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Safety and Security Risk Assessment of Dangerous Goods Carriers Approaching Port Areas

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The increasing amount of dangerous goods transported by sea creates complex safety and security issues when carriers approach industrial port areas, particularly given the proximity of critical infrastructure and densely populated areas. Conventional risk assessment methodologies in port areas are often based on simplified static models, which are unable to take into account the dynamic nature of port operations or the potential domino effects that may result. In this context, this study aims to develop a real-time risk assessment tool that considers both safety and security events relating to the transport of hazardous substances in port areas. The proposed tool features a dynamic three-dimensional interface that enables the visualisation of risk contours during the ships transit through the port inland waterways, the docking and the handling of hazardous substances from the ships to the land. First, critical areas of the carrier are identified, and potential loss of containments are assessed in terms of both safety-related and security-related scenarios. The credibility of the scenarios following a release (expressed in annual probability) is evaluated for both safety and security events. The consequence evaluation is carried out based on real-time data inputs, such as weather conditions, operating parameters and the position of the carrier, using integral models for the physical effects of fires, explosions, and dispersion. Finally, credibility and consequence are combined, enabling real-time assessment of vulnerability and risk contours. This methodology is then applied to two case studies, representing a touristic and an industrial setting, to demonstrate the potential of the tool to support risk and emergency management.

Keywords: dangerous goods, risk analysis, port areas, real time assessment, 3D analysis, security vulnerability analysis, security risk assessment

1. Introduction

Maritime transport plays a key role in the global economy. Among goods transported by sea, dangerous goods (DG), particularly flammable and toxic substances, deserve particular focus, as they represent a highly critical cargo due to the severe consequences of major accidents involving the release of hazardous substances. Beyond the safety issues, these carriers may also be attractive targets for intentional attacks, given the potentially catastrophic outcomes that a deliberate release could cause, especially when transport routes pass through port areas, near fixed industrial installations, or densely populated areas. The presence of huge quantities of DG, movement of the carriers and proximity to vulnerable receptors may significantly amplify both human, environmental and economic impacts. Moreover, port areas may represent even more attractive targets, since carriers often transport large quantities of DG near fixed industrial installations, that also handle and store DG, increasing the risk of domino effects with potential severe consequences for people, assets, and the environment.

Regarding risk assessment methodologies concerning safety events, well-established quantitative methodologies are available for the transport of dangerous goods (TDG), including those developed by the CCPS (2008) and the

Dutch guidelines reported in the Purple Book (Uijt de Haag & Ale, 1999), which address both the likelihood and consequences evaluation specifically tailored for TDG risk assessment. By contrast, available methodologies addressing security aspects, provide only qualitative and semiquantitative methodologies, such as the transportation security vulnerability assessment from the CCPS (2008) and the semi-quantitative methodology for the multimodal TDG proposed by (Reniers & Dullaert, 2013).

Therefore, the currently available methodologies are not capable to account for both accidental and intentional events into a quantitative framework for integrated safety and security (ISS) scenarios, with particular reference to the TDG transported by carriers in the proximity of port areas.

Within the Italian context, risk evaluation for TDG in port areas is often based on shortcut methods, which are simplified method and that do not account for dynamic evaluations. Although these approaches are useful for preliminary screening, they are not substance specific. This leads to similar risk outcomes for different classes of flammable or toxic materials, and sometimes to results that do not fully represent realistic accident scenarios. Moreover, such methods do not support real-time assessment of scenarios evolution, as they are not designed to include dynamic inputs such as changing meteorological conditions or the actual position of the vessels and inventory of the transport unit. This significantly limits their applicability for emergency management, where timely and accurate information is essential to support decision-making processes.

The aim of this study is to develop an integrated safety and security (ISS) risk assessment methodology for vessels approaching port areas. This methodology is implemented in a dedicated three-dimensional (3D) software to enable real-time visualisation of potential consequences and associated risks. It aims to support the identification of the most critical carriers, in terms of type of substance, quantity and berthing location, and critical sections of the route in waterways, in terms of people and assets involved. Furthermore, the resulting framework is intended to support the identification and prioritisation of preventive measures and emergency response management in both accidental and intentional events involving carriers of DG in port areas.

