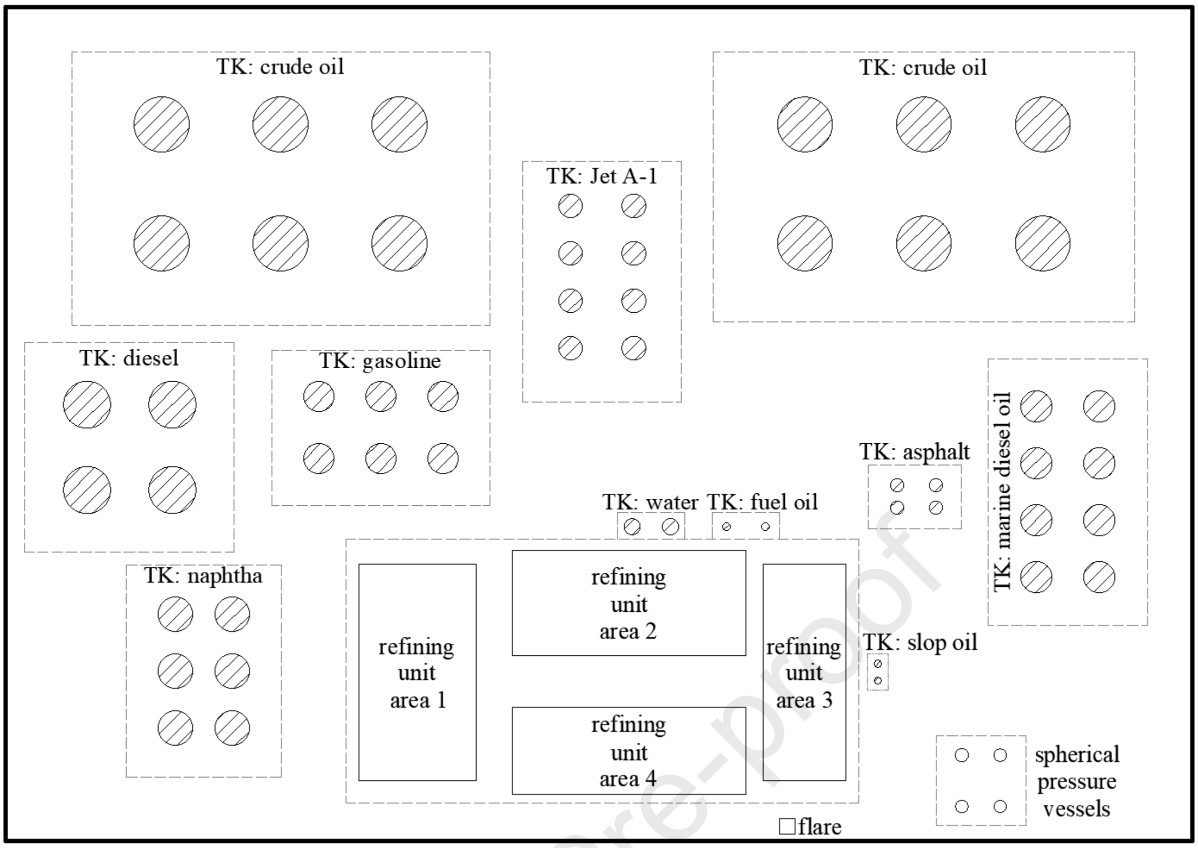

Figure 1: Plan view of the crude oil refinery testbed (adapted from [62]) [TK: liquid storage tanks].

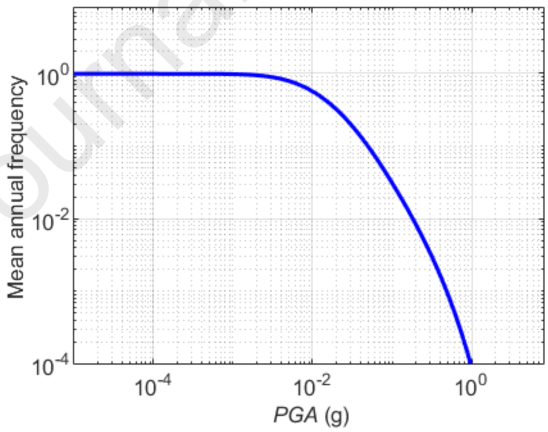

Figure 2: Seismic hazard curve at the refinery's site.

Table 1: Refinery structures considered in the exposure model of the refinery testbed

Storage assets	No. of assets	Process assets	No. of assets
Gasoline tank	6	Horizontal pressure vessel	8
Fuel oil tank	2	Vertical pressure vessel type CL1	12
Marine diesel oil tank	8	Vertical pressure vessel type CL2	8
Jet A-1 tank	8	Flare	1
Naphtha tank	6	1-story RC building	3
Crude oil tank	12	2-story RC building	17
Diesel tank	4	4-story RC building	7
Slop oil tank	2	1-story steel building	10
Liquid asphalt tank	4	2-story steel building	9
Water tank	2	Process tower	5
Spherical pressure vessel	4	30m steel chimney	3
		80m steel chimney	1
		RC chimney	1

The susceptibility of individual refinery assets to earthquake damage is identified via asset-specific damage states, which are denoted by lowercase letters "ds". However, the impact of an asset's failure – whether operational or structural – varies in significance concerning the overall operational integrity of the refinery. Therefore, it is required to homogenize the asset-level damage states into a set of refinery-level damage states, which are denoted by uppercase letters "DS" in order to accurately reflect their functional consequences. These five distinct global DSs, range from "none" to "severe" disruption and are listed in Table 2. For each DS, the operational status (in terms of functionality) is presented along with the expected extent of repairs that need to be undertaken for the damaged structures in the aftermath of an earthquake. The homogenization process has been carried out considering the following factors: (1) the significance of each asset in the refining process, (2) the potential business disruption consequences (such as downtime and cost) for the entire refinery, (3) the asset's location, (4) potential cascading effects from failure and the spread of damage due to loss of containment and subsequent fires, and (5) expert judgment. It is important to note that, given the significant operational interdependencies among assets and the complexity of the refining process, the failure of a single asset will affect the refinery's functionality, with the extent of the impact depending on a complex interplay of factors that cannot be quantified in this context.

It is noted especially that in case DS4 (severe level of disruption) is attained, the refinery may remain partially operational at low capacity while the damage is addressed, or slowly reduce operations in the process of being shut down. As a general remark, one should bear in mind that stopping the refining process takes a lot of time (in the order of a couple of days) and is a procedure with many inherent risks (e.g., fire, explosion, machinery failure, unexpected chemical reaction, etc.) as numerous complex physical and chemical procedures and reaction chains have to be terminated (e.g., [69,70]). In other cases, only an isolated part of a refinery may be damaged and other parts may keep operating at a minimum level. For example, let two or more liquid storage tanks be severely damaged in the aftermath of an earthquake. Assuming that they are located far away from the refining unit areas, the overall production of the facility is significantly reduced until the situation (e.g., material release, fire) is under control. The refinery personnel will need to take all the required measures to ensure the safety of the facility and will thus have to keep some equipment in operation, e.g., moving product away from the damaged areas or even sending it away from the facility via pipelines. Thus, occurrence of DS4 can lead to a multitude of operational outcomes that cannot be addressed without further case-specific analysis.

Table 2: Refinery global Damage States in terms of operational disruption as per [62]

Damage State	DS0	DS1	DS2	DS3	DS4
Level of disruption	None	Low	Moderate	Extensive	Severe
Operational status	–	Refinery is operational at almost 100% capacity	Refinery is operational with some parts at a reduced capacity	Refinery is partially operational at a reduced capacity	Refinery is partially operational at low capacity and may be shut down
Repairs required	–	Some assets require scheduling of minor repairs	Some assets require immediate major repairs	Some assets require extensive repairs	Many assets require extensive repairs and/or replacement

3. Refinery operation scenarios

The amount of fuel circulated, processed, and stored within the refinery is related to its operational status. It determines the behavior of the individual structures, essentially dividing them into two categories (Table 1), namely storage assets and refining process assets. In more detail:

- Storage assets include liquid storage tanks and spherical pressure vessels. They are characterized by their fill ratio (ranging from 0, in the case of empty assets, to 1, in the case of fully-filled assets), which dominates their structural/dynamic behavior [30,71]. It also determines the amount of flammable material available at the site. This is a crucial parameter for estimating any potential post-earthquake cascading consequences. Therefore, it is deemed necessary to account for the fill ratio of these assets in each considered alternative scenario for the operational status of the refinery.
- Process assets that are not related to the storage of final or intermediate fuel products (see Table 1) are characterized by a binary variable, describing whether they are in operation or not, depending on the scenario description.

To account for the effects of seasonality and periods of maintenance, six alternative operational scenarios are defined to characterize any day between (and including) major maintenance actions, so-called turnarounds of the refinery. They are summarized in Table 3 and are further detailed in the forthcoming sections.

