Quantitative Risk analysis of ammunition transshipments in harbors

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Abstract

Ammunition transshipments are a key part of the logistical operations of the armed forces and are often executed via ships. These transshipments pose a risk to the people present in the area surrounding the harbor, where the loading/unloading of the ship takes place. A method is presented to perform a quantitative risk assessment of such ammunition transshipments, where a scenario based approach is used. Engineering models are used to calculate the possible explosion effects (blast, debris/fragments and heat radiation) and Probit relations are used to determine the probability of lethality for unprotected persons. Two well-known concepts to describe third party risk are used to show a practical example of the risk analysis method. With this quantitative method an assessment can be made if the planned ammunition transshipments do not create too great a risk for the people in the area surrounding a particular harbor.

Introduction

Part of the logistical operations for the armed forces involve the transport of ammunition and explosives to for example military bases. In case of an out of area mission generally significant amounts of ammunition and other supplies have to be transported over large distances, often by ship. In a harbor the ship is loaded / unloaded by transferring the ammunition containers from trucks/trains to the ship, or vice versa. As a result of this transloading, large quantities of ADR Class 1 ammunition and explosives are handled in the harbor before stored aboard the ship. The transloading of ammunition in ISO containers in a harbor poses a potential risk to the surrounding area, the third party risk (TPR), in the unlikely event of an explosion. Stakeholders need to be able to make a proper assessment of the risk posed by this transloading, so an informed decision can be made if the risk to the surrounding area, especially to the people in the area, is at an acceptable level. For this purpose, a quantitative risk assessment (QRA) can be performed.

In this paper a method is presented to perform a QRA of the transloading of containers filled with ammunition/explosives to/from a ship in a harbor. A step-wise approach is used where first, a set of scenarios is determined for a specific harbor and for the planned transshipments on a yearly basis. This set of scenarios defines the total amount of ammunition and explosives that need to be transshipped in a specific harbor, in a specific period (a year), over a number of transshipments, a number of containers per transshipment, etc. Then, for each individual scenario, the probability of an accidental explosion is calculated. For each individual scenario, the explosion effects, such as the blast and launched debris, are calculated. With the use of lethality models, the expected levels of lethality for points of interest, such as specific buildings in the harbor, are calculated. To calculate the level of risk, the probability of an explosion and the expected level of lethality are needed as input. Two common concepts for the TPR are the Individual Risk (IR) and the societal or group risk (GR).

Additionally, the results of a QRA can be used to define the maximum amount of Class 1 ammunition and explosives that can transshipped on a yearly basis in a particular port, while keeping the level of risk for the surrounding area to acceptable levels.

Risk associated with ammunition transshipments

When transshipping ammunition or explosives there is an inherent probability that an accident occurs that can lead to an accidental explosion of the involved ammunition. Such an explosion can lead to casualties and damage in the surrounding area. For a risk analysis the risk is defined as the consequence of an event multiplied with the probability of a such an event occurring. In a risk analysis involving the transport/storage of ammunition the consequence is often expressed as the expected number of lethal injuries per year or the probability per year of a lethal injury. Here, the probability of an event is the probability of an accidental explosion during an ammunition transshipment, P_{expl}. In order to determine that probability, possible causes for an explosion need to be defined. A study conducted by the English Health and Safety Executive (HSE) gives a good overview of the accident types that can lead to an explosion [1]. The study identifies fire, and an impact or collision as main types of accidents that can cause an explosion during a transshipment in a harbor. In more detail these accidents are describes as:

- Fire in a vehicle that damages the cargo;
- Accident or collision of a vehicle that damages the cargo;
- Accident with a crane that damages the cargo;
- Fire aboard a ship that damages the cargo (in this paper only container/general cargo/CONRO ships are considered where the cargo is stored on the top deck);

The study [1] does mention other causes, but these are not considered here, as they are relevant only for other modes of transport. With the now known accident causes, the chances on these events (the event frequency) and the resulting probability of an explosion due to these events can be defined. The HSE study [1] provides this probability of an explosion per event, $P_{expl,event}$, see Table 1. It is clear that not every accident leads to an explosion, as in general military ammunition is quite robust and is designed not to initiate accidentally. It must be noted that these probabilities are based on historic data. Because the historic data is quite scarce, there is quite some uncertainty in these numbers, estimated to be up to a factor of 2. To be conservative in the estimate of the total probability of an explosion during an ammunition transshipment, the total probability is multiplied with a safety factor of 2.

