Risk model for large scale munition transshipments in sea ports

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Abstract

Large-scale munition transshipments may pose significant risks to people, infrastructure, and the environment—especially in busy sea ports where vital economic activities and industry are often concentrated. This paper describes the method developed by TNO to perform a quantitative risk assessment (QRA) in order to evaluate these operations. It employs models for determining the probability of explosion, explosion effects (blast and heat), and various consequences (such as lethality, structural damage, and industrial accidents). The results are subsequently expressed into four risk metrics: location-specific individual risk, group risk, risk of domino reactions, and financial risk. By comparing these risk metrics to predefined assessment criteria, informed decisions can be made regarding the level of risk, potential damages and risk mitigation measures for large-scale munition transshipments. It also forms the basis for risk acceptance decisions by national authorities. This methodology gives insight into how to deal with risk in sea-land logistical operations with munitions.

Introduction

Large-scale munition transshipments in the Netherlands may involve the movement of large quantities of munitions from ship to shore, or vice versa. These activities can be a source of risk to the surroundings. Given the large quantities involved, the effects and consequences of a potential accidental explosion can be significant up to distances of several kilometers. It is thus key to quantitively assess whether the planned transshipments pose an acceptable level of risk to the environment, and to explore the conditions and possibilities to facilitate transshipment activities.

A risk-based approach is essential here, as opposed to effect-based approaches that are, for example, more common to assess safety at munition storage sites. An effect-based method is suitable in that context, as storage sites are generally constructed such that they adhere to established separation distances, such as the Inter-Magazine Distances (IMD) specified in AASTP-1 [1]. As a result, if an accident occurs, it will likely only affect a limited portion of the stored munition, thereby limiting the overall expected effects. Due to the storage constraints present on ships and trains, it is not feasible to maintain similar required separation distances. Instead, the scenario at hand involves a large quantity of inseparable munitions whose effects cannot be reduced in case of an accident. Moreover, the presence of munition during transshipment is transient compared to storage sites. This temporal aspect is a critical factor that cannot be accounted for in effect-based approaches. A risk-based approach thus becomes crucial to give insight into mitigating the risk due to these large scenarios to acceptable levels.

Moreover, the fact that these activities take place in sea port environments brings its unique set of challenges that need to be addressed by the QRA. Sea port areas are generally complex, higher-risk environments that accommodate process industry, storage of dangerous goods and critical infrastructure (e.g. power plants), which themselves can be a source of risk. The handling of munitions in such environments must therefore be carefully coordinated with other activities in the area. Risk to people is thus not the only factor to consider; potential damage to various types of installations along with subsequent reactions, and the overall financial consequences have become important elements to also include in the QRA. Nevertheless, the risk to individuals and groups remains important. As sea port areas are often under continuous development, ensuring that a QRA is future-proof can be challenging, particularly because populations exposed to potential hazards may fluctuate considerably over time and location. Finally, it is important to assess the probability of an explosion by carefully considering the logistics of the transshipment process.

Above factors add to the complexity of potential accidents, underscoring the need for a reliable QRA methodology that fits transshipment scenarios. This paper presents the most recent risk methodology that addresses these challenges, and builds upon earlier research by TNO on this topic [2]. This paper is structured as follows (Figure 1): First, we discuss the accidental explosion scenarios and how accident probabilities are determined. Then, we present an overview of the models used to calculate explosion effects and consequences involved. Four key risk metrics are introduced hereafter and applied to a (hypothetical) case. We conclude with recommendations for future work.

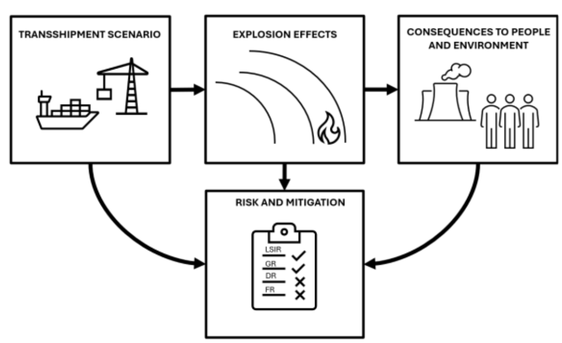

Figure 1: Overview of the risk model.