2. Methodology

2.1. *Overview*

In this work, a methodology for real-time 3D ISS risk assessment for carriers transporting DG in port areas is presented. The proposed methodology is derived from the framework originally developed within the Securdomino project (Marroni et al., 2025), which introduced a real-time 3D tool for ISS risk assessment for fixed installations, including the evaluation of domino effects. This framework has now been adapted to a new application context. While the original approach was developed for fixed plants, the present work extends and adapts its core concepts to address the specific challenges posed by maritime TDG and port operations, including some specific issues like carriers' continuous movement, different types and quantities of hazardous substances, and surrounding areas characteristics variability. By combining 3D representation, real-time data acquisition, and ISS risk assessment, the methodology provides a dynamic evaluation of both accidental and intentional release scenarios in port areas.

The methodology consists of the following four steps. In Step 1, documentation related to the carriers under analysis is retrieved from the port authority system, enabling a comprehensive characterization of vessels operating within the port area and identification of the most critical ones (Section 2.2). In Step 2, the port area is inspected using drones to collect data required for the generation of a 3D interactive environment. The 3D map is subsequently produced through aerial photogrammetry techniques (Section 2.3). In Step 3, the 3D map is made interactive by linking carrier-related information, vessel positioning, and meteorological conditions, as described in Section 2.4. The final step consists of the real-time evaluation of consequences and risk associated with accidental and intentional scenarios (Section 2.5).

2.2. *Context Definition and Carrier Characterization*

The port environment and DG carriers are characterized in collaboration with port authorities through the analysis of vessel traffic data, cargo manifests, berthing plans and emergency procedures. For each carrier, inventories are defined in terms of substance type, quantity and packaging, together with navigation routes, operational timing (day/night) and applicable safety and security preventive and mitigative barriers. This step allows the identification of the most critical carriers, whose involvement in an accident or attack may lead to the most severe consequences.

2.3. *Port area Inspection by Drone and 3D Reconstruction*

Following the context definition, the port area is inspected using drones to collect the spatial data required for 3D reconstruction. After obtaining the necessary authorizations, aerial images and videos are acquired to capture the layout of docks, navigation channels, storage areas and nearby industrial installations. The collected data are processed using photogrammetry software to generate an interactive 3D representation of the port environment, including berths, vessels, navigation routes, and surrounding infrastructures. Post-processing techniques are applied to enhance the representation and level of detail of key elements.

2.4. *Data Integration in the Tool*

Static and real-time data are associated with the 3D environment to enable dynamic scenario representation. Carriers and port infrastructures are implemented as interactive objects, characterised by static information such as vessel typology, main dimensions, hull configuration, transported substances and maximum inventory. Real-time inputs include meteorological conditions (wind speed and direction, temperature, stability class) and carrier positioning via GPS.

2.5. *Real-time ISS Consequence and Risk evaluation in Port area*

The tool includes the evaluation of physical effects associated with fires. The models adopted by (Marroni et al., 2024) for fixed installations are also applied in the present study. These models already strike a good balance between computational efficiency and the accuracy of the results, making them suitable for real-time applications.

For what concerns frequency evaluation, the same approach adopted for TDG in inland waterways proposed by (P.A.M. Uijt de Haag, 2005) is used for gathering standard loss of containment frequency values for unintentional (safety-related) events. For security scenarios, Eq. 1 is used to evaluate the frequency of the final outcomes, f_{FO}:

$$f_{FO} = f_A \cdot P_S \cdot P_I \tag{1}$$

where f_A is the frequency of the intentional attack or unintentional loss of containment, P_S is the probability of success of the attack, and P_I is the probability of ignition.

The frequency of intentional attacks is derived from (American Petroleum Institute (API), 2013) based on context where the port is located

Table 1. Compatibility matrix used for risk assessment, adapted from (Laurent et al., 2021). Capital letters indicate territorial vulnerability classes (from F – industrial areas to A – densely populated residential areas).

Impact zones → Pool fire → Frequency f_{FO} ↓	High lethality 12.5 kW/m^2	Start lethality 7 kW/m^2	Irreversib. injuries 5 kW/m^2	Reversible injuries 3 kW/m^2
$f_{FO} < 10^{-6}$	DEF	CDEF	BCDEF	ABCDEF
$10^{-6} < f_{FO} \le 10^{-4}$	EF	DEF	CDEF	BCDEF
$10^{-4} < f_{FO} \le 10^{-3}$	F	EF	DEF	CDEF
$f_{FO} > 10^{-3}$	F	F	EF	DEF

Probabilities P_S and P_I are evaluated through Event Tree Analysis, adapted to the port area context to represent different attack modes and the performance of safety and security barriers specific to port areas and maritime transport, including access control systems, surveillance measures, patrols, emergency response capabilities, and traditional safety systems using reference value from (Casson Moreno et al., 2022; Landucci et al., 2017).