Table 3: Refinery operational scenarios.

Scenario No	Description	Remarks
1	Typical day of the year	including minor maintenance
2	Refinery turnaround	major maintenance period
3.1	High-winter time	effect of seasonality
3.2	High-summer time	
4	Low-demand scenario	extreme scenario
5	Peak-demand scenario	extreme scenario

3.1. Scenario 1: Typical day of the year

The refinery operates under normal capacity within a typical day of the year. The fill ratio (FR) of the fuel storage assets in this scenario is presented in Table 4. Fuel storage assets undergo periodic maintenance every 10-15 years unless a non-seismic-related failure (e.g., leakage due to extensive corrosion of the steel shell, failure of connected equipment, etc.) is detected before the scheduled maintenance (see API STD 653:2014 [72]). The duration of this maintenance period is typically between 6 to 18 months, depending on the properties of the tanks (i.e., dimensions, material stored), the extent of any non-seismic damage detected, as well as any potential upgrade of the attached electrical, electronic, and mechanical equipment. Therefore, especially for a sizeable group of tanks where the same material is stored, it is reasonable to consider that within a typical day of the year, at least one tank undergoes maintenance. Furthermore, the following aspects are considered for setting the fill ratios of fuel storage assets:

- Regardless of the material stored, at least one or more tanks/vessels will be full for operational reasons. For example, stored material may be part of a selling contract to a designated customer.
- The level of water stored in TK-15 (see Table 4) tanks fluctuate continuously as water is used in the refining process.
- The level of slop oil stored in TK-13 (see Table 4) tanks fluctuate continuously, as slop oil is essentially a waste product of the refining process, which is stored temporarily in tanks before being sent to the biological cleaning unit for processing that removes environmentally harmful agents.
- The amount of material stored in the remaining tanks/vessels can be considered random since the refining process and selling of products via trucks, pipelines, and the marine terminal (if any) are continuously progressing.

Then, process assets are operational within a typical day of the year.

Table 4: Scenario 1 (typical day of the year): Fill ratios of storage assets.

ID	Product	Fill ratio (FR)	No. assets
TK-2	Gasoline	2 with 95%, 3 with random FR, 1 under maintenance	6
TK-3	Fuel oil	2 with random FR	2
TK-5	Marine diesel oil	2 with 95%, 5 with random FR, 1 under maintenance	8
TK-6	Jet A-1	1 with 95%, 6 with random FR, 1 under maintenance	8
TK-8	Naphtha	1 with 95%, 4 with random FR, 1 under maintenance	6
TK-9	Crude oil	3 with 95%, 8 with random FR, 1 under maintenance	12
TK-10	Diesel	1 with 95%, 3 with random FR	4
TK-13	Slop oil	2 with random FR	2
TK-14	Liquid asphalt	1 with 95%, 1 with random FR	2
TK-15	Water	2 with random FR	2
TK-16	Liquid asphalt	1 tank with random FR, 1 under maintenance	2
SPV	Butane & Propane	2 with 95%, 2 with random FR	4

TK: liquid storage tank (numbering refers to specific geometry and content type per [62,63])
SPV: spherical pressure vessel

As a remark, in the interval between two turnarounds, partial shutdown for periodic minor maintenance of one or two refinery processing units typically takes place with its duration ranging from 30 to 60 days. In such a case, the refinery functionality is slightly reduced but the rest of the units remain operational. Given the fact that data for the shutdown of individual refining units is not available and reasonable assumptions cannot be made, it is assumed that this partial shutdown can be folded into the randomness already assumed in Scenario 1, which represents a typical day of the year.

3.2. Scenario 2: Refinery turnaround

The refinery is shut down for major periodic maintenance, a procedure also called turnaround [73], which typically lasts about two months and takes place every three or four years [74,75]. Before a turnaround, process units are shut down sequentially for safety and operational reasons, and afterwards, they are also sequentially restarted. The capacity of the refinery during the turnaround period is minimal and a limited amount of fuel is circulated. In that sense, most of the fuel storage assets are full, as presented in Table 5, while a limited number of them with random FR indicate that the selling of products is still ongoing during the turnaround period, even at a reduced rate. It should be noted that the level of water stored in TK-15 and slop oil in TK-13 are considered random given that these tanks are part of the refining process. During the turnaround period, most of the processing assets will be out of order. Still, in case of an earthquake, these assets may be damaged. Essentially, in such a case, the "functionality disruption" presented in Table 2 will be considered as delays in restoring full operation of the refinery. For example, a catastrophic failure of the flare may not result in an explosion, fire, etc., because this asset would be out of order during said period. Still, significant delays would be expected in restarting the facility, signaling a severe functionality disruption.

Table 5: Scenario 2 (refinery turnaround): Fill ratio of storage assets.

ID	Product	Fill ratio (FR)	No. assets
TK-2	Gasoline	3 with 95%, 2 with random FR, 1 under maintenance	6
TK-3	Fuel oil	2 with random FR	2
TK-5	Marine diesel oil	5 with 95%, 1 with random FR, 1 with 35%, 1 under maintenance	8
TK-6	Jet A-1	3 with 95%, 2 with random FR, 2 with 35%, 1 under maintenance	8
TK-8	Naphtha	1 with 95%, 4 with 35%, 1 under maintenance	6
TK-9	Crude oil	6 with 95%, 3 with 35%, 2 with random FR, 1 under maintenance	12
TK-10	Diesel	2 with 95%, 2 with 35%	4
TK-13	Slop oil	2 with 35%	2
TK-14	Liquid asphalt	1 with 95%, 1 with 35%	2
TK-15	Water	2 with 95%	2
TK-16	Liquid asphalt	1 with 95%, 1 under maintenance	2
SPV	Butane & Propane	3 with 95%, 1 with 35%	4

TK: liquid storage tank (numbering refers to specific geometry and content type per [62,63])

SPV: spherical pressure vessels

3.3. Scenario 3: Effect of seasonality

Seasonality does affect the operation of the refinery mainly in terms of the fuel amount that is stored in tanks [76]. Considering that the examined refinery testbed is located in the northern hemisphere, the demand for Jet A-1, gasoline, diesel, and marine diesel oil is increased during summertime due to increased tourism and travel. On the contrary, during wintertime, the demand for diesel and LPG (stored in spherical pressure vessels) is higher due to the increased demand for heating. In general, the duration of the relative winter/summertime depends on the country/region. It should be noted that targeting a finer resolution about seasonal variations, e.g., to account for the effect of shorter holiday breaks, may be an intriguing but also challenging objective. To do so properly, would require monitoring, data from everyday operation, and a statistical analysis of the obtained facility-specific operational data for long periods of time, e.g., over a decade. It would also require removing the effect of external parameters that can influence oil prices, such as political decisions, conflict, increase or reduction of crude oil production, etc. (e.g., [77]). Such a type of analysis is currently out of the scope of the present study. Moreover, for the same reasons, the daily fluctuation of oil consumption (e.g., [78]), which is related to the amount of fuel exported from the refinery daily, is not considered. In that sense, a proxy is proposed to indirectly account for site/region-specific effects by employing expert opinion to adjust the percentage of high-winter/summer time.

Owing to the above, Scenario 3 is subdivided into two discrete cases, namely Scenario 3.1 for high-winter time and Scenario 3.2 for high-summer time. The fill ratio of storage assets for the high-winter and high-summer scenarios are listed in Table 6 and Table 7, respectively, indicating the high variation of fill ratios due to the high demand. Finally, the process assets are typically operational.

Table 6: Scenario 3.1 (high-winter time): Fill ratios of storage assets.

ID	Product	Fill ratio (FR)	No. assets
TK-2	Gasoline	3 with 95%, 2 with random FR, 1 under maintenance	6
TK-3	Fuel oil	2 with random FR	2
TK-5	Marine diesel oil	3 with 95%, 4 with random FR, 1 under maintenance	8
TK-6	Jet A-1	4 with 95%, 3 with random FR, 1 under maintenance	8
TK-8	Naphtha	3 with 95%, 3 with random FR	6
TK-9	Crude oil	5 with 95%, 6 with random FR, 1 under maintenance	12
TK-10	Diesel	1 with 95%, 3 with random FR	4
TK-13	Slop oil	2 with random FR	2
TK-14	Liquid asphalt	1 with 95%, 1 with random FR	2
TK-15	Water	2 with random FR	2
TK-16	Liquid asphalt	1 with 95%, 1 with random FR	2
SPV	Butane & Propane	1 with 95%, 3 with random FR	4

TK: liquid storage tank (numbering refers to specific geometry and content type per [62,63])
SPV: spherical pressure vessels

Table 7: Scenario 3.2 (high-summer time): Fill ratios of storage assets.