Accident scenarios

Accidents can occur during transshipment activities. There is a small probability that these accidents escalate into a large scale detonation reaction of the involved munitions. Examples of these accidents often include the collision of trucks or reach stackers, accidents during crane operations, etc. A more detailed breakdown of possible accidents is given in Ref. [3]. The QRA starts by defining accident scenarios, i.e. scenarios where an accident might leads to an explosion of the munitions. These scenarios provide the input to calculate the expected explosion effects and consequences. The probability and effects of a munition-related accident during transshipment is influenced by various factors, including the type of munitions, storage conditions, and logistical operations. Due to the complexity and variability of these factors, it is not feasible to model every detail. Therefore, we make simplifying, often conservative, assumptions about the transshipment scenario to enable manageable risk calculations. We identify three key aspects that define the scenario:

- Location of the Potential Explosion Site (PES)
- Net explosive quantity (NEQ)
- Probability of an accidental explosion.

The PES location is taken as the transshipment area where all ship-to-shore transshipment activities can take place, as illustrated in Figure 2. The area bounded by the red contour includes the quantity stored aboard, but also e.g. moving cranes and driving trucks taking part in munition handlings. This entire area will thus act as a source of the explosion, from which the explosion effects are projected to the surrounding area. By defining it as such, all transshipment activities in the area that may lead to an explosion are covered by the modelled explosion effects.

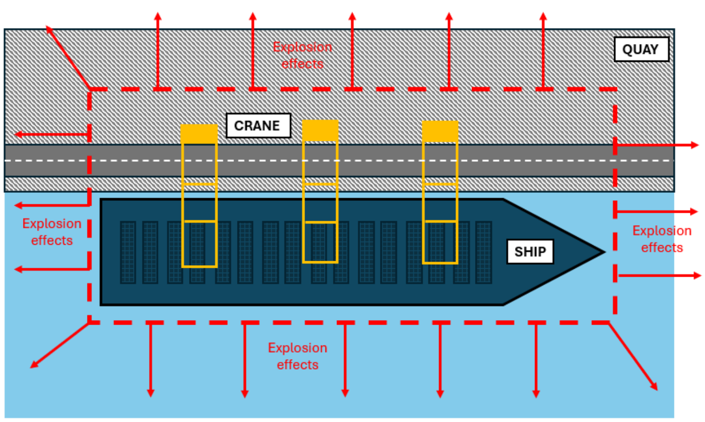

Figure 2: PES contour defined as the transshipment area

For the explosive quantity attributed to a PES area, we make the following assumptions:

- The maximum credible event (MCE) is equal to the aggregated NEQ of all ammunition and explosives aboard the ship(s) and vehicles involved with the transshipment, plus the total aggregated NEQ of all ammunition and explosives on the quayside.
- All munition is aggregated as HD1.1, except HD1.4 articles and explosives, which present little hazard in case of initiation. The explosion effects are thus consistent with a detonation of the full NEQ. Detailed reasoning behind this assumption can be found in Ref. [2].

Aggregating the full quantity is related to the required separation distances (IMD from AASTP-1 [1]) between ISO containers, in which the munitions are typically transported aboard ships. The IMD criteria cannot be met in practice given the storage configuration aboard the ship/train, or during the transshipment process. As an example, the IMD required according to AASTP-1 [1] to prevent sympathetic reactions between two ISO containers is Blast Distance (BD) 14. If we assume an upper bound to the NEQ that can be stored inside an ISO of 2500 kg HD1.1, the separation distance would become $4.8 \cdot (2500)^{\frac{1}{3}} \approx 65$ m. Since appropriate spacing between ISO containers cannot be maintained at all times, sympathetic detonations cannot be excluded and the quantity must be aggregated.

Sub scenarios

As HNS operations involve large amounts of munitions, scenarios can be further broken up into sub scenarios to help achieve acceptable risk levels. Two aspects of the transshipment process are considered in order to define such sub scenarios.

First, note that the amount of munitions aboard the ship gradually decreases during a transshipment, as munitions are moved to the train. This gradually reduces the risk exposure from PES ship during the process. By defining a sub scenario that contains the full NEQ for half the duration of a transshipment, and a second sub scenario that contains 50% of the NEQ for the other half of the duration, the risk calculation avoids being overly conservative. Currently, it is opted for a rough, stepwise reduction since the explosion effects and their consequences only show significant differences when the NEQ changes with a factor of 2. This is in part because explosion effects do not scale linearly with the NEQ [4] [5]. Increasing the amount of sub scenarios (for example, include those that correspond to 75% and 25% of the total NEQ) would result in small changes to the risk estimates that do not influence the outcome significantly.