Risk is evaluated using the compatibility matrix defined in the Italian land-use planning legislation (Laurent et al., 2021), reported in

Table 1. Territorial categories range from A (densely populated residential areas) to F (industrial and non-built areas) and are assigned for each combination of frequency and impact zone. Since the compatibility matrix is scenario-based, the resulting risk assessment is inherently scenario-based.

3. Case study application

To demonstrate the applicability and flexibility of the proposed methodology within different port contexts and hazardous substances involved, two representative case studies are analysed. The selected case studies refer to two ports characterized by significantly different operational profiles: a touristic port (case A) and an industrial port (case B). Both port areas are considered to have been active for over 100 years and to be located in a Country with a mild socio-economic and political climate. The two cases mainly differ in terms of vessel types, nature of the handled DG and port activities, with the first case characterized by the presence of tourists and the second by industrial activities, including fixed installations handling hazardous substances nearby.

In case A, the port is primarily dedicated to leisure navigation and passenger-related activities and does not routinely handle and transport hazardous substances. Nevertheless, fuel supply operations represent a critical issue within the port area. Accordingly, the analysis focuses on fuel barges, which transport significant quantities of diesel fuel, used to refuel different kind of vessels. In case B, an industrial port is considered. This type of port is characterized by the regular handling and transport of DG associated with industrial activities in the surrounding area. In this context, the analysis considers both fuel barges transporting diesel fuel and chemical tankers transporting xylene. Xylene was chosen for investigation due to its extensive transportation by sea and its inclusion by (International Maritime Organization (IMO), 2000) on the list of the twenty most hazardous substances in case of a maritime accident. Xylene is characterised by flammable and explosive properties, as well as significant toxicity to the marine environment. Within this framework, focusing specifically on the effects on human health, the impact of dispersion in the marine environment is neglected.

3.1. *Case A: Touristic Port*

In order to identify the most critical element, the hazard-based method presented in Section 2.1 is adopted. Given the touristic nature of the port and the absence of permanent storage facilities for hazardous substances, the most critical carriers are the fuel barges used to refuel vessels within the port. These vessels are single-hull fuel barges transporting approximately 150 tonnes of diesel fuel each, within the port area and in proximity to passenger areas and other sensitive port infrastructures. Therefore, fuel barges are identified as the critical elements and constitute the focus of the analysis. The 3D reconstruction of the port area is shown in Figure 1.

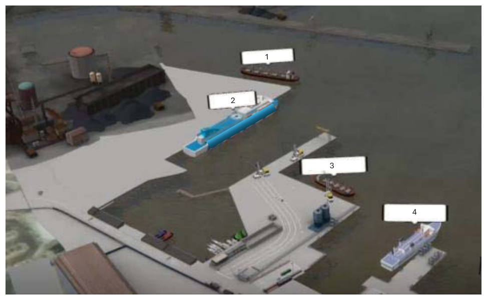

Fig. 1.3D reconstruction of the touristic port area.

Concerning safety-related events a partial rupture of the flexible hose during bunkering operations is considered as reference release scenario, leading a release diameter of 25.4 mm. The occurrence frequency is estimated directly from the Purple Book (P.A.M. Uijt de Haag, 2005), which reports failure probability for a partial rupture, of $6 \cdot 10^{-4}$ events/y. To obtain the annual frequency this value is multiplied by the estimated number of bunkering operations per year, assumed here as 1080 (approximately three per day), obtaining a final frequency of $6.5 \cdot 10^{-1}$ events/y.

For security-related events, a collision scenario is considered. In this case, an intentional collision between a vessel and the fuel barge is assumed, leading to structural damage and an instantaneous release of 75 m^3 of diesel. The frequency of the intentional attack is assumed as once in the life of the plant, leading to f_A equal to 0.01 events/y. In this simplified scenario, the attack is modelled as a defined chain of events, while recognizing that alternative threat pathways may exist. The attackers infiltrate the port facility from the open sea and are detected by the perimeter surveillance and access-control systems monitoring maritime access route; however, the emergency response unit fails to neutralize the attackers, resulting in successful attack. Reference value and methodology for the frequency assessment is adapted to port areas context from (Casson Moreno et al., 2022; Landucci et al., 2017). The attack success frequency $f_A \cdot P_S$ results equal to $3.3 \cdot 10^{-4}$ events/y. Considering P_I ,the probability of ignition, equal to 1, the pool fire frequency can be evaluated using Eq.1, leading to f_{FO} equal to $3.3 \cdot 10^{-4}$ events/y. Figure 2 shows the Event Tree developed for the specific chain of considered events.