Table 1 Frequencies of accidents and associated probability of an accidental explosion.

Event, unit	Event frequency / unit	Probability of explosion / event
Fire in a vehicle, km	$5.0 \cdot 10^{-9}$ / km	1.0
Accident or collision with a vehicle, km	$1.0 \cdot 10^{-7}$ / km	0.001
Fire aboard a CONRO/general cargo, # of ships	$1.0 \cdot 10^{-6}$ / ship	1.0
Fire aboard a container ship, # of ships	$2.0 \cdot 10^{-8}$ / ship	1.0
Crane accident with container, # of crane moves	$2.0 \cdot 10^{-6}$ / move	0.011

From these numbers it can be seen that a crane accident and a fire aboard the ship are most likely to occur. In order to find the probability of an explosion per type of accident, one has to multiply the event frequency with the probability of an explosion per event. For example, the probability of an explosion caused by an accident during a crane move is calculated to be $2.2 \cdot 10^{-8}$ / crane move.

To calculate the total probability of an explosion for an ammunition transshipment the following equation can be used[1]:

$$P_{expl} = 2 \cdot \sum P_{event} \cdot N_{event} \cdot P_{expl,event} \tag{1}$$

Where P_{expl} is the total probability of an explosion per transshipment, P_{event} is the probability of a type of accident occurring, N_{event} is the amount of times the event occurs in a transshipment and $P_{expl,event}$ is the probability of an explosion as a result of the considered accident type.

Scenarios

The goal of the QRA is generally to calculate the risk of all transshipments that are planned to be performed in a particular harbor in a single year. The risk of each transshipment is calculated and added up to determine the total risk. The first step is to define scenarios, where each scenario contains a set of planned transshipments with the same representative net explosive quantity (NEQ). All scenarios combined represent all the transshipments that are planned

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[1] The probability of an explosion as a result of event A is P, the probability that no explosion occurs is $1 - P$. The probability of at least one explosion with N occurrences of A is equal to 1 minus the probability that no explosion occurs with N occurrences of A, so $(1 - (1 - P)^N)$. If $P \ll 1$, than this can be approximated with $N \cdot P$ (such that $N \cdot P$ still remains $\ll 1$).

in a particular harbor in a single year. Each scenario also contains other parameters needed to be able to calculate the probability of explosion, the explosion effects and consequences.

As the NEQ is quite a dominant factor for the magnitude of the explosion effects and thus the consequences to the environment, and the NEQ roughly determines the size of a transshipment (e.g. number of containers involved), all other parameters in a scenario are related to the representative NEQ for that scenario. The scenarios that are used in the QRA contain the following parameters:

- The representative NEQ in kg TNT of all munition articles involved in a single transshipment;
- Number of planned transshipments, with the chosen representative NEQ, in a single year;
- NEQ per ISO container based on the representative NEQ of a scenario;
- Number of containers per transshipment based on the representative NEQ of a scenario;
- Number of kilometers travelled by vehicles used in a single transshipment based on the representative NEQ of a scenario;
- Time taken to complete transshipment based on the representative NEQ of a scenario;

To help establish how many transshipments with a certain representative NEQ need to be planned in a particular harbor on a yearly basis, historic data can be used. A cumulative (relative) distribution of the NEQ of all transshipments performed in a certain time period can provide insight into for example the number of transshipments with a certain NEQ. For such a distribution, the NEQ of each transshipment is collected, sorted on increasing NEQ order and plotted as relative distribution. An example of such a distribution is given in figure 1.