Second, part of the munitions are eventually located in freight trains at a railyard. If this railyard is located far enough outside the transshipment area around the ship (Figure 2), a second PES location can be defined, i.e. PES train. This PES is bounded by the contour around the rail yard holding including a buffer zone where truck trailers are parked alongside the freight train. The NEQ associated with this sub scenario is equal to the train capacity, and some additional buffer with munitions present on the vehicles parked alongside. Note that the definition of this scenario strongly depends on the logistics of the sea port, and has to be closely coordinated with MoD personnel in advance. In order to define a separate PES ship and PES train, internal safety also must be checked through the IMD as prescribed in AASTP-1 [1]. Ony if the IMD is met, the two PES locations (i.e. ship, train) can be considered and modelled separately, because the total effects cannot be larger than the effects of a single PES. Note, however, that these separation distances are not tailored to an explosion aboard a ship, but generally apply to explosions in light structures such as rail-car or freight container loaded with munitions.

Probability of explosion

Next, the probability of an explosion is attributed to each (sub) scenario. To determine these probabilities, the possible causes in the form of accidents for an explosion are first mapped out. We follow the method presented in a report by the Health and Safety Executive (HSE) [6], which describes the relation between base accidents that can occur at each mode in the transshipment process to the probability of an accidental explosion resulting from that base accident. Base accidents include trucks on fire, collisions of trucks, fire on cargo ships, crane accidents with containers, and ship collisions among other things. Later, additional assumptions were introduced to adapt this method to the Dutch context [3]. This has resulted in the TNO Transshipment Tool (TTT) developed by TNO for this purpose [3]. The TTT has been used in QRAs for munition transshipments in the past [2]. Important input for the TTT is the number of handling actions conducted with containerized munitions, which strongly depend on the logistical procedure. This input is used to compute the probability of an explosive accident at each transshipment modality. The number of containers is estimated using historical transport data from the Dutch MoD. Including the annual frequency of the transshipment activity helps to distinguish between large quantities that occur only a few times per year, and more conventional transports by the MoD.

The probability for a (hypothetical) transshipment scenario is broken down in Table 1. In order to arrive at the total *annual* probability of an explosion for a transshipment scenario, the subtotal is multiplied by the projected number of annual transshipments. Furthermore, a safety factor of 2 is incorporated to account for uncertainties present in the historical data underlying the base probabilities [2].

Base accident	**Unit**	**Base accident /unit**	**Explosion /base accident**	P_e
Truck on fire	km	$5 \cdot 10^{-9}$	1	$1 \cdot 10^{-6}$
Truck collision	km	$1 \cdot 10^{-7}$	$1 \cdot 10^{-3}$	$2 \cdot 10^{-8}$
Train on fire	trains	$4 \cdot 10^{-9}$	1	$8 \cdot 10^{-9}$
Train derailment	trains	$3 \cdot 10^{-7}$	$1 \cdot 10^{-3}$	$6 \cdot 10^{-10}$
Accident with reach stacker	lift	$2.5 \cdot 10^{-6}$	$1 \cdot 10^{-3}$	$1 \cdot 10^{-6}$
Sub total				$2.031 \cdot 10^{-6}$

Table 1: Breakdown of the accident probability for a fictional case where 200 kms are driven by trucks, two trains are involved and 400 lift operations are performed by reach stackers.

Explosion effects and consequence models

Given the scenarios at hand, multiple models are employed that predict the explosion effects and related consequences that could occur as a result of these transshipment scenarios. Table 2 provides an overview of the explosion effects and consequence models employed in the QRA methodology, along with the corresponding output quantities calculated by these models.

	Explosion effects and consequences	***Quantities (units)***
Explosion effects	Air blast	Side-on peak overpressure (kPa), side-on peak impulse (Pa.s), positive phase duration (ms)
	Heat and fire	Fire ball radius (m), irradiance (W/m^2), burn duration (s)
Consequences	Free-field lethality (head-body injury [7], lung injury [7], thermal injury [8])	Probability of lethality (-)
	Inside-building (Gilbert) lethality	Probability of lethality (-)
	Damage to industrial installations	Heavy damage that may lead to significant domino reaction, light damage, no damage
	Damage to buildings and infrastructure	Description of damage level for various building types.

Table 2: Overview of explosion effects and consequence models.

Explosion effects

Air blast parameters are computed using the methodology presented in Ref [9]. We assume that the explosion can be modelled as a hemispherical TNT explosion emanating from the outer boundary of the defined PES contour. This is a simplified approach, but it serves as a good approximation in the far-field, which is most relevant for external safety assessments. Heat and fire effects are calculated using separate models for the fire ball and jet flame, both developed by TNO [10].