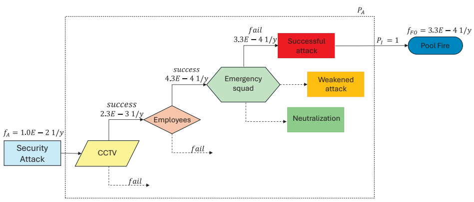

Fig. 2.Event tree for the considered attack chain for case A.

To assess the physical effects associated with the diesel release, a pressure of 1.2 bar, a temperature of 20°C, a release duration of 7200 s and meteorological conditions of 4F and 13D are assumed. Due to the coastal setting, where stronger winds are more prevalent, wind speeds exceeding the conventional 2 m/s and 5 m/s (currently 4 m/s and 13 m/s, respectively) are expected.

3.2.*Case B: Industrial Port*

The port area is characterized by regular handling and transport of DG, supporting both commercial and industrial operations. The analysis considers two critical vessel types:

- single-hull fuel barge transporting 150 tonnes of diesel fuel
- chemical tankers transporting 30 tonnes of xylene[a].

The 3D reconstruction of the port area is shown in Figure 3. For safety-related events, a full-bore rupture of the flexible hose during bunkering operations is considered as the release scenario, replacing the partial failure assumption of the previous case. The occurrence frequency is estimated using the same reference, the Purple Book (P.A.M. Uijt de Haag, 2005) , which reports failure probability of $6 \cdot 10^{-5}$ event/operations for a full-bore arm rupture with a diameter of 63 mm. As for case A, the annual frequency is obtained by multiplying failure probability by the estimated 1080 bunkering operations per year, obtaining a final frequency of $6.5 \cdot 10^{-2}$ events/y. Security-related events are addressed through the same collision scenario adopted for the touristic port, involving an intentional impact between a vessel and the fuel barge, causing structural damage and an instantaneous release of 75 m³ of diesel. To further explore hazardous scenarios within the industrial port, the release of xylene from a tanker vessel is considered. For consistency, the release diameter is maintained equal to that used in the safety, while, for security scenarios, a catastrophic rupture with immediate release of the inventory is assumed. This comparative approach highlights the differences in potential consequences resulting from incidental events involving different DG and vessel types. Regarding frequency assessment, the same methodology and assumptions adopted for Case A are applied, as described in Section 3.1 and illustrated in Figure 2.

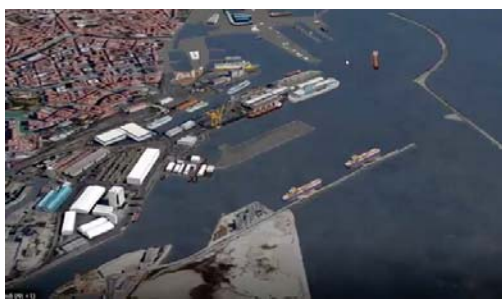
Fig. 3.3D reconstruction of the industrial port area.

4. Results and Discussion

This section presents the results obtained from the application of the proposed methodology to the two case studies introduced in Section 3. The analysis focuses on the evaluation of damage distances and associated risk levels resulting from both accidental and intentional release scenarios in port areas.

[a] The mixture of isomers is considered pure m-xylene.

4.1. *Case A*

The damage distances obtained for the case A are summarised in Table 2. As expected, the security-related scenario, characterised by a catastrophic rupture, leads to greater damage distances compared to the safety-related scenario. Under both meteorological conditions, the maximum damage distances associated with the high lethality effects (i.e., 12.5 kW/m² impact zone) is 34 m, while the effects become negligible (so, after the 3 kW/m² impact zone) after 79 m in the most severe scenario. These results indicate a relatively limited spatial extent of the thermal effects within the port area, which is consistent with the nature of the analysed carrier and the quantity of diesel involved.