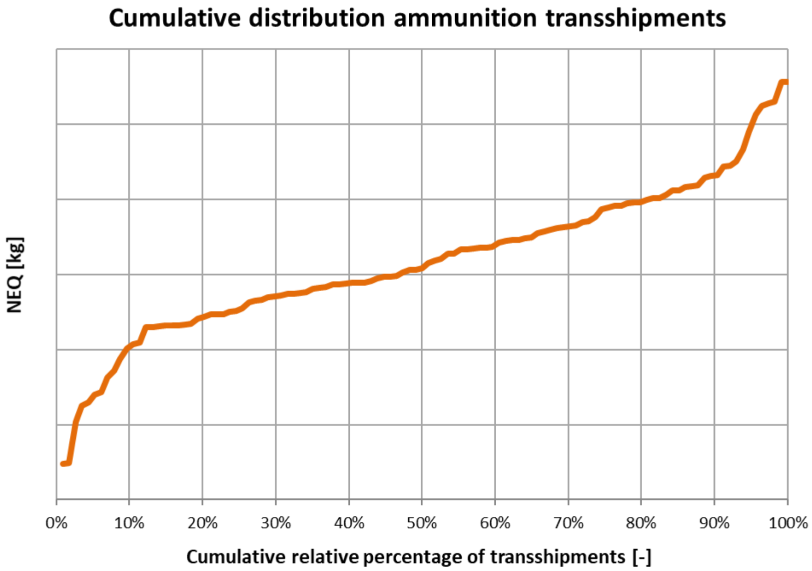

Figure 1: Cumulative distribution of the NEQ NL ammunition transshipments. Based on data from the Dutch Ministry of Defence from the period 2002-2015.

The NEQ that can be stored into one 20-ft ISO container is dependent on many factors, one of these is how efficiently the ammunition articles can be positioned inside the container. From data obtained from the Dutch MoD it is found that this packing efficiency increases when larger volumes of the same munition articles are transshipped or in general when transshipments involve higher NEQ's. In this paper it is assumed that the NEQ per ISO container mostly depends on the representative NEQ of a scenario, with a maximum of roughly 2,500 kg NEQ for one 20-ft ISO container.

The number of containers per transshipment based on the representative NEQ of a scenario is thus found with the NEQ per ISO container for that scenario. The amount of containers involved is directly determined from the representative NEQ value for that scenario (total NEQ divided by NEQ/container equals the number of containers).

During a transshipment various vehicles can be involved, apart from the cargo crane, e.g. trucks or reach-stackers. As these vehicles are a possible source of an accident that can lead to an explosion, these need to be accounted for in the probability of an explosion. In this paper it is chosen to represent this probability by the amount of travelled vehicle kilometers. For each container a number of vehicles need to travel a certain distance to load / unload the container from a ship. So, with the known number of containers per transshipment based on the representative NEQ of a scenario and the travelled distance per container that is transshipped, the total number of kilometers travelled by vehicles used in a single transshipment, based on the representative NEQ of a scenario, can be determined.

The time it takes to fully complete a single ammunition transshipment is an important parameter as well, as it governs the amount of time the surrounding area, and thus the people in this area are exposed to the risk originating from that transshipment. The time needed for a transshipment largely depends on the amount of containers that need to be transshipped plus a fixed amount of time that is needed for mooring/departing preparations, etc. Again, if the number of containers per transshipment based on the representative NEQ of a scenario is known, the total transshipment time is easily determined.

For the QRA assumptions are made on the munition involved in a transshipment, type of ship involved and location of the possible explosion site (PES). The assumptions are listed below:

1. The maximum credible event (MCE) is assumed to be: the total 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;
2. The munition articles and explosives belonging to Hazard Division (HD) 1.4 present only a small hazard in the event of initiation [2], and are thus not accounted for the in the total aggregated NEQ, i.e. MCE, of an ammunition transshipment;
3. All munition articles and explosives involved in a transshipment are considered to be HD 1.1, expect the HD 1.4 articles and explosives;
4. If multiple ships are involved in a single transshipment, e.g. ships docked at the same quay, the NEQ of all munition articles and explosives aboard all involved ships should be aggregated. The aggregated NEQ aboard the ships combined with the NEQ of all ammunition and explosives on the quay side or aboard other vehicles equals the total NEQ of a transshipment with multiple ships, i.e. the total amount is the MCE here;
5. The type of ship involved in an ammunition transshipment is assumed to be either a CONRO, container and roll-on/roll-off, container or general cargo ship where the container with ammunition are stored above deck aboard the ship.
6. The location of the PES is assumed to be the location of the container crane(s) that is (un)loading the ship(s). In case there are multiple cranes (un)loading the ship(s), each crane location is considered to be a PES. In that case, the probability of an explosion per crane location is reduced, and becomes equal to the total probability of an explosion, for the scenario representative for that particular transshipment, divided by the number of cranes involved. The total probability of an explosion does not directly depend on the number of cranes involved, but on the number of crane movements, vehicle kilometers and type of vehicles/ships involved.