Debris and fragment effects are currently neglected in the QRA, mainly because this hazard from large scale explosive accidents onboard ships is not well understood and available models lack accuracy [11]. For example, the fragment model included in Dutch risk analysis software Risk-NL has not been validated for large quantities [10]. Available accident data does indicate that the fragment hazard is likely not leading for far-field lethality for large NEQs (> 500,000 kg TNT eq., as is often the case during HNS transshipments), but rather dominated by injuries related to building damage due to blast effects, see for example Ref. [12]. Modelling blast is thus likely adequate for assessing risk to people in the far field. In addition, damage to buildings resulting from large-scale explosive accidents can be primarily attributed to blast effects. In contrast, exposure of certain industrial installations to fragments may result in outcomes different from those caused by blast alone. Think of blast resistant storage tanks within several hundred meters of the PES location, which can withstand significant blast loads, but may still fail upon impact of high velocity fragments. One may think that Debris and Fragment Distances (DFD) from AASTP-1 could serve as an initial reference for determining safe distances. For example, DFD6 provides an equation for the distance at which domestic buildings can be safely sited given the debris and fragment hazard of ISO containers loaded with HD1.1. However, these DFD distances only reflect the hit probability of "hazardous" fragments striking the human body, which is insufficient for assessing industrial installation types of varying sizes and materials. Given the difference in exposed surface area between the human body and, for instance, storage tanks, the hit probability at DFD distance is considerably higher for the latter. To prevent such incidents, transshipment should ideally occur at locations far from (>km) vulnerable industrial facilities. If not, the possible consequences of this knowledge gap should be reported and discussed with the relevant parties, or a detailed study could be conducted to fill the knowledge gap.

Consequences

Consequence models in this QRA are broadly subdivided into lethality models and structural damage models, both of which require input in the form of explosion effects. Since we limit ourselves to blast and heat effects, the quantities in Table 2 will provide the input. Most lethality models are also implemented in the Dutch risk analysis software Risk-NL used for QRAs for munition storage depots [10]. These include the Gilbert model for inside-building lethality resulting from secondary explosion effects (e.g. building collapse, window breakage), and models for lethality of an unprotected person in the free-field, namely:

- Lung injury due to blast [7]
- Head-body injury due to collisions by blast [7]
- Injury by heat radiation [8].

The total free-field probability of lethality can be written as:

$$P_{l,FF} = 1 - (1 - P_{l,lung})(1 - P_{l,head-body})(1 - P_{l,heat}). \qquad (1)$$

The second category of consequences relate to structural damage to buildings, critical infrastructure and industrial installations that could lead to cascading effects. Note that these are additional consequences compared to the previous paper on this topic [2], but are considered important additions in this context. Especially in chemical and process industry, regulatory requirements and technical standards address the prevention and mitigation of cascading effects on industrial sites [13]. Given that the transshipments take place in relative vicinity to such industry, it is considered important to adopt these considerations in this QRA.

Damage thresholds for industrial installations are discussed in-depth in Ref. [14], which is a report based on literature (e.g. ACTA [15] , HSE [16]) and reconstructions of historic accidents near industry such as in Cyprus [17]. For large quantities of munition, blast waves will generally be the determining factor for damage to industrial installations and carry relatively high impulse. From the perspective of (P, I)-diagram, this implies that the blast load lies in the region of the static impulse asymptote, where only the peak overpressure determines the level of damage. For common industrial installations, peak pressure damage thresholds are given in [14].

Risk metrics

The transshipment scenarios, explosion effects and consequence models are used as input to calculate four risk metrics. Each of these metrics covers a different aspect of the risk associated with munition transshipments. As stated in the introduction, practical experience has shown that these QRAs must go beyond evaluating risk to people, both at the individual and group level. It is equally important to consider the potential for domino reactions within surrounding industry and the financial implications of damage. These dimensions are critical for developing a comprehensive understanding of the overall risk. Moreover, the outcome of each risk measure is useful as it can be compared to predefined assessment criteria, which often depend on national legislation or international agreements. This section summarizes the definition and calculation procedure of each of these risk measures.

Location-specific individual risk (LSIR)

Location-specific individual risk (LSIR) can be defined as the probability that an unprotected, continuously exposed person outside of the location dies as a direct result of an accident caused by the activity. We calculate LSIR using the flow chart depicted in Figure 3, which refers to the effect and consequence model described in the previous section. For the calculation procedure, the area around the PES is first discretized to a regularly spaced grid and LSIR is evaluated in each grid cell. For each transshipment scenario i, we compute the explosion effects based on the distance from the PES to each grid cell, and the resulting total free field lethality probability $P_{l,FF}$ according to Eq. (1). The LSIR for scenario i is calculated by multiplying the total free field lethality probability by the probability of explosion for that scenario:

$$LSIR_i = P_{l,FF} P_{e,i} \qquad (2)$$

The total LSIR for all scenarios combined then is calculated according to:

$$LSIR = 1 - \Pi_i \,(1 - LSIR_i). \qquad (3)$$

Iso-risk contour plots can subsequently be drawn based on the results stored on the calculation grid. For instance, Dutch legislation often uses the iso-LSIR contour where $LSIR = 10^{-6}$ is used to determine LSIR acceptance.