Table 2. Damage distances associated with a release resulting from safety related scenario (panel a) and security related scenario (panel b).

a)

Weather 4F		Weater 13D	
Impact zones	Damage distance [m]	Impact zones	Damage distance [m]
High lethality	17	*High lethality*	21
Starting lethality	22	*Starting lethality*	24
Irreversible injuries	24	*Irreversible injuries*	26
Reversible injuries	29	*Reversible injuries*	29

b)

Weather 4F		Weather 13D	
Impact zones	Damage distance [m]	Impact zones	Damage distance [m]
High lethality	28	*High lethality*	34
Starting lethality	46	*Starting lethality*	61
Irreversible injuries	57	*Irreversible injuries*	69
Reversible injuries	71	*Reversible injuries*	79

According to the compatibility matrix adopted for land-use planning (Table 1), combining these damage distances with the estimated frequencies reveals that the resulting risk levels are compatible with the territorial vulnerability classes present in the analysed port area. However, despite the limited damage distances and regulatory compatibility, the results highlight a relevant critical aspect specific to touristic ports, namely the nature of the exposed population. Such environments are typically characterised by the presence of tourists, who are generally not trained in emergency response procedures. This aspect, while not explicitly captured by the compatibility matrix, represents an important element to be considered in emergency planning and risk management activities in specific context like this. Figure 4 shows the risk contours overlaid on the port environment in the worst-case scenario. This demonstrates the proposed tool's ability to visualise spatial risk distribution.

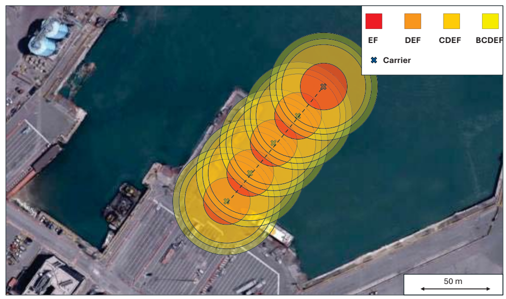

Fig. 4.Risk contours in the worst-case scenario overlaid on the port area considering the carrier location.

3.2. *Case B*

Damage distances associated with the industrial port case study are reported in Table 3. As for the touristic port, the security-related scenarios result in larger damage distances than the safety-related ones, confirming the relevance of intentional events in a comprehensive risk analysis. Figure 5 shows the risk contours overlaid on the industrial port environment in the worst-case scenario. The general considerations observed for the industrial port are consistent with those discussed for the touristic port, and the resulting risk levels remain broadly compatible with the territorial vulnerability classes defined for the analysed area. Nevertheless, the industrial context introduces additional issues related to the proximity of fixed installations handling hazardous substances, which increases the potential for domino effects. Moreover, a key result is the comparison between diesel and xylene releases. Despite the significantly lower quantity of xylene simulated

(30 tonnes) compared to diesel (150 tonnes), the damage distances associated with xylene are substantially larger. For instance, under 4F conditions, the high lethality zone for xylene exceeds 100 m, compared to approximately 25 m for diesel, while the 3 kW/m² threshold (reversible effects) extends beyond 250 m in several scenarios. These results clearly indicate that xylene represents a highly critical substance in the port context. The findings underline the importance of substance-specific assessments, as simplified approaches based only on transported quantities may significantly underestimate the potential consequences of accidents involving certain hazardous substances.

Table 3. Damage distances associated with a release resulting from safety related scenario (panel a) and security related scenario (panel b).

a)

4F			13D		
Impact zones	Damage distance [m]		Impact zones	Damage distance [m]	
	Diesel	Xylene		Diesel	Xylene
High lethality	25	107	*High lethality*	30	92
Starting lethality	44	150	*Starting lethality*	57	143
Irreversible injuries	54	185	*Irreversible injuries*	65	181
Reversible injuries	68	263	*Reversible injuries*	75	212

b)

4F			13D		
Impact zones	Damage distance [m]		Impact zones	Damage distance [m]	
	Diesel	Xylene		Diesel	Xylene
High lethality	28	118	*High lethality*	34	117
Starting lethality	46	164	*Starting lethality*	61	182
Irreversible injuries	57	201	*Irreversible injuries*	69	225
Reversible injuries	71	254	*Reversible injuries*	79	263

It is also worth noting that xylene is characterised by significant toxicity to the marine environment. Although the present study deliberately neglects the effects of dispersion in water and focuses exclusively on impacts on human health, this aspect should not be overlooked in the future for a comprehensive risk assessment framework.