The reason that the MCE is assumed to be the total aggregated NEQ of all ammunition and explosives involved in the transshipment is that the required separation distances, to prevent sympathetic detonation, cannot be met in practice. The required separation distances, called quantity distances (QD's), for military munition articles and explosives are for example given in the NATO publication AASTP-1 [2]. From this publication the required QD between two ISO containers filled with 1,000 kg NEQ of HD 1.1 ammunition is 50 meters. Aboard a ship this requirement simply cannot be met. Because sympathetic detonation of all ammunition involved in the transshipment cannot be excluded, the MCE is assumed to be the total aggregated NEQ of all involved ammunition and explosives, excluding HD 1.4 articles.

The ammunition mixing and aggregation rules described in the NATO publication AASTP-1 state that when articles of HD 1.1 are mixed in storage with the articles of HD 1.3/1.5/1.6, the NEQ of all articles should be aggregated as HD 1.1. The AASTP-1 gives two options for the mixed storage of HD 1.1 and 1.2: 1) The NEQ of all ammunition is aggregated as HD 1.1, or 2) only the HD 1.2 is considered. The option that provides the largest QD needs to be adopted. For an ISO-container, the first option (aggregate the NEQ of all ammunition involved as HD 1.1) will always require equal or larger QD's than the second option. Therefore, it is assumed that all ammunition and explosives involved in a transshipment should be aggregated as HD 1.1.

To aggregate the NEQ of all ammunition aboard all ships involved in the transshipment is a conservative assumption. In some docking configurations (for example back-to-back), it is possible that the ships themselves act as a barrier providing protection against sympathetic detonation. It is left to the expert(s) involved in a risk analysis to make the decision to keep this assumption or to choose otherwise.

Currently the models that are available to describe the explosion effects cannot properly account for ammunition stored below deck aboard a ship. In such a case, the construction of the ship could add to the debris being launched from an explosion, on the other hand the ship will provide some protection against fragments being launched and influences the blast generated by the explosion. In case the ammunition is stored on top of the cargo deck the debris and fragments generated by the ammunition stored in the containers are dominant and no substantial contribution from the ship itself is expected. Also the blast from the explosion is minimally influenced.

During the transshipment many vehicles e.g. trucks and reach-stackers will drive across the harbor with ammunition containers and thus have no fixed location. A good assumption for the location of the explosion is to select the location that provides the highest probability of an accident. The location of the container crane that is (un)loading the ship is a good selection. The crane has the high contribution to the total probability of an explosion in almost all cases. Because it is close to the ship and all vehicles transporting ammunition containers will come close to the crane, this is deemed the best fixed location for the PES.

Explosion effects and lethality models

To calculate the risk associated with an ammunition transshipment, models are needed to calculate the effects of an explosion. In this paper engineering models are used to determine the effects of an explosion of a certain NEQ [kg TNT]. The following effects are included in these models:

- The side-on peak pressure for HD 1.1 explosions;
- The side-on impulse for HD 1.1 explosions;
- The positive phase duration for HD 1.1 explosions;
- The fragment and debris launch for HD 1.1 and 1.2 explosions;
- The heat radiation for HD 1.3 explosions.

The blast parameters, pressure, impulse and positive phase duration, are determined using the same relations as in the DDESB Blast Effects Computer [3]. The used debris model is a simplified version of the Klotz Group software, developed in an international group of experts in the field of explosives safety, in which TNO also participates [4, 5]. The fragmentation model is thoroughly described in a report by TNO. It first calculates the initial launch conditions and fragment size distribution, then the ballistic flight conditions and finally the impact conditions and target penetration [6]. The heat radiation model is subdivided into a fire ball model and jet flame model, both developed by TNO [6].