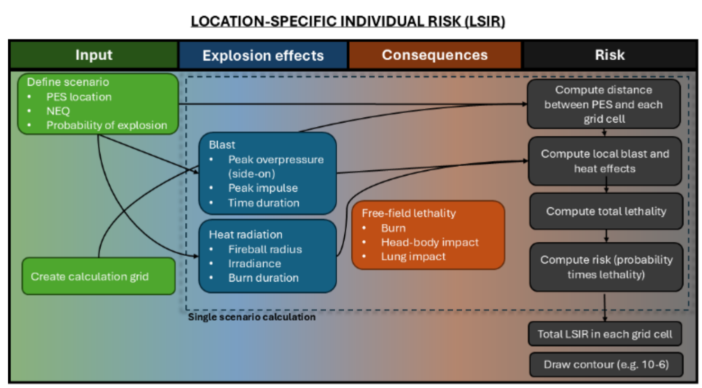

Figure 3: Flowchart outlining the calculation procedure for LSIR, indicating the required user input, explosion effects and consequence models.

Group risk (GR)

Group risk is defined in the Netherlands as the probability that ten or more persons will die as a result of an accidental explosion at the PES. According to Dutch regulations, incidents causing fewer than ten fatalities are not classified as group risk. GR accounts for the presence of concentrated groups of people at specific locations, as well as the added protection or hazard due to the presence of buildings. Figure 4 outlines the calculation procedure for GR. In addition to the scenario input, the GR calculation also requires a population file. The Dutch government maintains public population databases [18] that can be used as the basis for a population file. This data can be amended with additional input from local stakeholders, such as the port authority. The population file contains the expected number of people present inside and outside each building during daytime and nighttime. For to-be-developed areas or recreational areas (e.g. beaches), areal population densities are assumed based on national guidelines [18]. Populations related to roads, railways and waterways (e.g. passers-by, truck drivers, boat passengers) are not accounted for in GR in the Netherlands, but may depend on national legislation. Based on the population file and expected total lethality, the number of expected fatalities per building is determined per scenario according to Eq. (4). Note that different lethality models apply to the population outside N_{FF} and inside buildings N_{IB}:

$$N_{building} = P_{l,FF}N_{FF} + P_{l,IB}N_{IB} \quad (4)$$

The total number of fatalities for a scenario is found by summing over all buildings contained in the population file. By doing this for each defined scenarios, the GR outcome can be represented by an $F(N)$ −graph, where F is the cumulative annual probability and N the number of expected fatalities. This is a common means of presenting information about group risk, or societal risk [19]. This curve can be assessed against orientation values, or to quantify the effect of risk mitigation measures. Other GR visualization methods are currently also being explored.

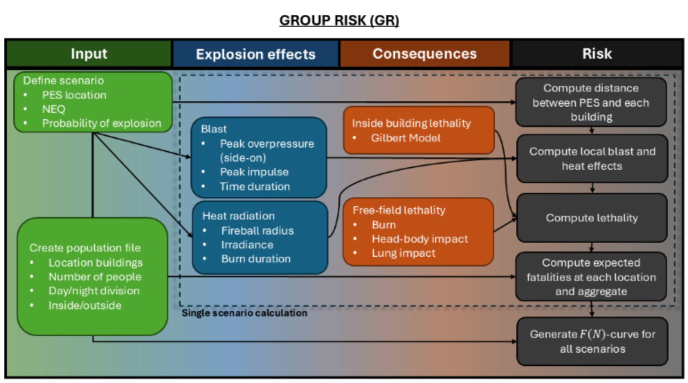

Figure 4: Flowchart outlining the calculation procedure for GR, indicating the required user input, explosion effects and consequence models.

Domino reactions (DR)

Domino reactions (DR) are defined as either:

- The loss of containment of dangerous substances, which pose a direct hazard to human health;
- Total loss of power generating production at a power plant.

If an accidental explosion is expected to trigger DR, mitigation strategies may be required to arrive at an acceptable level of risk for all parties involved. In general, large scale domino reactions should be avoided. To assess whether a domino reaction is likely to occur it requires three steps:

1. Identify vulnerable locations
2. Establish a damage threshold for each vulnerable location
3. Check if the expected effects exceed the damage threshold.

