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Safety in container terminal facilities: two different complementary Approaches to estimate the Consequences of the leakage of Flammable Substances

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ABSTRACT

A very important issue for people involved in safety assessment to understand is the difference between what could happen after the failure of a containment system that causes the release – because of the failure itself – of a flammable substance, and what should be considered as an always present risk, also during normal conditions, without any evident failure. The scope of this article is to explain two approaches (one for each case) whose aim is totally different but if developed together it could help to reach a higher level of safety. Each approach will be applied to a different Italian container terminal facility.

1 INTRODUCTION

Container terminals are pivotal nodes in global trade, facilitating the movement of goods across continents. The handling and storage of flammable substances within these facilities present significant safety challenges, necessitating robust risk assessment and management strategies. Understanding the potential consequences of containment failures and the inherent risks during normal operations is essential for developing effective safety protocols. This study explores two complementary approaches to assess the safety risks associated with flammable substance leakage in container terminals, applying each to distinct facilities in Italy to provide a comprehensive safety evaluation.

2 STATE OF THE ART

The safety of container terminals, especially concerning the handling of hazardous materials, has been extensively studied. Bruzzone and Longo developed the TRAINPORTS simulator, a 3D simulation tool designed to enhance training in container terminals, emphasizing the importance of simulation in safety training. (Bruzzone et al., 2013)
Further, Bruzzone and Massei discussed the integration of strategic engineering in developing safety strategies during critical periods, highlighting the role of simulation and artificial intelligence in crisis management. (Bruzzone et al., 2021)
Additionally, Bruzzone et al. (2022) presented an innovative virtual lab aimed at improving safety and port operations, demonstrating the application of virtual simulation in assessing port accidents and crises.
These studies underscore the critical role of simulation and modeling in enhancing safety protocols within container terminals.
Complementing these findings, other researchers have contributed significantly to the field. Chen et al. (2023) proposed a safety assessment model for handling dangerous

goods in port areas, focusing on resource allocation and risk mitigation strategies.

Similarly, Török and Ozunu (2020) analyzed the hazardous properties of ammonium nitrate and modeled explosions using TNT equivalency, providing insights into the potential risks associated with specific hazardous materials.

These contributions highlight the multifaceted nature of safety assessments in container terminals, encompassing simulation-based training, strategic engineering, and material-specific risk analyses.

3 APPROACH N. 1 – RELEASE IN CASE OF FAILURE

This approach is typically part of the risk analysis applied to Major Accident Installations, subject to the so-called European "Seveso Directive", but can be applied virtually to every installation to define the consequences deriving from an accident scenario, helping for example in a design stage to identify the right location for a target (e.g. a sensitive or high crowded building), whose distance from the hazardous area should be greater than the maximum damage area consequent the ignition of the flammable substance released after a failure to the containment system. This approach will be applied to the "dangerous goods parking area" of a container terminal located in the port of Vado Ligure (SV), Liguria, Italy.

The area dedicated to dangerous goods has a rectangular shape with sides of length 110 m and 15 m, and is made up of 96 ground slots (16 columns by 6 rows) for the storage of containers up to the third stacking tier, for a total of 288 TEUs. It is intended for the storage of 20" and 40" containers containing goods labelled dangerous for the International Maritime Dangerous Goods Code (IMDG Code) of International Maritime Organization (IMO).

Figure 1a Area of study – Genoa Port

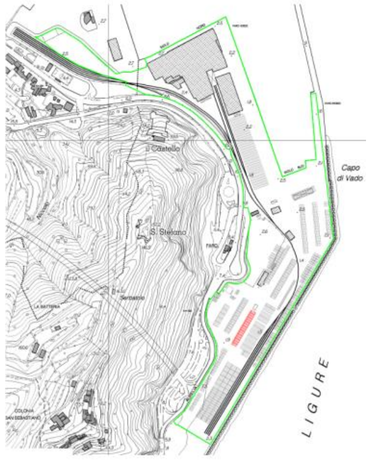

Figure 1b Area of study – Genoa Port

The Top Events (TEs) identified subjecting the facility layout and the substances handling and storage operations to operability analysis are:

- releases of flammable liquids during handling operations;
- releases of flammable liquids without any operation.