The current models for the debris and fragment launch from an ISO-container are axisymmetric (i.e. rotationally symmetric with respect to a central vertical axis). From tests it is known this is a crude assumption [7], yet it simplifies the analysis. As the explosion effects are modelled axisymmetric, only the distance to the PES is relevant for the magnitude of the effects.

For the risk analysis the effects of an explosion need to be related to the potential consequences. For a QRA it is common to look at number of expected fatalities in the surrounding area. To determine the number of fatalities, models are needed to calculate the probability of a lethal injury, due to a specific explosion effect or combination of explosion effects. For this purpose Probit relations are used, generally having the form:

$$Pr = A + B \cdot \ln X \tag{2}$$

Where A and B are constants and X is the variable that is related to a particular explosion effect, e.g. side-on peak pressure, or combination of explosion effects. The Probit values can then be converted to probabilities (P) using:

$$P = \frac{1}{2} \cdot \left(1 + \operatorname{erf}\left(\frac{Pr-5}{\sqrt{2}}\right)\right) \tag{3}$$

Where P is the probability of lethality, Pr is the previously calculated Probit value and erf is the Gauss error function.

A distinction is made between models that calculate the probability of lethality for people in the open field and for people inside buildings. In this paper all people are assumed to be unprotected (i.e. not wearing protective equipment of any kind). For people in the open field the following lethality models are implemented:

- Probability of lethality for an unprotected person due to impact of fragments and debris [8];
- Probability of lethality for an unprotected person due to blast effects, subdivided in:
  - Lethal lung injuries [8];
  - Lethal head or body injuries due to collision with an object (both stationary or launched) [8];
- Probability of lethality of an unprotected person due to heat radiation effects [9].

For people inside buildings the following lethality models are implemented:

- The probability of lethality for people inside buildings due to a combination of secondary explosion effects, such as collapsing buildings, window failure, blast effects inside a building, etc. [10];
- Probability of lethality for people inside buildings due to impact of fragments or debris [8];

For the risk assessment the probabilities of all the above mentioned causes of lethal injuries are added up to a single probability of a lethal injury, either for a person in the open or in a building, for a specific position relative to the explosion source, expressed in a distance to the explosion.

Individual risk

A common concept to describe TPR, third party risk, in QRA for ammunition storage / transport is individual risk (IR). In the Netherlands, IR is defined as (translated from Dutch law):

Risk for an arbitrary location outside a site, expressed as the probability per year that a person suffers lethal injuries as a direct result of an accident within the site, where a hazardous substance or hazardous waste is present, given that the person is unprotected and continuously present on the arbitrary location.

In this definition of the IR it is assumed that buildings are not present at the considered location, regardless of the actual situation. Also, the person is defined to be continuously present, which means that the magnitude of the IR is solely determined by the properties of the PES. To determine the IR, all transshipments that are planned to be performed in a particular harbor in a single year are considered. The scenarios contain all these transshipments, so for each scenario the contribution to the IR is calculated and all contributions are added up to determine the total IR. For an arbitrary location *A* at distance *r* from the PES, and for scenarios *i* = 1 to n, the total IR is determined as follows:

$$IR\ (r) = \sum_{i=1}^{n} P_{expl,i} \cdot P_{lethal}(NEQ_i, r) \cdot N_i \tag{4}$$

Where $P_{expl,i}$ is the probability of an explosion per transshipment for scenario i, $P_{lethal}(NEQ_i,r)$ is the probability of a lethal injury as a function of the representative NEQ_i of scenario i and distance r to the PES, and N_i is the number of planned transshipments in a single year for scenario i. Now that for any arbitrary distance r the IR can be calculated, the result can be presented in iso-risk contours.

To determine if the risk to third parties is at an acceptable level, a limit value for the IR is used. A common limit for the IR is $1.0 \cdot 10^{-6}$/year for inhabited objects, meaning that at the location of an inhabited object the IR may not be higher than this limit value.