Damage thresholds for loss of containment or total loss of power production can be found in Ref. [14], which gives threshold values for heavy damage $p_{th,h}$ (kPa) and light damage $p_{th,l}$ (kPa) for typical industrial installation types such as oil storage tanks, pressure vessels and pipe bridges. The subsequent damage level is determined according to:

$$[\text{Damage level}] = \begin{cases} \text{No damage} & \text{for } p < p_{th,l} \\ \text{Light damage} & \text{for } p_{th,l} \leq p < p_{th,h} \\ \text{Heavy damage} & \text{for } p \geq p_{th,h} \end{cases} \quad (5)$$

Evaluating the subsequent effects of a DR (e.g. determining the scale of a loss of containment, or increased lethality risk) is beyond the current assessment method's scope. In the Netherlands, DR must be avoided. Output of the DR analysis is given in a table with damage levels for each industrial installation per scenario. Alternatively, iso-pressure contours are visualized on a map relating to specific pressure damage thresholds. This damage contour can be used for spatial planning purposes, in coordination with local stakeholders.

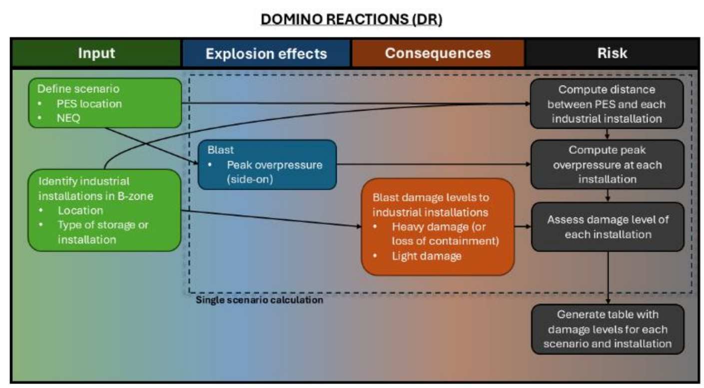

Figure 5: Flowchart outlining the calculation procedure for DR, indicating the required user input, explosion effects and consequence models.

Financial risk (FR)

Financial risk gives an indication of the expected financial losses (in EUR or USD) in case of an accidental explosion. This metric can be informative for example during international operations, when the host nation and the sending nation are different. Currently, this number is based on the expected damage of buildings and infrastructure in the surroundings. More specifically, it includes the predicted rebuild cost after buildings are damaged by worst-case explosion. The blast damage models are based on analysis and interpretation of accident and test data from various sources [20] [21] [22]. Subsequently, the damage is translated to a financial loss percentage. Input (besides the scenario) required for FR calculations is thus relevant building data such as value, construction type (masonry, RC-moment frame, pre-engineering metal buildings, etc.), or other infrastructure that needs to be included. Other types of damage (and costs) in the form of e.g. damaged ships, loss of inventory, down-time of port facilities are currently not included in the estimate. Thus, this risk metric is purely informative and provides a lower bound estimation of the financial loss in case of an accidental explosion.

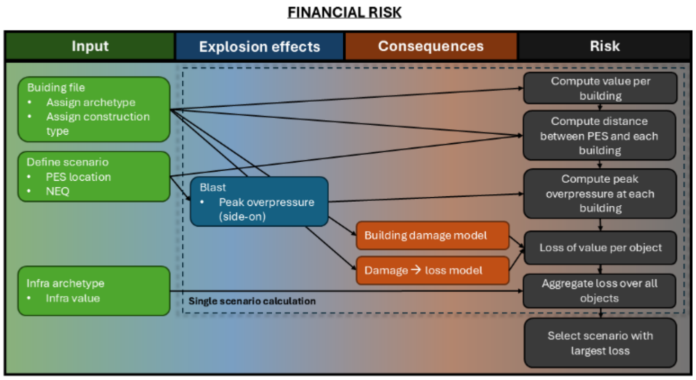

Figure 6: Flowchart outlining the calculation procedure for FR, indicating the required user input, explosion effects and consequence models.

Case study

To illustrate its use, we apply the risk model presented in this paper to a fictional case study. <u>Note that the location, quantities involved in the transshipment process, explosion probabilities and outcomes are for illustrative purposes only.</u> The transshipment location consists of a ship and train location, separated by roughly 300 m, as visualized in Figure 7. The key descriptors of the transshipment scenarios are given in Table 3. Two scenarios are included:

- **Scenario 1**: Transshipment of a large quantity of munition from ship to train, which occurs only a few times a year. As the IMD criteria can be met (see Figure 7: PES locations and corresponding IMD contours from AASTP-1.Figure 7), the scenario is broken up in a sub scenario for the ship (Scenario 1a) and the train (Scenario 1b).
- **Scenario 2**: Transshipment of a smaller quantity of munition from the ship directly onto trucks, which can occur more frequently on a yearly basis. All transshipment activities occur within the area defined as PES ship.