The second TE won't be object of discussion in this article because the calculated frequency of occurrence of its correlated accident scenario is minor than 1.0E-07 occ/year, so its probability can be considered negligible; moreover, it won't create any consequence because the amount of vapors in the flammability/explosivity range was found to be negligible as well, i.e., such that ignition was not possible.

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3.1 Releases of flammable liquids during handling operations

This Top Event considers the loss of containment of a tanktainer (this event is believed to be more conservative in terms of the severity of the associated consequences than the loss of containment of a container due to a failure of the packages in it) during loading, unloading, transshipment, storage and handling operations, i.e., in the presence of personnel who - in the event of release - could act promptly to limit the consequences of the incident.
The fault tree analysis is represented by the figure below.

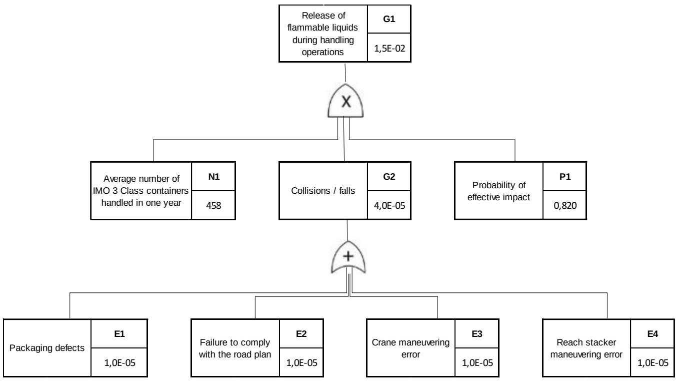


Figure 3a Fault Tree Analysis

f	Event	Rate/ Probability	Source	Frequency/ Probability
E1	Packaging defects	1,0E-05 occ/year	Literature and historical knowledge	**1,0E-05** occ/year
E2	Failure to comply with the road plan	1,0E-05 occ/year	Literature and historical knowledge	**1,0E-05** occ/year
E3	Crane maneuvering error	1,0E-05 occ/year	Literature and historical knowledge	**1,0E-05** occ/year
E4	Reach stacker maneuvering error	1,0E-05 occ/year	Literature and historical knowledge	**1,0E-05** occ/year
P1	Probability of effective impact	0,820 -	"Il rischio nel settore trasporti", G. Spadoni.	**0,820** -
N1	Average number of IMO 3 Class containers handled in one year	458 occ/year	Terminal movimentation data	**458** occ/year

Figure 3b Fault Tree Analysis

Resolving the fault tree yields that the release of flammable liquids during handling operations is characterized by an expected frequency of occurrence of 1.5E-02 occasions/year.

The maximum amount of substance released as a result of cracking a tanktainer during the handling operations was calculated using TNO's Effects 7.6 software based on the following input data:

- substance: ethanol;
- hole diameter: 12.7 mm;
- container volume: 28 m^3.

The release rate of ethanol from the borehole, based on the above assumptions, was found to be 0.4 kg/s.
Given that the event under consideration occurs "during handling operations" i.e., during continuously manned operations, it was chosen an intervention time of 10 minutes, so that the amount of substance released is 240 kg.
The spilled liquid may form, at most, an unconfined puddle of 1.9 m radius from the ground projection of the release point (which is conservatively considered a tanktainer stacked on the perimeter of the ASMP).
The figure below shows the event tree related to the release of flammable liquids during handling operations.

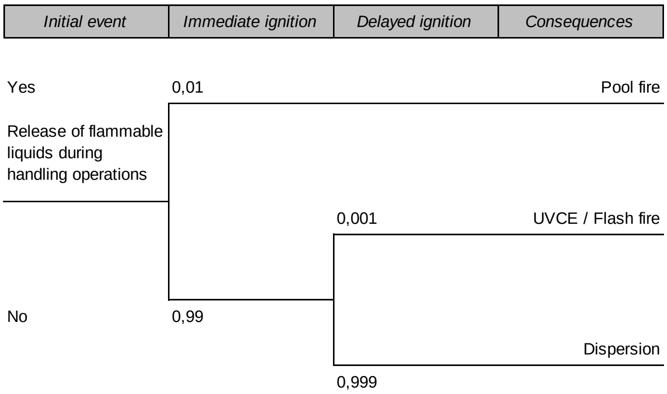


Figure 4a Event Tree of flammable liquids

Event	Source	Note
Immediate ignition	Cox, Lees & Ang	Minor Leak (< 1 kg/s)
Delayed ignition	Cox, Lees & Ang	Probability of explosion given ignition

Figure 4b Event Tree of flammable liquids

So, the expected frequency of occurrence of the accident scenarios is:

- TE 1 - Pool fire: 1,5E-04 occ/year.
- TE 1 - UVCE / Flash fire: 1,5E-05 occ/year.