ID	Product	Fill ratio (FR)	No. assets
TK-2	Gasoline	1 with 95%, 5 with random FR	6
TK-3	Fuel oil	2 with random FR	2
TK-5	Marine diesel oil	1 with 95%, 7 with random FR	8
TK-6	Jet A-1	1 with 95%, 7 with random FR	8
TK-8	Naphtha	1 with 95%, 5 with random FR	6
TK-9	Crude oil	3 with 95%, 8 with random FR, 1 under maintenance	12
TK-10	Diesel	1 with 95%, 3 with random FR	4
TK-13	Slop oil	2 with random FR	2
TK-14	Liquid asphalt	1 with 95%, 1 with random FR	2
TK-15	Water	2 with random FR	2
TK-16	Liquid asphalt	2 tanks with random FR	2
SPV	Butane & Propane	2 with 95%, 2 with random FR	4

TK: liquid storage tank (numbering refers to specific geometry and content type per [62,63])
SPV: spherical pressure vessels

3.4. Scenario 4: Low-demand scenario

Apart from the typical scenarios of the refinery operation examined in Sections 3.1–3.3, it is worth considering an extreme scenario, where the production of the refinery is significantly slowed down due to reduced demand. The latter could be attributed to very high oil prices (e.g., energy crisis) or government-enforced restrictions to travel and transportation (e.g., lockdown due to a pandemic [79]). In such a case, most of the storage assets are expected to be full (Table 8) and thus more vulnerable to earthquake-induced damage [62,71]. Finally, the refinery process assets are typically operational, although the entire production of the refinery is reduced to a mere minimum, due to low demand for oil products.

Table 8: Scenario 4 (low demand scenario): Fill ratio of storage assets.

ID	Product	Fill ratio (FR)	No. assets
TK-2	Gasoline	5 with 95%, 1 with random FR	6
TK-3	Fuel oil	2 with random FR	2
TK-5	Marine diesel oil	6 with 95%, 1 with random FR, 1 under maintenance	8
TK-6	Jet A-1	6 with 95%, 1 with random FR, 1 under maintenance	8
TK-8	Naphtha	4 with 95%, 1 with random FR, 1 under maintenance	6
TK-9	Crude oil	9 with 95%, 2 with random FR, 1 under maintenance	12
TK-10	Diesel	3 with 95%, 1 with random FR	4
TK-13	Slop oil	1 with 95%, 1 with random FR	2
TK-14	Liquid asphalt	1 with 95%, 1 with random FR	2
TK-15	Water	2 with random FR	2
TK-16	Liquid asphalt	2 with 95%	2
SPV	Butane & Propane	2 with 95%, 2 with random FR	4

TK: liquid storage tank (numbering refers to specific geometry and content type per [62,63])
SPV: spherical pressure vessels

3.5. Scenario 5: Peak-demand scenario

A peak-demand scenario is also examined. In such a case, the refinery production capacity is increased to maximum (above normal capacity) to meet the increased market demand (e.g., post-COVID19 era [80,81]). To that effect, the fill ratio of the tanks can be considered to be mostly random (see Table 9), as fuel batches move rapidly through the refinery, filling up and emptying tanks in a (seemingly) random fashion. Finally, the refinery process assets are typically operational.

Table 9: Scenario 5 (peak-demand scenario): Fill ratios of storage assets.

ID	Product	Fill ratio (FR)	No. assets
TK-2	Gasoline	1 with 95%, 4 with random FR, 1 under maintenance	6
TK-3	Fuel oil	2 with random FR	2
TK-5	Marine diesel oil	1 with 95%, 6 with random FR, 1 under maintenance	8
TK-6	Jet A-1	1 with 95%, 6 with random FR, 1 under maintenance	8
TK-8	Naphtha	1 with 95%, 5 with random FR	6
TK-9	Crude oil	2 with 95%, 9 with random FR, 1 under maintenance	12
TK-10	Diesel	1 with 95%, 3 with random FR	4
TK-13	Slop oil	2 with random FR	2
TK-14	Liquid asphalt	2 with random FR	2
TK-15	Water	2 with random FR	2
TK-16	Liquid asphalt	1 with 95%, 1 with random FR	2
SPV	Butane & Propane	2 with 95%, 2 with random FR	4

TK: liquid storage tank (numbering refers to specific geometry and content type per [62,63])
SPV: spherical pressure vessels

3.6 Refinery operation schedule

The examined crude oil refinery testbed is located in Greece, a typical Mediterranean country, where the weather conditions and local economy influence which of the scenarios shown in Table 4 – Table 9 is active at any given time. Scenarios 1 to 3 are related to the "typical" operation of the plant, while extreme Scenarios 4 and 5 cannot be included in the typical annual operation schedule and are separately examined. Such a schedule is illustrated in Figure 3 and spans over a 5-year timeframe, where the 4-year time interval between two successive refinery turnarounds appears. It should be noted that for operational reasons, the refinery turnaround in the considered oil refinery testbed takes place in October and November, i.e., between the high-summer and high-winter time periods. Moreover, the high-summer/winter periods are considered to last roughly 3 months each in the Mediterranean latitudes, with potential modifications in the future due to the effect of climate change. The peak- and low-demand scenarios, i.e., Scenarios 4 (Table 8) and 5 (Table 9), respectively, are treated as random. In other words, it is assumed that there is no *a priori* knowledge of the occurrence of peak or low demand in the refinery operation. The extreme Scenario 4 of low demand is assumed to occur at any time over the entire year with a 1% probability; the period of refinery turnaround is excluded, since turnaround is scheduled and executed typically outside the peak demand periods. Contrarily, the extreme Scenario 5 of peak demand is assumed to only occur during the high-winter or high-summer time with a 5% probability. Therefore, Scenario 5 is limited to appearing within the 6 peak months of every year, obviously without coinciding with refinery turnarounds. It should be noted that the probabilities of occurrence for extreme Scenarios 5 and 6 are assumptions that have been defined based on expert opinion.

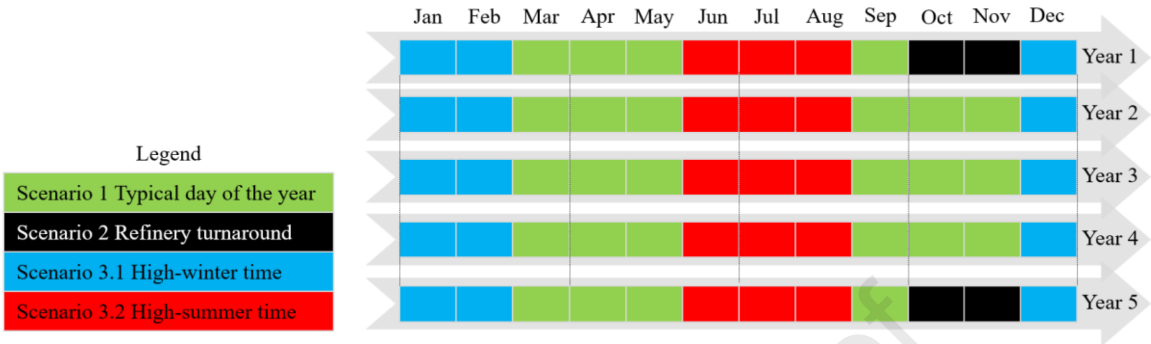

Figure 3: Typical refinery operation time schedule.

The consideration of the operational scenarios allows a fine-grained understanding of the expected status of the refinery assets in the aftermath of an earthquake event. Such detailed information is useful for developing plans and mitigation actions. Still, refinery stakeholders and operators are also interested in seismic risk estimates that are time/scenario-agnostic in the sense that they are not tied to a specific period of the year or corresponding operation scenario. This coarse-grained long-term view of the refinery can be useful for insurance purposes [82]. In that sense, the individual scenarios are aggregated into an "average" year using appropriate annualized weights (AW) that are derived from the typical schedule of the plant (Figure 3) on the 4-year time period that includes a turnaround. It should be noted that AWs are not logic tree weights and are not related to any Bayesian or subjective probability. Actually, AWs represent the annualized probability of scenario occurrence and are listed in Table 10, along with the respective calculation formula. Specifically, 2 months out of 48 are set aside for turnarounds in every four-year period, thus leaving 46 months to be distributed between the remaining five scenarios. In more detail, for the low-demand scenarios, a 1% probability of occurrence over 46 out 48 months (2 months or turnaround are excluded) yields a computational number of months equal to $0.01 \times (48 - 2) = 0.46$. For the high-demand scenario, a 5% probability of occurrence is considered within the 6 months of winter/summer-time per years, this resulting to a computation number of months equal to $0.05 \times 6 \times 4 = 1.20$. Regarding the typical day, we have 6 months per year from (2 months of turnaround are excluded) which the months of the low-demand scenario (corresponding to the typical day and excluding the high-winter/summer time) have to be deducted, thus resulting to $[(6 \times 4) - 2] - 0.46/2 = 21.77$. The computation months for the refinery turnaround period equal the actual months within the 4-year period, i.e., 2 months. The computational months for the high-winter time equal the ones for the high-summer time. For scenarios 3.1 and 3.2 respectively, we have 3 actual months per year from which those corresponding to low and peak demand are deducted, thus resulting in $(3 \times 4 - 1.20/2 - 0.46 \times 3/12) = 11.285$. Finally, the computational number of months per scenario in the 4-year period is divided by the actual total number of months for this period, namely 48 months, to compute the annualized weight.