To give an example, for an arbitrary harbor a set of three scenarios is defined in Table 2. The three scenarios contain all transshipments that are planned to be performed in the considered harbor in a single year. To determine the total IR the contribution of each of the transshipments of each scenario to the IR is calculated and added up. For the three scenarios, given in Table 2, the $1 \cdot 10^{-6}$ IR-contour is presented in Figure 2 on a map of a arbitrarily chosen harbor in the Netherlands. The calculations show that the $1.0 \cdot 10^{-6}$ IR-contour, for the three example scenarios combined, is located at a distance of 465 meters from the PES. With the IR-contour an assessment can be made if the considered harbor can accommodate the ammunition transshipments without creating too much risk for the surrounding area. Such an assessment typically considers inhabited buildings, critical infrastructure, recreational facilities etc., however this is out of the scope for this paper.

Table 2 Overview of three example scenarios for a particular harbor and the associated probability of an accidental explosion.

NEQ [kg TNT]	Number of transshipments per year [-]	NEQ per container [kg TNT]	Number of containers [-]	Distance travelled by vehicles [km]	Time to complete transshipment [hours]	Probability of accidental explosion [-/year]
1,000	10	500	2	1	3	$1.36 \cdot 10^{-6}$
10,000	10	2,000	5	2,5	3	$2.86 \cdot 10^{-6}$
100,000	5	2,500	40	20	6	$1.00 \cdot 10^{-5}$

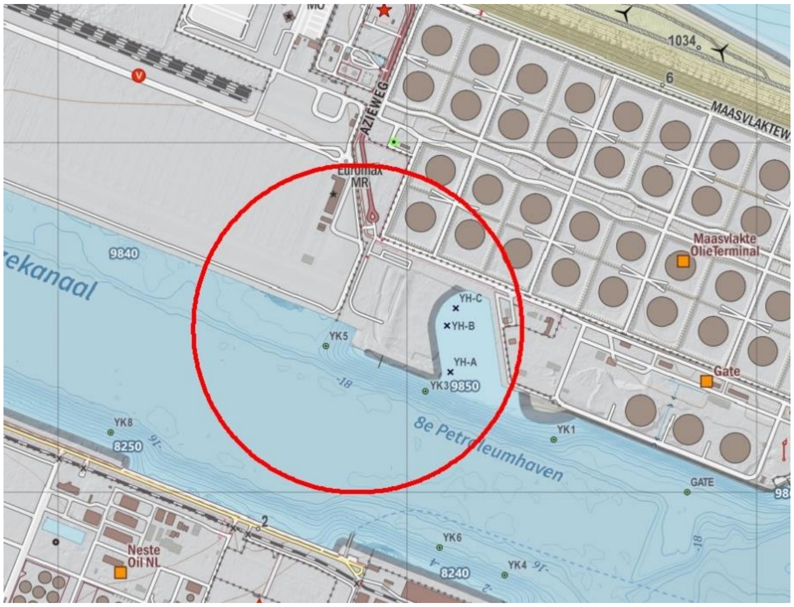

Figure 2 Plot of the 1.0·10^{-6} IR-contour, for all three scenarios in Table 2 combined, on a background map (source of map: 'www.opentopo.nl').

Group risk

A second common concept used to describe TPR in QRA's for ammunition transport / storage is referred to as the societal risk or group risk (GR). The GR is expressed in a cumulative F(N) curve, which presents the cumulative frequency per year that N or more fatalities can occur as a direct result of an accident involving the ammunition. Again, all transshipments that are planned to be performed in a particular harbor in a single year are considered. In this paper only fatal injuries as a direct result of an explosion are considered for people that are located outside the site, where the transshipment takes place. Also, this paper only considers people that are not involved with the ammunition transshipment, i.e. third parties. These individuals can for example work in an office building located near the site where the transshipment takes places. For the GR the actual surrounding area of the transshipment site is important, contrary to the IR.

To calculate the GR, for each scenario the expected number of fatalities is calculated, using the appropriate lethality models and the presence of people within the area of influence (the area where lethal injuries can be expected as a result of an explosion). The frequency per year that an explosion can occur is equal to the probability of an explosion for each scenario, just as for the calculation of the IR. To calculate the cumulative frequency that N or more fatalities occur, the expected number of fatalities per scenario is sorted in decreasing order and these frequencies are cumulated.