Scenario	Location	NEQ (kg TNT eq.)	Freq. (year^{-1})	Annual probability of explosion
1a	PES Ship	200,000	4	$1.5 \cdot 10^{-5}$
1b	PES Train	100,000	4	$3 \cdot 10^{-5}$
2	PES Ship	100,000	40	$1 \cdot 10^{-4}$

Table 3: Case study transshipment scenarios and sub scenarios. Annual explosion probabilities account for all base accidents that might occur during a full year of operation, accounting for the required transshipment capability at the transshipment site.

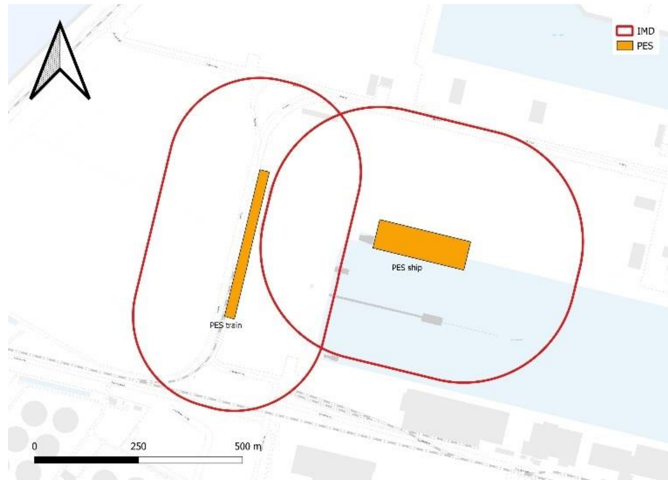

Figure 7: PES locations and corresponding IMD contours from AASTP-1.

Following the risk model from this paper, LSIR is first calculated in each grid cell as defined on the map. Based on this grid, an iso-LSIR contour can also be drawn, for example where LSIR is equal 10^{-6} as is visualized in Figure 8. These iso-contours aid stakeholders to communicate and accept risk, for example, by distinguishing which activities or types of land-use zones are allowed within certain risk zones.

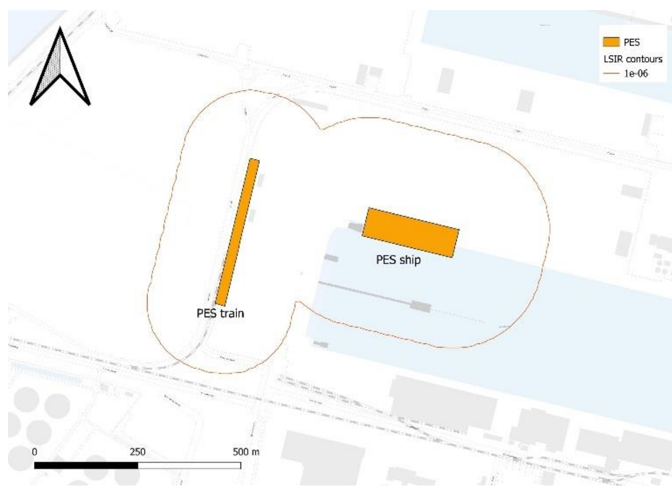

Figure 8: The total LSIR of all scenarios combined, represented by an iso-contour of 10^{-6}.

Next, we calculate GR, which is expressed in the form of an $F(N)$-graph. Figure 9 shows the case study scenarios, both in case of daytime (green) and nighttime (yellow) operation. Each point on the graph(s) corresponds to a single scenario (either 1a, 1b or 2). The orientation values that are commonly maintained in the Netherlands are also plotted in the same graph. Note that the GR exceeds these orientation values both during daytime and nighttime transshipment operation, although the risk is significantly reduced during nighttime scenarios. It may therefore be necessary to explore additional risk mitigation strategies. Strategies to reduce GR can include, for instance, implementing evacuation and calamity planning procedures. Again, it is stressed however that this case study is purely hypothetical.