Table 10: Annualized weights (AWs) of scenarios.

Scenario	Normalized	AW
1 Typical day	21.77/48	0.4535
2 Refinery turnaround	2/48	0.0417
3.1 High-winter time	11.285/48	0.2351
3.2 High-summer time	11.285/48	0.2351
4 Low-demand	0.46/48	0.0096
5 Peak-demand	1.20/48	0.0250
	Total	1.0000

4. Methodology

The refinery status in the aftermath of an earthquake is examined by employing the seismic fragility curves of the individual assets (see Section 2); the corresponding analytical fragility curves are offered in the dedicated repository [63] for all assets under examination [62]. Fragility is defined as [83,84]:

$$F_{LS}(IM) = P[LS \text{ violated}|IM] = P[D > C_{LS}|IM] \quad (1)$$

In Equation (1), F_{LS} is the cumulative distribution function, D is the EDP demand and C_{LS} is the EDP capacity threshold paired to a specific Damage State (DS). Using this definition and in an attempt to demonstrate the effect of alternative fill ratios on the seismic fragility of storage assets, the fragility curves of liquid storage tank TK-5 are indicatively presented in Figure 4. As expected, the higher the fill ratio (FR), the higher the susceptibility to the seismically-induced damage. Similar conclusions hold for a spherical pressure vessel (Figure 5).

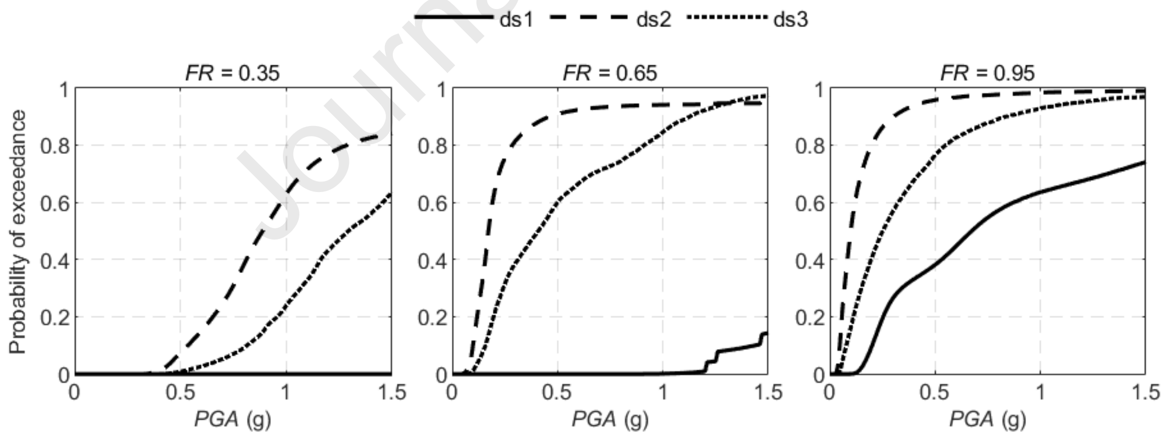

Figure 4: Liquid storage tank TK-5: Fragility curves for different fill ratios where ds denotes the asset-specific damage state. The ds2 fragility does not necessarily reach 100% as the corresponding EDP (base plate plastic rotation) saturates, a feature of the unanchored system where the "base plate plastic rotation" demand does not present a notable increase with increasing uplift (or seismic intensity) [30,32]. General note: damage states of liquid storage tanks are neither sequential nor mutually exclusive; this means that these damage states can be verified simultaneously in a tank after an earthquake.

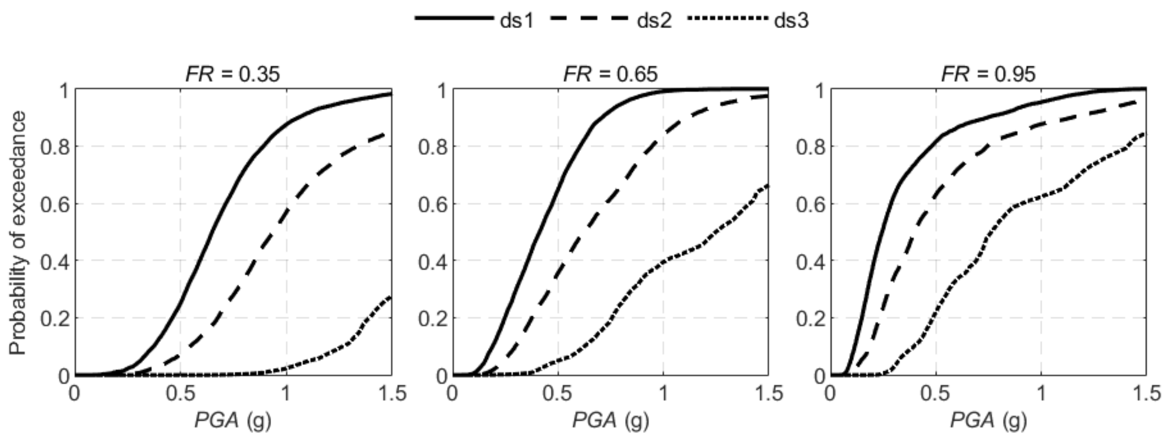

Figure 5: Spherical pressure vessel: Fragility curves for different fill ratios, where ds denotes the asset-specific damage state.

The intensity measure (IM) allows the seamless flow of seismic intensity information for the seismic hazard analysis to the structural analysis. It serves as an interface variable between seismology and structural engineering. Several metrics are available in the literature to be considered as IMs; they can be divided into two broad categories, namely asset-aware (e.g., spectral accelerations) and asset-agnostic (e.g., peak ground acceleration), either scalar or vector. In this study, a facility-wide application is presented; hence the selected IM should cover a spectrum of assets with essentially different geometric and dynamic properties. Using structure-specific IMs for each considered asset (with potentially increased efficiency and sufficiency) would lead to the formulation of a rather complicated and even impractical risk assessment framework for the refinery as an integrated system, at a minimum requiring vector hazard analysis[85]. Two IMs are proposed for the facility-level application: (1) the average spectral acceleration over a range of periods, AvgSA, i.e., a moderately asset-aware IM, and (2) the Peak Ground Acceleration, PGA [37,86] that is adopted as being familiar to most operators.

The plant's condition is evaluated at four distinct levels of PGA, namely 0.08g, 0.16g, 0.24g, and 0.36g. The three latter levels correspond to the EN 1998 (Eurocode 8) PGA design values for Significant Damage (10% probability of exceedance in 50 years) for the three seismic zones of Greece, while the lowest level is equivalent to the Damage Limitation (50% probability of exceedance in 50 years) for the lower PGA value of 0.16g, being actually 50% of it.

Per the assigned fragilities, each asset has a distinct probability of being in each asset-specific ds. For example, the results for an almost full ($FR = 0.95$) liquid storage tank TK-5 are illustrated in Figure 6 for the four IM levels considered. For this FR, it is ds2 that has the highest probability of occurrence in all cases. This is the "most probable damage state" and, after being homogenized into the five global DSs of Table 2 (see [62]), it is adopted as a simple metric to help visualize the impact of each IM level on individual assets.

Finding the most probable DS is straightforward for process assets, contrary to storage assets with random FR. In other words, a single fragility curve per damage state is available for each process asset (e.g., chimney, building, flare, etc.). Contrarily, N alternative fragility curves per damage state are available for each storage asset, where N equals the number of fill ratios examined. For the sake of homogeneous visualization, the combined fragility approach [71] was adopted, assuming equal weights for the different fill ratios due to the lack of better information that would have allowed a more elaborate treatment. In more detail, for a given IM level, the probability of a certain DS occurring is obtained from the partial fragilities (each corresponding to a single FR). Then, the mean probability for this DS is computed from all FRs considered. This process is carried out for all 5 DSs. The most probable DS is the one with the highest probability. It is noted that tanks under maintenance are by definition expected to be in DS0, because in general lower FR leads to a lower probability of failure (e.g., [30,62,71]). Finally, note that this visualization approach will assign the same DS to all similar structures (i.e., those having the same fragility). This is not necessarily realistic unless there is a high correlation among said structures. One should interpret such visualization results with care, treating them only as indicative of a "most probable" behavior that may never happen.