In order to evaluate the effects of the above incident scenarios, software simulations were conducted using TNO's EFFECTS 7.6 calculation program.

The standard meteorological conditions adopted for the software simulations of the events are:

- stability class: D
- wind speed: 3 m/s
- humidity: 66%
- ambient temperature: 20°C.

In the following table are reported the results of the simulations.

			Damage radius [m]			
TE n.	Top Event	Scenario	12,5 kW/m^2	7 kW/m^2	5 kW/m^2	3 kW/m^2
01	Releases of flammable liquids during handling operations	Pool fire	10,7	13,3	14,5	16,1

Figure 5 Results of the simulations

4 APPROACH N. 2 – LEAKAGE DURING NORMAL CONDITIONS

This approach is typically part of the “Classification of hazardous areas for the presence of flammable gases or flammable vapours and combustible dusts” conducted in accordance with the European Directive 2014/34/UE and must be applied to all workplace whenever flammable substances are involved. The scope is to produce the classification of areas (ATEX zones) where flammable gas or vapour hazards may arise and may then be used as a basis to support the proper design, construction, operation and maintenance of equipment for use in hazardous areas. This approach will be applied to the “dangerous goods parking area” of a container terminal located in the port of Genoa (GE), Liguria, Italy. The company performs activities of disembarking and embarking, handling, storing and shipping of various containerized or palletized goods and materials; these activities involve, limited to the disembarking and embarking phases, ships of different types, which are moored at docks under concession.
The terminal's operational area covers a total area of 1.160.000 m2, of which 980.000 m2 is divided into 6 modules, occupied by 16.000 ground slots, for container storage.
Dangerous goods are present in the individual units of the dangerous goods parking area in different quantities from time to time, depending on the commercial needs to be met, but in total never more than 2.538 TEUs.

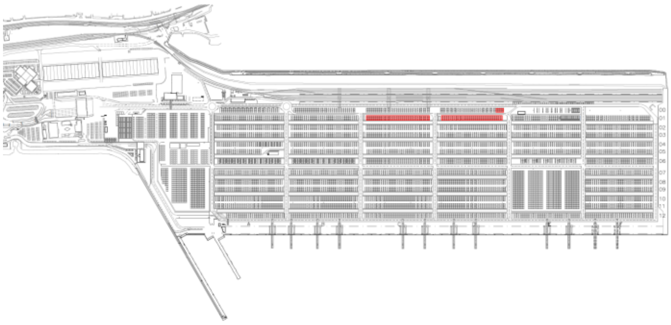


Figure 6 Goods Parking Area

It is intended for the storage of 20" and 40" containers containing goods labelled dangerous for the International Maritime Dangerous Goods Code (IMDG Code) of International Maritime Organization (IMO).

The final scope of this approach is to determine the extension of three different areas where flammable materials are involved, in which different types of electrical and mechanical devices shall be used to avoid a potential ignition source. The areas are defined as follows:

- Zone 0: area in which an explosive gas atmosphere is present continuously, or for long periods, or frequently (e.g. the inside of a tank);
- Zone 1: area in which an explosive gas atmosphere is likely to occur occasionally in normal operation (e.g. the surroundings of a vent);
- Zone 2: area in which an explosive gas atmosphere is not likely to occur in normal operation, but, if it does occur, will exist for a short period only (e.g. the surroundings of a flange/valve or any discontinuity).

Also, in this second approach it was believed more conservative to consider a tanktainer as a possible leakage source. The flammable materials considered were chosen between the whole list of IMO goods handled in the terminal considering the quantitative and the flammability properties:

- Ethyl ether: flammable liquid contained in an IMO T11 tank container;
- Dimethyl ether: flammable liquefied substance contained in an IMO T50 tank container.