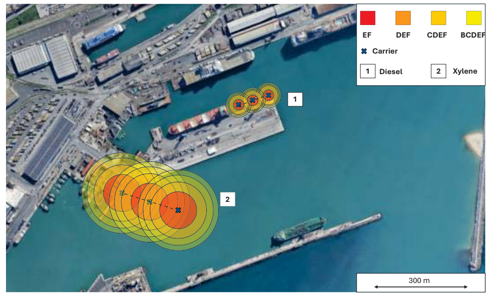

Fig. 5.Risk contours in the worst-case scenario overlaid on an industrial port environment, showing a comparison of the spatial extent of risk associated with diesel (1) and xylene (2) considering the carrier position.

5. Conclusions

This work presents a real-time, 3D, ISS risk assessment methodology for the TDG in port areas. The proposed framework combines quantitative risk assessment techniques with real-time data integration and 3D visualisation, providing a dynamic tool capable of supporting both risk analysis and emergency management activities in complex port environments. The application to two representative case studies highlighted how different port contexts are associated with different risk profiles and issues. In the touristic port scenario, the results showed relatively limited damage distances and compliance with land-use compatibility criteria; however, particular attention must be paid to the characteristics of the exposed population, often composed of untrained individuals, specifically in case of intentional attack. In contrast, the industrial port scenario revealed more severe potential consequences, especially due to the presence of DG with high impact potential and the proximity of fixed industrial installations handling hazardous substances, which may cause domino effects. The comparison between diesel and xylene further demonstrated the necessity of substance-specific analyses, as xylene produced significantly larger damage distances, despite a lower simulated quantity. This finding confirms the importance of moving beyond simplified approaches in port risk assessment, including substance-specific evaluations. Finally, the use of a real-time 3D environment proved to be a valuable tool not only for risk assessment but also as a decision-support system for emergency management, enabling rapid visualisation of evolving scenarios and affected areas. Future developments will focus on extending the methodology to additional DG and presenting the results in 3D maps. The approach will also incorporate domino effects on industrial assets as well as the consequences of DG dispersion in the marine environment, in order to provide a more comprehensive representation of the risks associated with TDG in port areas.

References

American Petroleum Institute (API). (2013). *ANSI/API Standard 780 – Security risk assessment methodology for the petroleum and petrochemical industry*.

Casson Moreno, V., Marroni, G., & Landucci, G. (2022). Probabilistic assessment aimed at the evaluation of escalating scenarios in process facilities combining safety and security barriers. *Reliability Engineering and System Safety*, *228*. https://doi.org/10.1016/j.ress.2022.108762

CCPS. (2008). *Guidelines for chemical transportation safety, security, and risk management*. Wiley.

International Maritime Organization (IMO). (2000). *Manual on Chemical Pollution. Section 1: Problem Assessment and Response Arrangements* (1999 edition). IMO.

Landucci, G., Argenti, F., Cozzani, V., & Reniers, G. (2017). Assessment of attack likelihood to support security risk assessment studies for chemical facilities. *Process Safety and Environmental Protection*, *110*, 102–114. https://doi.org/10.1016/j.psep.2017.06.019

Laurent, A., Pey, A., Gurtel, P., & Fabiano, B. (2021). A critical perspective on the implementation of the EU Council Seveso Directives in France, Germany, Italy and Spain. *Process Safety and Environmental Protection*, *148*, 47–74. https://doi.org/10.1016/j.psep.2020.09.064

Marroni, G., Dentone, D., Crosara, S., Kuipers, S., Casson Moreno, V., & Landucci, G. (2024, January). *Real-Time Three-Dimensional Safety-Security Assessment Of Process Facilities In Critical Areas*.

Marroni, G., Guarguaglini, M., Kuipers, S., Dentone, D., Casson Moreno, V., & Landucci, G. (2025). A Practical Three-Dimensional Tool for Real-Time Safety-Security Risk Assessment of Process Facilities. *Chemical Engineering Transactions* , *117*, 553–558. https://doi.org/10.3303/CET25117093

P.A.M. Uijt de Haag. (2005). *Guidelines for Quantitative Risk Assessment: Purple Book*. Ministerie van Volkshuisvesting en Ruimtelijke Ordening (VROM).

Reniers, G. L. L., & Dullaert, W. (2013). A method to assess multi-modal Hazmat transport security vulnerabilities: Hazmat transport SVA. *Transport Policy*, *28*, 103–113. https://doi.org/10.1016/j.tranpol.2012.05.002

Uijt de Haag, P. A. M., & Ale, B. J. M. (1999). *Guidelines for Quantitative Risk Assessment (Purple Book)*. Committee for the Prevention of Disasters, the Hague (NL).