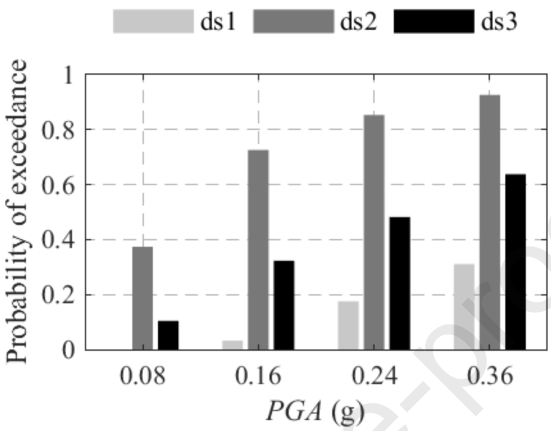

Figure 6: Liquid storage tank TK-5 with $FR = 0.95$: Probability of exceeding asset-specific damage states (ds) for predefined levels of seismic intensity.

5. Results and discussion

5.1 Scenario results

An aggregated approach is adopted to evaluate the performance of the refinery: For each operational scenario and IM level, the most probable DS for each asset is identified and then all assets of the same DS are binned together. The results are presented in Figure 7 for all scenarios, where the percentage of assets in each DS is presented on the horizontal axis for the four considered IM levels, which are shown on the vertical axis. As expected, increasing the IM level results in an increase of assets being in higher DSs. Overall, the worst-case scenario is Scenario 4 (low-demand) since the majority of storage assets are more or less full and consequently more vulnerable to seismically-induced damage. Within the same concept, Scenario 2 (refinery turnaround), 3.1 (high-winter time), and 4 (low demand) are characterized by an increased percentage of assets in DS4 (severe level of disruption), which is mainly attributed to the number of fuel storage assets being full. The number of assets in DS1 (low level of disruption) and DS2 (moderate level of disruption) is limited; this is indicative of the narrow window of intensities that can result in such intermediate levels of damage or disruption, as most assets tend to have non-trivial consequences when damaged [62].

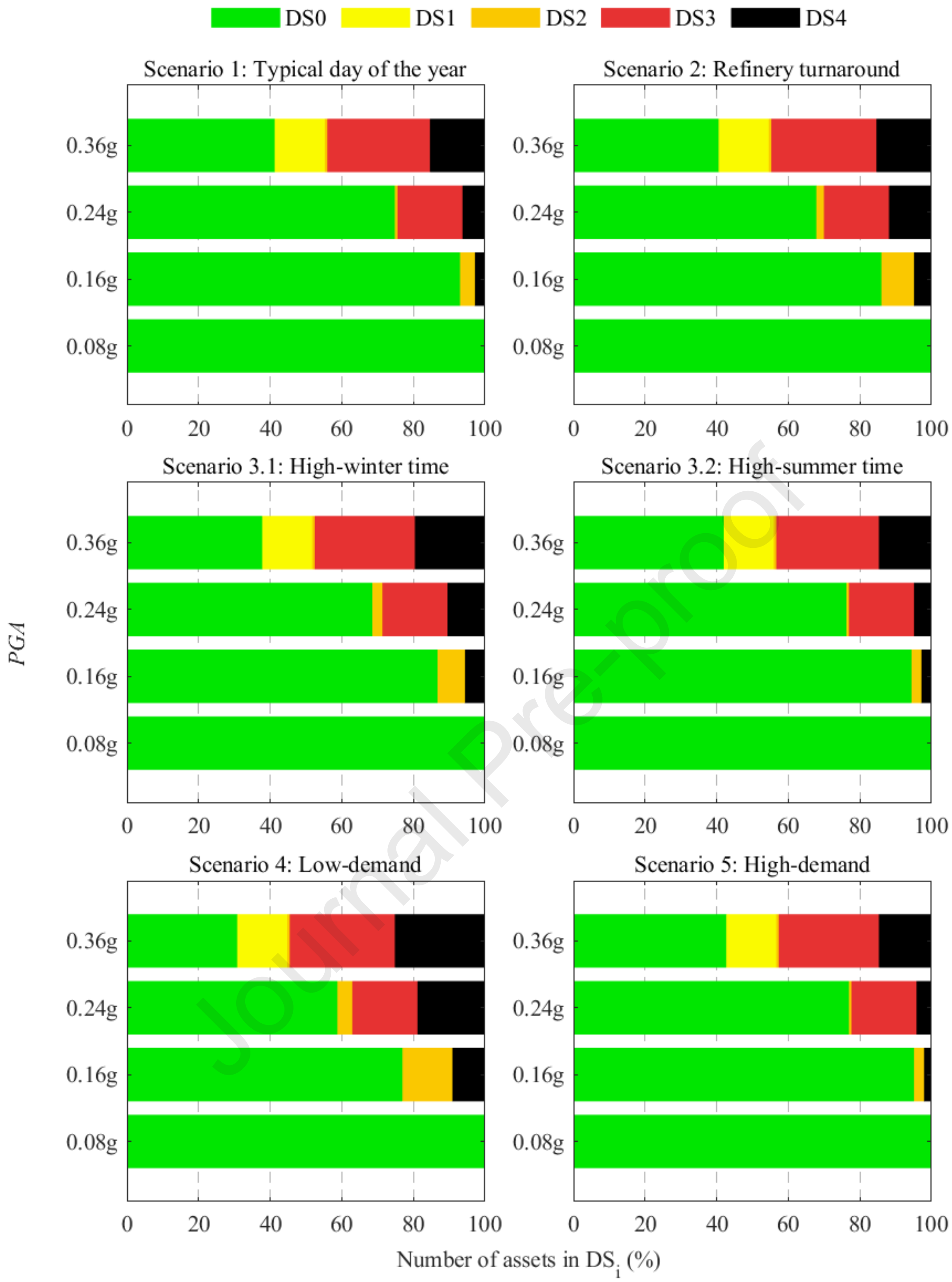

Figure 7: Percentage of assets in each damage state per scenario for increasing levels of PGA.

The aggregated results presented in Figure 7 can offer more clarity when viewed in terms of DS maps. As an all-green map would be rather uninformative, we skip the lowest PGA level of 0.08g, and turn to the moderate PGA of 0.16g and the "beyond-design" value of 0.36g. The respective refinery plan views of the most probable DS for Scenario 1 appear in Figure 8 and Figure 9.