The following data are needed to calculate the GR:

1. Size of surrounding area, where lethal injuries can be expected as a result of an explosion during the transshipment (area of influence). The size of the area of influence is assumed to be the 'inhabited building distance' (IBD) [2], as PES an ISO-container should be used.
2. Details on the presence of people within the area of influence:
   a) Location of occupied objects relative to the source of the explosion. Objects can be buildings, but also outdoor recreational facilities. A good example of a list that defines what an object can represent is for example given in a HSE report [11];
   b) Number of people present in an occupied object;
   c) Protection that an occupied object provides to the people present in that object. In this paper two options are considered: In the open field or inside a building. The relevant lethality models are chosen based on these two options;
   d) Duration that people are present in an occupied object. This is used to determine a factor that indicates the probability that people are present during the time the transshipment takes place, the simultaneous presence factor;

In order to obtain information on the presence of people at specific locations (item 2a above) several sources are available, such as a national population database, national/local database of occupied objects and the database of inhabitants from a municipality. In practice, a combination of multiple sources has to be used to gather all required information on the presence of people within the area of influence of the transshipment site.

An example calculation of the group risk is made, using the scenarios defined in Table 2. The size of the area of influence is determined by the scenario with the largest representative NEQ value, here scenario 3. The associated IBD for scenario 3 is 1,040 meter. Table 3 gives the data for the presence of people within this area of influence. Using the explosion effect models for each scenario and the appropriate lethality models for each of the objects, one can calculate the expected number of fatalities per object. For each scenario the expected fatalities per object are added up. For each scenario, defined in Table 2, the expected number of fatalities and the probability of explosion is given in Table 4. Figure 3 presents the cumulative F(N) curve for the example scenarios, see Table 2, and the presence of people in the surrounding area, see Table 3.

Table 3 Data for presence of people within area of influence as used for the example.

ID	Type of building	Distance to PES [m]	Max. number of people present [-]	Open field / inside building	Simultaneous presence factor [-]
1	Office building	280	20	inside building	1
2	Quay area	350	10	open field	0.5
3	Office building	618	4	inside building	1
4	Factory building	704	20	inside building	1
5	Factory building	715	10	inside building	1
6	Office building	832	4	inside building	1

Table 4 Overview of the expected number of fatalities for each of the three example scenarios, see Table 2.

Scenario	Probability of an accidental explosion [-/year]	Expected number of fatalities [-]
5x 100,000 kg NEQ per year	$1.00 \cdot 10^{-5}$	6.9
10x 10,000 kg NEQ per year	$2.86 \cdot 10^{-6}$	1.0
10x 1,000 kg NEQ per year	$1.36 \cdot 10^{-6}$	0

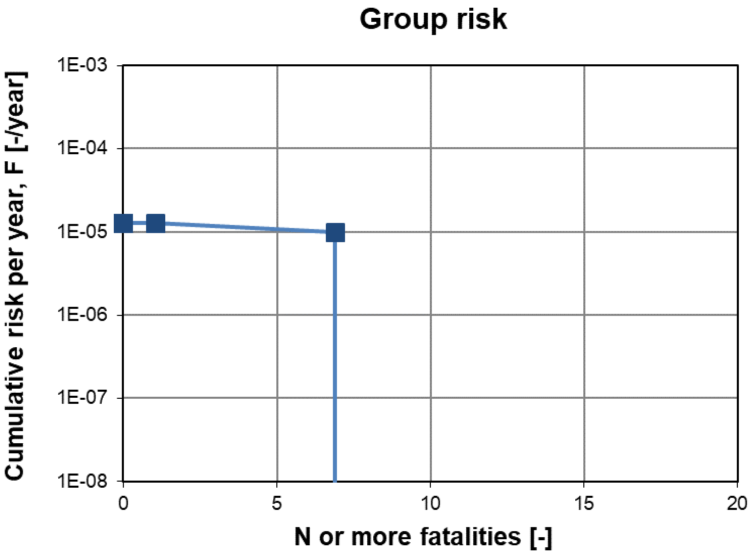

Figure 3 Plot of the group risk in a cumulative F(N) curve for the three example scenarios defined in Table 2.