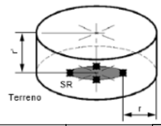
The sources of emission identified were:

- SE01: Tank container T11 bottom valve;
- SE02: Tank container T11 vapour phase valve;
- SE03: Gas tank container T50 bottom valve.

Following the intent of this approach, the leakage of the flammable substance from the sources of emission is considered – even if with a very low frequency (not likely to occur in normal operation) – as always present, giving rise to the definition of three different areas of “Zone 2”.
SE01 is defined as the leakage of ethyl ether (liquid) from the bottom valve of a T11 tank container, forming a liquid puddle on the ground whose vapours are in flammability range.
SE02 is defined as the release in atmosphere of ethyl ether (vapour) from the vapour phase valve of a T11 tank container.
SE03 is defined as the leakage of dimethyl ether from the bottom valve of a T50 tank container. Given that dimethyl ether is liquefied by the pressure at which it is stored, the expansion consequent to its release will result in its instantaneous vaporization.
Considering the natural ventilation of the area and its availability, considering different coefficients and calculation methodologies imposed by the applicative guide of the

European Directive, it was possible to define the shape and the extension of the ATEX zones generated by the sources of emission.

SE	Ambient	Emission degree	Ventilation availability	Dilution degree	ATEX zone	Hazardous distance r	Hazardous distance r'
SE01	AA01	Second	Good	Medium	Zone 2	4,1 m	1,6 m



SE	Ambient	Emission degree	Ventilation availability	Dilution degree	ATEX zone	Hazardous distance r	Shape
SE02	AA01	Second	Good	High	Zone 2 NE	0,5 m	Spheric

*Figure 7a ATEX Zone*s

It's important to note that in case of vapour released into the atmosphere, the role of ventilation is crucial to obtain a NE (Negligible Extension) zone, that is considered a non-hazardous zone where normal equipment can be used.

SE	Ambient	Emission degree	Ventilation availability	Dilution degree	ATEX zone	Hazardous distance r	Shape
SE03	AA01	Second	Good	Medium	Zone 2	0,5 m	Spheric and conic

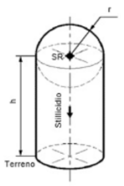


Figure 7b ATEX Zones

The hazard zone was calculated at a height from the ground of h = 2.8 m, considering, therefore, the emission from the bottom valve of a gas tank container stored at the second stacking tier. Simulations show that, starting from the third stacking tier, the emission - due to the higher air velocity - generates a Zone 2 NE. The envelope of the ATEX zones generate by SE01 and SE03 is represented below.

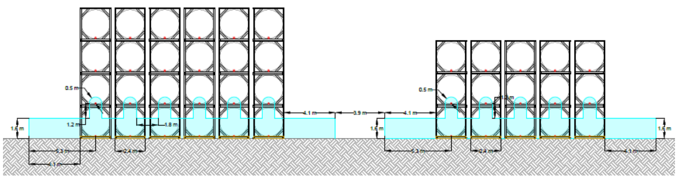


Figure 7c ATEX Zones

CONCLUSIONS

This study evaluated two complementary approaches to assess the safety risks associated with the handling and storage of flammable substances at container terminal facilities. Each approach was applied to a different terminal in Italy to address distinct aspects of risk—one focused on accident scenarios following containment failure, and the other on assessing risk under normal operating conditions.

The first approach, applied to the terminal in Vado Ligure, simulated the consequences of flammable substance release in the event of containment failure. Analysis highlighted that personnel presence during handling operations can mitigate incident severity due to the potential for timely intervention. The calculated occurrence frequency of scenarios, including pool fires and unconfined vapor cloud explosions, allows for a targeted safety design, ensuring hazardous zones are appropriately distanced from sensitive areas.

The second approach, implemented at the Genoa terminal, centered on defining ATEX zones where flammable gas atmospheres may occur in normal conditions. By classifying hazardous zones based on factors such as emission frequency and ventilation, the study provides a framework for selecting compliant equipment and designing safe work environments. Natural ventilation played a critical role in reducing hazard zones, particularly in scenarios involving vapor emissions.

Together, these approaches demonstrate a comprehensive safety assessment model, covering both potential failure events and regular operational risks. Integrating both methods enables a holistic risk management strategy, enhancing safety protocols in container terminals handling flammable materials. Future work could focus on refining these models with real-time monitoring and response systems to further enhance safety in such high-stakes environments.

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