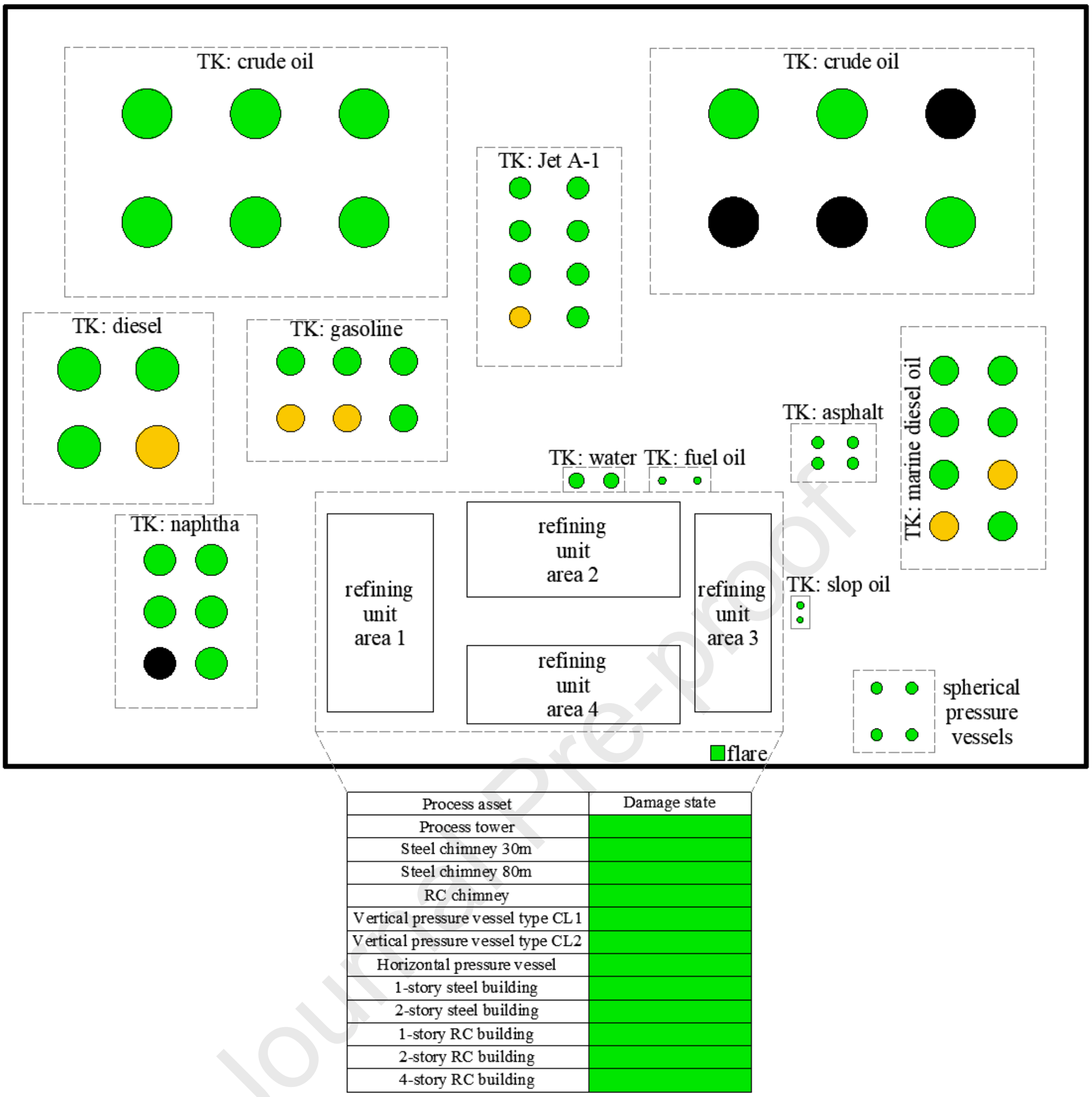

Figure 8: Scenario 1 (typical day of the year): Most probable DS of assets for $PGA = 0.16$g [DS0: green, DS1: yellow, DS2: orange, DS3: red, DS4: black].

For an earthquake event with $PGA = 0.16$g (Figure 8) only liquid storage tanks and in particular one naphtha tank and three crude oil tanks are expected to sustain significant damage, while one diesel, two gasoline, and two marine diesel oil tanks are expected to sustain minor damage. Contrarily, no damage is expected within the refining unit areas. Therefore, for this moderate level of seismic intensity within a typical day of refinery operation, one can expect having few tanks that have been damaged with potential loss of containment and triggering of cascading adverse effects, such as a pool fire. If no fire or explosion occurs, any fuel leakage and consequent spills are expected to be contained within the containment berm surrounding each tank [87]. For an earthquake event with an increased intensity, i.e., $PGA = 0.36$g, a large number of assets is expected to suffer significant damage (Figure 9) including several storage and process assets. It is important to identify that (a) two spherical pressure vessels are damaged, which increases the potential for explosion due to the stored high-pressure gas and (b) a lot of equipment is damaged in the equipment-supporting buildings. In the latter case, numerous processes are interrupted and the refining chain is severely broken, while leakage and fire may break out from failed piping that is attached to the equipment.

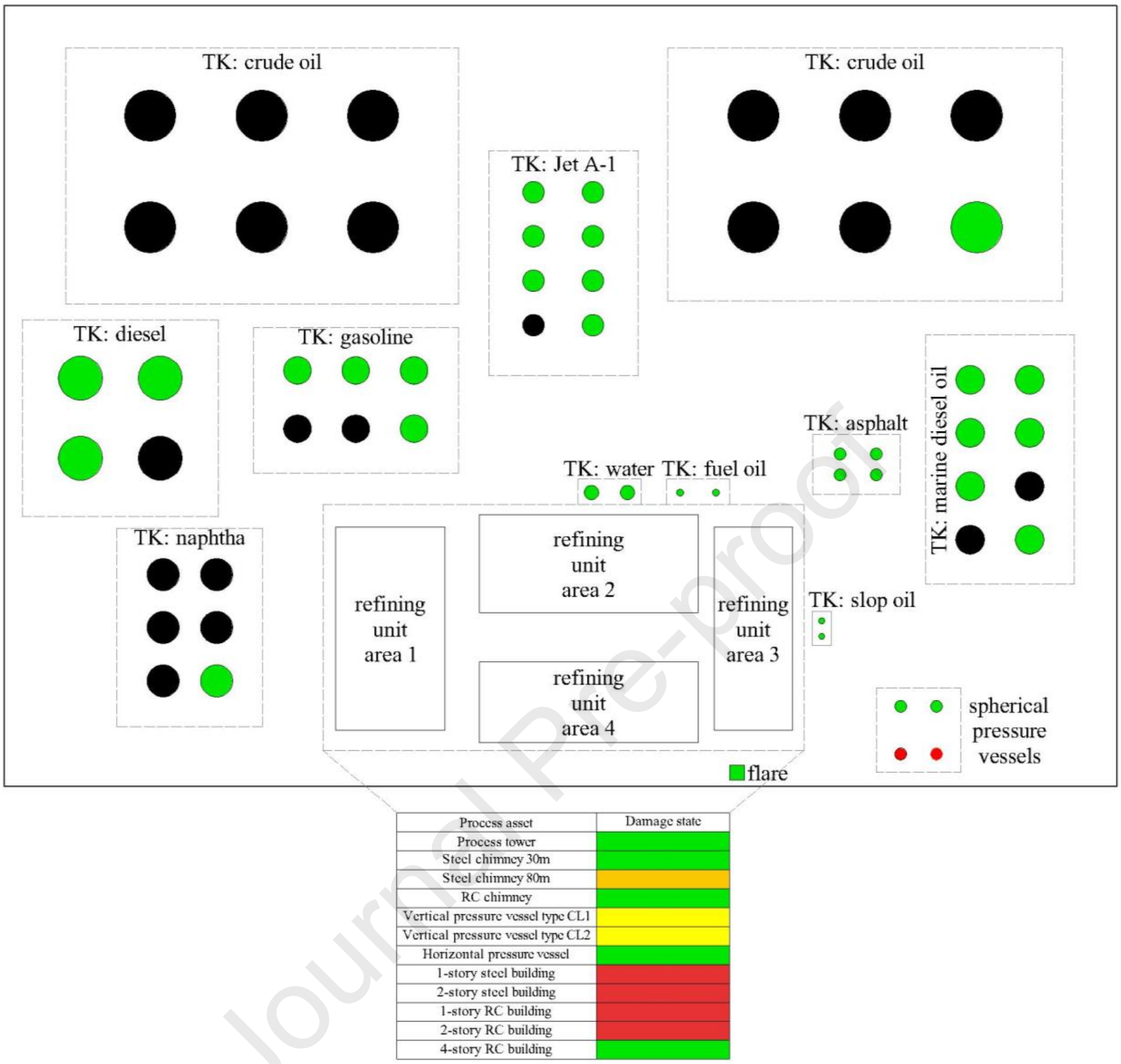

Figure 9: Scenario 1 (typical day of the year): Most probable DS of assets for $PGA = 0.36$g [DS0: green, DS1: yellow, DS2: orange, DS3: red, DS4: black].

The distribution of the failed or non-failed assets within the plant in case of an earthquake event during the refinery turnaround is shown in Figure 10 considering a seismic event with a $PGA = 0.16$g and in Figure 11 for a seismic event with a $PGA = 0.36$g. As discussed in Section 3.2, during the turnaround period many storage assets are full (Table 5) and consequently a lot more assets are expected to sustain damage compared to the typical day scenario (Figure 8). This situation is significantly intensified for increased levels of seismic intensity, i.e., $PGA = 0.36$g, as shown in Figure 11. The failure of multiple tanks inevitably increases the potential for catastrophic events, such as explosions, pool fires, and flush fires due to fuel leakage from tanks. It should be noted that the failure or not of the process assets depends only on the seismic intensity level, regardless of the operational scenario and therefore the same conclusions are drawn for Scenarios 1 and 2 per IM level.