The combination of IR and GR give a good representation of the risk posed by ammunition transshipments to the people in the surrounding area. The IR and GR can be used to judge the acceptability of the proposed transshipment scenarios for a specific harbor, by comparing these parameters with existing governmental guidelines. If the risk posed is deemed unacceptable, risk mitigation measures can be applied, the proposed scenarios can be adjusted, or the transshipments can be performed in another harbor.

Conclusions

During an ammunition transshipment in a harbor there is a probability of an accident that can lead to an accidental explosion of the involved ammunition. This paper gives an overview of a method to perform a quantitative risk analysis (QRA) of ammunition transshipments in a harbor. The paper focusses on the risks that are related to the loading/unloading of a ship with containers filled with ammunition and/or explosives.

An overview is given of the type of accidents that are considered as a potential cause of an explosion. Based on (historic) statistics on these types of accidents, the probability of an explosion can be determined. To account for uncertainties, as a result of limited available data, a safety factor is introduced in the calculation of the probability of an explosion.

For the QRA of ammunition transshipments a scenario based approach is used. The first step is to determine the representative NEQ (net explosive quantity in kg TNT) per transshipment. The NEQ of a transshipment is the dominant factor for the explosion effects and consequences. Each scenario contains the following additional parameters, related to the NEQ: number of transshipments per year, NEQ per ISO container, number of ISO-containers per transshipment, number of kilometers travelled by vehicles and the time taken to complete a transshipment.

Engineering models are used to calculate the blast effect of an explosion, the debris/fragment generation and the heat radiation. For the blast effects, the side-on peak pressure, side-on impulse and positive phase duration are modelled. It is assumed that the debris/fragment generation is axisymmetric, i.e. rotationally symmetric around a central vertical axis. With the determined explosion effects, the probability of a lethal injury for an unprotected person can be calculated. In the lethality models Probit relations are used, relating a specific explosion effect or a combination of effects to a Probit value. This value can then be converted to a probability of lethality. A distinction is made between lethality models that are suited for a person in the open field or person inside a building.

Finally, two concepts to describe risk for third parties are presented and discussed: the Individual Risk and the Societal or Group Risk. The combination of the Individual and Group risk gives a good representation of the risk posed by ammunition transshipments to the people in the surrounding area. With an example set of scenarios, the method is shown in practice. Comparison of the Individual risk and Societal risk to the respective national standards provides stakeholders with valuable information on the risks associated with the assessed transshipments. With this information stakeholders are able to make an informed decision if the level of risk is acceptable for people in the surrounding area and on possible risk mitigation measures.

Recommendations

Aboard a cargo ship containers with ammunition can, as an alternative to the assumption made in this paper, be stored inside a ship or in an open cargo compartment, instead of on the cargo deck. In the case that the containers with ammunition are placed internally in a ship, the debris and fragment throw and blast propagation are affected by resistance of the ship hull. Unfortunately, current models to calculate explosion effects do not account for this. To make this QRA method more widely applicable, efforts should be made to develop models that can account for the effect of the structure of the ship on an internal explosion of a container filled with ammunition and/or explosives.

Similarly, the structure of the ISO containers affects the explosion effects. In the debris model it is assumed that the debris generation is axisymmetric, but tests have shown that this assumption is very crude. Also, the way the ballistic flight conditions are modelled for container debris can be improved [7]. Alternative approaches could be developed from the models developed by the Klotz Group for the Klotz Group Engineering Tool [12]. Improving these models provides a more realistic view on the explosion effects and consequences, and thus helps to give a more realistic calculation of the risk of ammunition transshipments.

Quite some uncertainty remains in the determination of the probability of an explosion. This is mostly due to the (fortunately) scarce occurrence of these events. Future efforts can be made to develop alternative methods to determine the probability of an accidental explosion in the context of an ammunition transshipment. Also, efforts can made to reduce the uncertainty by enhancing the available data set or by using a hybrid approach (for example partly historic data and partly a fault tree analysis).

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