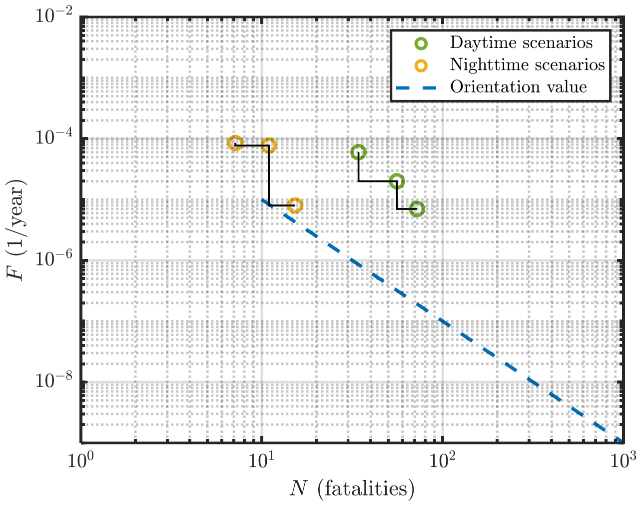

Figure 9: $F(N)$-curve, where the cumulative annual probability is plotted against the number of fatalities per scenario. The dotted line indicates common orientation values for GR.

To asses domino reactions, a location scan is first required to identify installations potentially vulnerable to DR, which would typically be verified through site visits. For this case study, we limit ourselves to two installations, namely an oil storage tank depot and a power plant, located in relative vicinity of the transshipment area. Table 4 summarizes the outcome of the DR assessment for these locations. At both locations, the damage threshold is not met based on the expected overpressure, so domino reactions are not expected. For all scenarios, the light damage threshold at the oil storage site is exceeded (~7 kPa), but this level of damage does not result in domino reactions. To give further insight to local stakeholders in light of future developments, iso-pressure contours based on relevant damage threshold are also provided. Figure 10 shows the iso-pressure contour for 21 kPa based on the largest ship and train scenario. Such contours can help in siting new facilities, or put requirements on the specific installation type.

Facility	**Damage threshold (kPa)**	**Sc. 1a (kPa)**	**Sc. 1b (kPa)**	**Sc. 2 (kPa)**
Oil storage site	Heavy: 21 Light: 7	10.4	18.2	7.74
Power plant	Heavy: 21 Light: 7	2.52	2.37	2.37

Table 4: Results of the DR assessment. Yellow boxes indicate light damage and green boxes no damage.

Figure 10: Pressure damage threshold contour of 21 kPa, including PES locations and potentially vulnerable sites.

The financial risk assessment leads to the results presented in Table 5, which includes the estimated financial loss, the loss relative to the total value, and the expected annual loss. The latter is found through multiplying the expected loss with the accident probability for each scenario. Alternatively, FR can be visualized on the map per building as in done in Figure 11. The colors help identify the largest contributions to FR.

Scenario	**Estimated loss [10^6 EUR]**	**Relative loss [% of total value]**	**Expected annual loss [EUR]**
1a	155	20.2	2326
1b	112	14.6	3356
2	135	17.7	13,540

Table 5: Results of the FR assessment.

Figure 11: Visual representation of FR assessment with the color indicating the annual expected loss per building.

Conclusions

The method described in this paper has described a risk model for large-scale munition transshipments that is more complete than its previous versions, and can be specifically tailored to the scenario at hand. First, transshipment scenarios are defined more accurately, e.g. by means of sub-scenarios. Second, the notion of risk was extended to include damage to buildings and critical infrastructure, as well as domino reactions. This has complemented the QRA in important ways to account for the unique environment of a sea port, by not exclusively considering risk to people. All in all, this paper has laid important groundwork for assessing risk during large-scale munition transshipments, and is already used to inform decisions on risk mitigation and acceptance in the Netherlands.

Recommendations and future work

The QRA method is in ongoing development and can be improved in several ways. Improved models for both the effects and consequences can be easily incorporated into this method. For example, in case that munition is stored internally in the ship, blast wave propagation may be affected by the surrounding ship structure which is currently not accounted for. Also, taking into account debris and fragments could provide necessary insight into added risk to certain types of industrial installations. The goal is to incorporate such models eventually in future versions of this risk model. Future work could also consider the risk of domino reactions in more detail. For example, damage is now assessed based on peak overpressure, but comparison to pressure-impulse (P, I)-curves could provide more insight and is especially relevant for smaller NEQ. The benefit of the presented approach, however, is that the general QRA framework remains valid while the individual models can be continuously updated and improved.

Although not explicitly mentioned in the paper, significant progress has also been made on implementing the risk calculation procedure in Python and QGIS. Automation of the calculation procedure in combination with dedicated modules for explosion effects and consequences are making the risk model increasingly user-friendly.

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Appendix

The Appendix is one-column. If you have an appendix in your document, you will need to insert a continuous page break and set the columns to one. If you do not have an appendix in your document, this paragraph can be ignored and the heading and section break deleted.