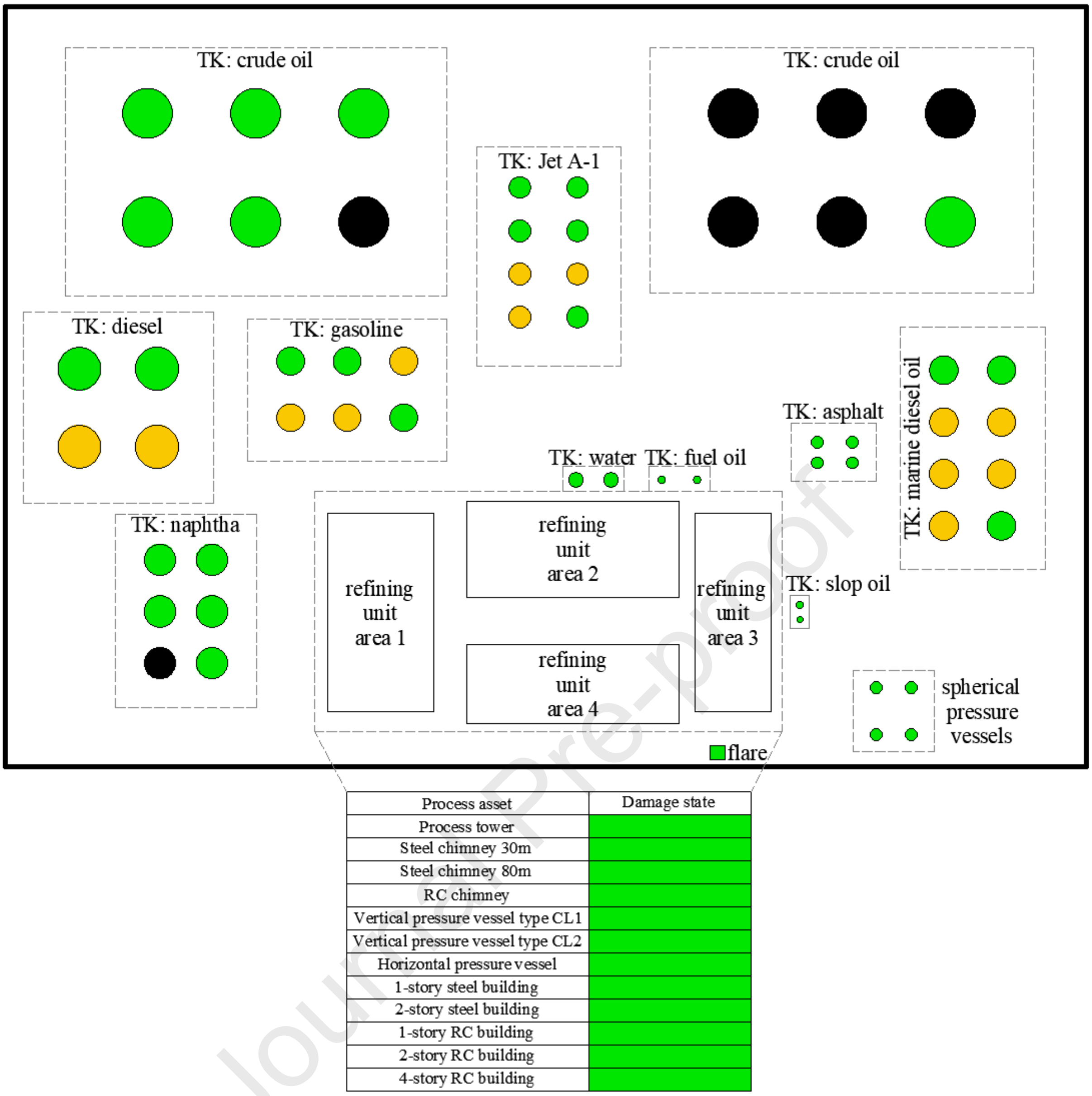

Figure 10: Scenario 2 (refinery turnaround): Most probable DS of assets for $PGA = 0.16$g [DS0: green, DS1: yellow, DS2: orange, DS3: red, DS4: black].

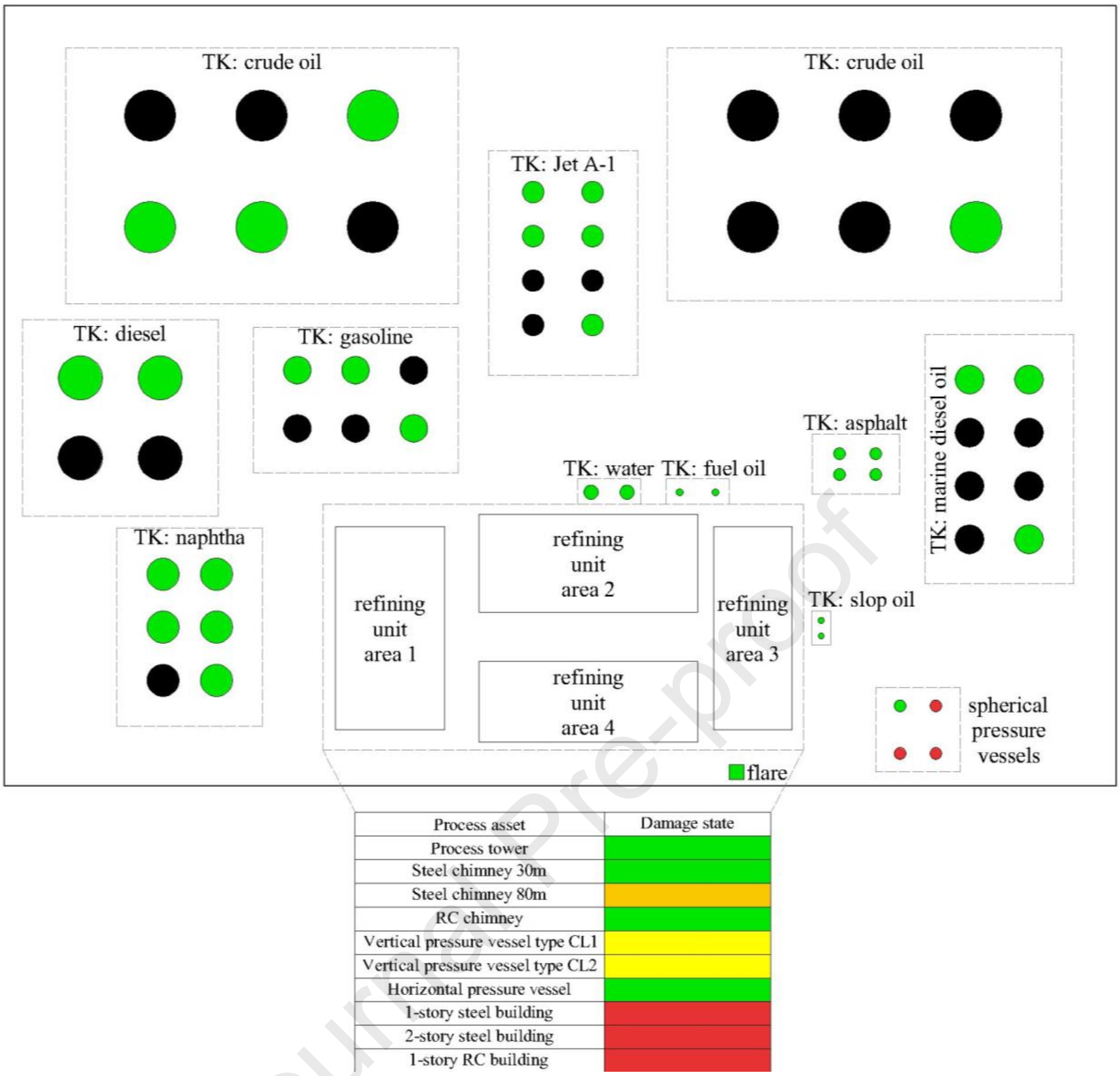

Figure 11: Scenario 2 (refinery turnaround): Most probable DS of assets for $PGA = 0.36$g [DS0: green, DS1: yellow, DS2: orange, DS3: red, DS4: black].

5.2 Combination of scenarios and typical approaches

Given the nonlinear nature of the consequences of asset damage, we contend that the superior approach is the direct consideration of individual operational scenarios. For maximum accuracy, the combination of the respective consequences should only be performed downstream, per refinery realization, and on an event-by-event basis, e.g., within the context of event-based probabilistic seismic hazard analysis [88]. Still, one has to recognize that this cannot be the norm in resource-constrained risk assessment studies. There is still some value to having an “averaged” combined scenario using the annualized weights (see Table 10) to provide (approximate) “averaged” estimates in a time-less and scenario-less manner about the expected number of assets in each damage state. Such summarized results can still help stakeholders plan emergency response and prioritize rehabilitation actions. The respective combined estimates are illustrated in Figure 12. In comparison to Figure 7, Scenarios 1 and 3 now dominate the results because their time span is the longest within the refinery schedule. Still, one should not focus on just the grand picture presented by such summarized graphs. It is not only the number of damaged assets but also their location and type; despite the homogenization of the DSs employed, some assets may still lead to significant downtime and monetary losses when considering cascading events at the facility level (e.g., [89,90]). Finally, note that one can also generate a map of the most probable DS for the combined scenario, similar to the ones of Figure 8 to Figure 11. As long as it is understood that this would be a composite of multiple actual realizations, with little chance of it ever actually occurring, it can still serve as a useful "heatmap" for weak spots. For reasons of brevity, it is not shown herein.

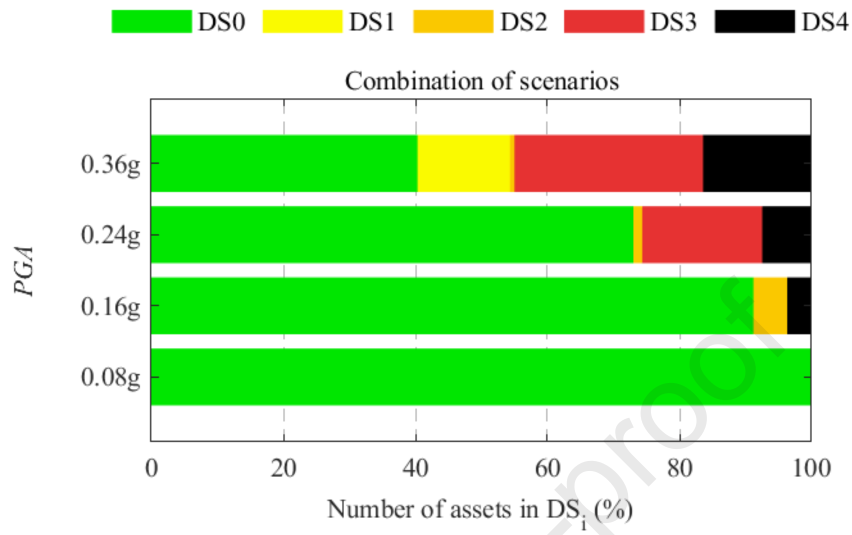

Figure 12: Weighted average percentage of assets in each damage state for all scenarios for increasing levels of PGA.

After examining the effect of the operational status of the refinery on the seismic performance estimates, it is worth comparing the results with the typical approach of a uniform fill ratio (e.g., [55,58]). To do so, two options are considered regarding the fill ratio of storage assets, namely a uniform FR at 65% and at 95%, i.e., storage assets are considered all to be either above half-full or almost full. High FR values are often adopted for reasons of conservativeness, with 95% being a usual choice by virtue of reflecting the worst-case scenario.

The comparison between the combined-scenario variable-FR Operational Approach and the typical uniform-FR approaches appears in Figure 13 for $PGA = 0.16\text{g}, 0.24\text{g}$, and 0.36g. As expected, regardless of the PGA level, considering a (high) uniform FR leads to an overestimation of damage. In case of $FR = 0.95$, few undamaged assets (DS0) are observed, while there is an overestimation of severe failures (DS3 & DS4). For $FR = 0.65$, an increased number of assets in DS2 is observed, while failures (DS4) are underestimated for lower PGA values. In general, there is no "perfect" uniform FR value one can employ. Moreover, this comparison illustrates that, for frequent events of low seismic intensity, considering a uniform FR for storage assets can lead to more conservative damage estimates that may affect the insurance cost of the process plant.

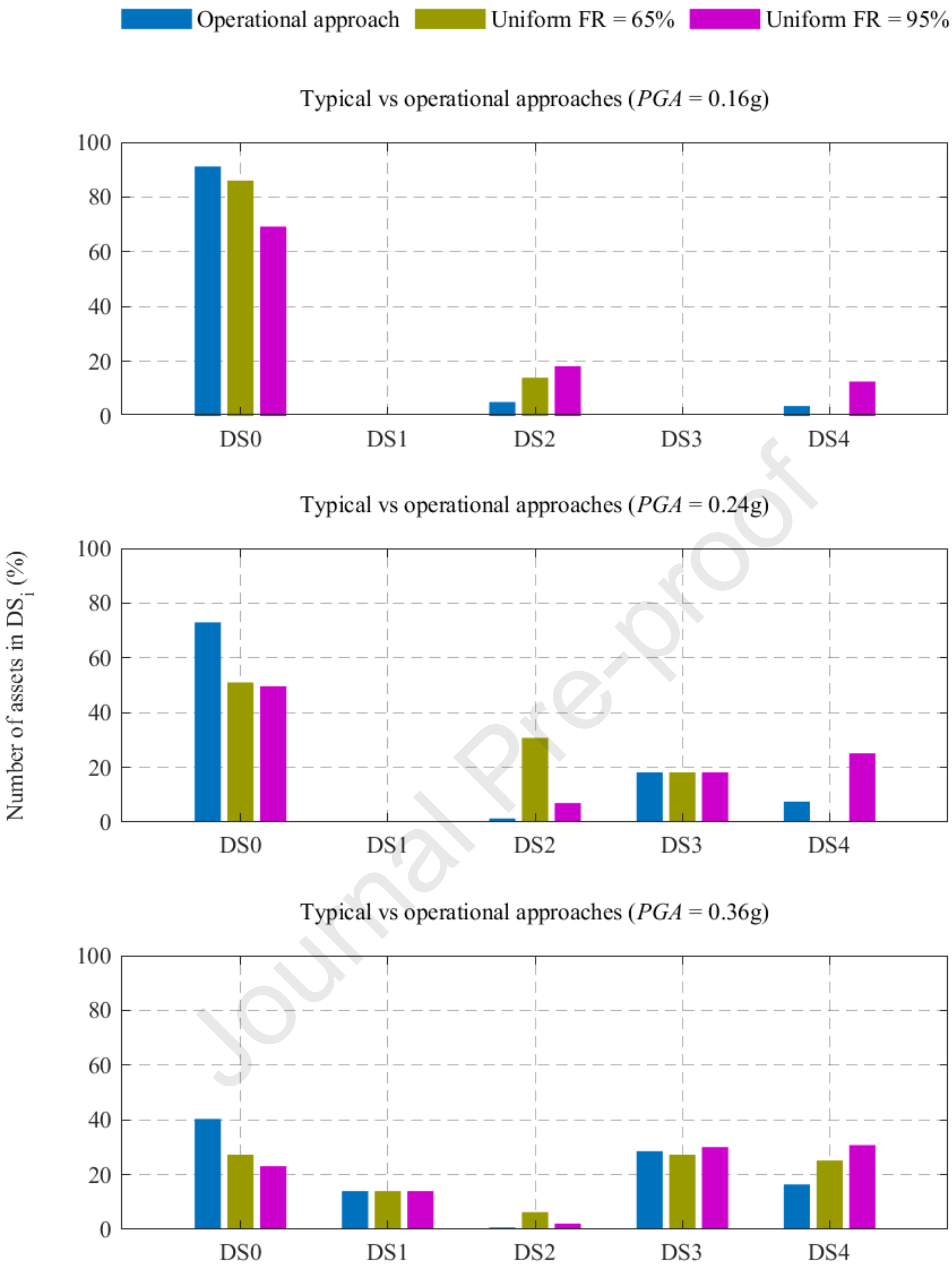

Figure 13: Number of assets (%) in each DS for increasing levels of PGA: Comparison of the combined-scenario operational approach to typical approaches with uniform fill ratio of storage assets.

6. Conclusions

The reliable estimation of seismic risk and resilience of oil refineries is essential to ensure their operability in the aftermath of an earthquake event, to set insurance premiums, and to develop, upgrade, and update emergency response plans. To do so, an open-data testbed developed by the authors [62] has been used to consider the actual operational status of the plant. Alternative scenarios are considered accounting for the effect of seasonality, periods of low and high demand, as well as periods of maintenance. These may not affect the behavior of assets associated with the refining process, but invariably determine the (distribution of) fill ratio for fuel-storage assets, which are typically the ones that carry the more severe cascading consequences.

Although cascading damages and domino effects are not addressed per se, their initiating events are studied in detail. Overall, the effect of the plant's operational status is substantial, as it largely determines the number, type, and location of assets that are expected to fail due to the ground shaking. The distribution of asset failure within the refinery plan offers an insight into the locations where cascading failures may be triggered and assists stakeholders in developing customized plans and businesslike procedures for emergency response actions and preventive measures. Moreover, the comparison of operational status results to the typical assessment approaches, where all storage assets are considered to be full or have a conservative uniform fill ratio, demonstrates that the latter approach leads to an excessive estimate of damage and it certainly cannot reflect the refinery's actual vulnerability. As a final remark, the results may not be directly applicable to other refining facilities, but the concept is. The aim and core novelty of the study is the introduction of the refinery operational status concept, which cannot be discounted when performing a comprehensive seismic risk assessment study for such critical facilities. Furthermore, open analysis data published by the authors for typical refinery structural systems [62,63] enable the combination thereof to study cascading effects and form alternative case studies in the future.

CRediT authorship contribution statement

V.E. Melissianos: Conceptualization, Methodology, Data curation, Supervision, Validation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **N.D. Karaferis**: Conceptualization, Validation, Formal analysis, Data curation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **K. Bakalis**: Conceptualization, Formal analysis, Data curation, Validation, Writing – review & editing. **A.K. Kazantzi**: Conceptualization, Validation, Formal analysis, Data curation, Supervision, Writing – review & editing. **D. Vamvatsikos**: Conceptualization, Validation, Methodology, Project administration, Supervision, Writing – review & editing, Funding acquisition.

Declarations of Conflicting Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Deployment and Assessment of Predictive modelling, environmentally sustainable and emerging digital technologies and tools for improving the resilience of IWW against Climate change and other extremes” under Grant Agreement No. 101069941.

Data availability

Source data is available at https://doi.org/10.5281/zenodo.11419659. Data generated in this study will be made available upon reasonable request.

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Operational Status Effect on the Seismic Risk Assessment of Oil Refineries

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Declarations of Conflicting Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.