A quantitative risk analysis approach to port hydrocarbon logistics

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Abstract

A method is presented that allows quantitative risk analysis to be performed on marine hydrocarbon terminals sited in ports. A significant gap was identified in the technical literature on QRA for the handling of hazardous materials in harbours published prior to this work. The analysis is extended to tanker navigation through port waters and loading and unloading facilities. The steps of the method are discussed, beginning with data collecting. As to accident scenario identification, an approach is proposed that takes into account minor and massive spills due to loading arm failures and tank rupture. Frequency estimation is thoroughly reviewed and a shortcut approach is proposed for frequency calculation. This allows for the two-fold possibility of a tanker colliding/grounding at/near the berth or while navigating to/from the berth. A number of probability data defining the possibility of a cargo spill after an external impact on a tanker are discussed. As to consequence and vulnerability estimates, a scheme is proposed for the use of ratios between the numbers of fatal victims, injured and evacuated people. Finally, an example application is given, based on a pilot study conducted in the Port of Barcelona, where the method was tested.

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1. Introduction and brief review of the literature

In this paper a method for applying quantitative risk analysis (QRA) to port hydrocarbon logistics is described and discussed. Ports are environments often overloaded with hazardous materials, both in bulk and containerised. Recent HazMat accidents at port terminals include those that occurred in 2004 in Porto Torres, Italy (tanker unloading benzene, two deaths, loss of ship), and in 2003 in Octiabrskaya, Russia (explosion and fire of tanker unloading crude oil, one death), Gdansk, Poland (four killed after the explosion of a petrol barge), and Staten Island, New York (two crew members dead while unloading a petrol barge).

The method here proposed was first devised as part of a Spanish project called FLEXRIS and applied to the premises of the Port of Barcelona, one of the largest ports on the Mediterranean Sea. Though based on a QRA approach [1], this method presents a number of novel features that deserve special consideration.

Over the last few decades much experience has been gained in the field of risk analysis of standard (petro)chemical plants. Now this knowledge is being applied to a wide range of industrial activities involving hazardous material handling, including ports. Nevertheless, few works on the application of QRA to navigational aspects and terminal operations are available. On a European level, this is probably due to the role played by the Seveso II directive [2], which does not affect these environments. But public authorities are beginning to feel concerned about how safe harbours are, not only with regard to land operations but also to the possibility of ship collisions and (un)loading accidents. The Spanish government, in compliance with IMO’s OPRC Convention1, has recently issued a decree [3] in which, among other things, port authorities, marine loading

1 The International Convention on Oil Pollution Preparedness, Response and Co-operation was issued by the International Maritime Organization in

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In view of these facts, a method is needed to standardise risk assessment in port settings. We feel that this structured procedure will help port system stakeholders (especially port authorities and hydrocarbon terminals) to optimise the performance of their investments in the fields of prevention and safety, by helping them to reduce the most significant risks. For example, newly projected terminals might be located by taking into consideration losses due to accident scenarios. The method devised allows port authorities to build an objective basis for making decisions about the conditions to be required of hydrocarbon terminal dealers, in order to guarantee safety.

Insights on different kinds of risk assessment for HazMat handling at port terminals can be found in the following:

- Rao and Raghavan [4], Thomas [5] and Hartley [6], who present the use of risk indexes specifically devised for port areas;
- Kite-Powell et al. [7], who attempt to build a risk assessment tool based on historical data for US ports;
- Tihovec and Carr [8], on the subject of safety management systems (with several examples of risk assessment techniques);
- Cunningham [9], who provides a demonstration of a risk matrix;
- Ronza et al. [10], on simplified event trees for port accidents;
- Darbra et al. [11], who provide a historical analysis of accidents in harbours.

Egidi et al. [12] briefly explain how they dealt with the problem of assessing HazMat accident risk at a sea-terminal, while recognising the scarcity of literature on this topic. Several risk assessment reports, made available to the public via the Internet, proved to be a valuable source of information. Some of these reports were taken into account while carrying out the present project [13,14], despite the fact that they are not actually complete QRAs. The Canvey Reports [15,16] were the first significant contribution to industrial port environment QRAs, and they are still relevant today. What these works lack, however, is an attempt at standardising the process of risk assessment of navigation and (un)loading operations for a generic port/terminal. This is what has been done in this project in the case of hydrocarbons, with a special regard to accident frequency estimation.

1990. The 1998 OPRC re-issue is now the principal legislation on counter pollution from a harbour authority and oil handling facility perspective.
2. Scope of the method

Only bulk hydrocarbons were considered. Moreover, only bulk transportation and handling are included within the scope of the research.

The analysis covers port waters (from port entrance to berths) plus (un)loading terminals. Accidents occurring during the (external) approach of the tankers to the port were not taken into account, nor were land accidents, such as those that can take place during storage and land transportation (within and outside the confines of the port). Finally, possible sabotage-related scenarios and accidents likely to occur during tanker maintenance operations were excluded from the analysis. Instead, navigation through port waters and (dis)charge were specifically addressed. For a discussion on the patterns of accidental events, such as the operation carried out when the accident occurred, see [10] and [11].

Therefore, the operations considered are (1) tanker navigating through the port, (2) tanker manoeuvring in the proximity of berths, (3) tanker (un)loading bulk hydrocarbons\(^2\) and (4) bunkering operations.

3. Description of the methodology

3.1. Collection of relevant information

The first step to take is, of course, to gather the relevant data that will be used during the analysis (see Fig. 1 for a schematic representation of the method). This is an extremely important phase and ensuring that it is carried out properly can save a great deal of time and avoid rough approximations. Critical data to be collected are as follows:

- The geographical location of the port.
- A detailed map of the port (at least of port waters, berthing lines and areas where hydrocarbon stevedoring companies are located).
- Climate data (average temperatures, humidity, wind roses and atmospheric stability). The critical data that are necessary for accident simulation models are (1) average ambient temperature, (2) average water temperature, (3) average relative humidity, (4) wind speed, and (5) atmospheric stability distribution.
- Technical data on berths and (un)loading locations. These data can be obtained from the port authority, but it is easier to collect them directly from the stevedoring companies that make use of the loading arms and berthing facilities. Critical data are (1) typical tank volumes for (un)loading tankers, (2) product temperatures and pressures both for ship transport and (un)loading, especially for refrigerated or liquefied products (LPG, LNG), (3) the number of loading arms per berth, (4) operational flow rates for loading arms and hoses, and (5) loading arm and hose diameters.

- Physical and chemical data for the hydrocarbon products taken into account. Critical data used later in the simulations are (1) density, (2) estimated molecular weight, (3) vapour pressure, (4) thermal conductivity, and (5) heat of combustion, etc.

- Traffic data. These are critical to the calculation of the frequencies of accidents. The best way to collect traffic data is by organising them according to product type and berth (see Table 1). They should be given by tanker visit per unit time (e.g. per year). In order to estimate them, one should refer to past data (for example the last 2 or 3 years), but if more accurate data or reliable estimations on future trade are available, these should be used instead. Likewise, bunkering operations data should be taken into account (operations per year). General traffic data (the number of ship visits to the port per year, regardless of ship cargo) are also needed, because they affect the frequency of ship collisions (the busier the port, the more likely collision events will be).

- Duration of (un)loading operations. This is also necessary for the estimation of the frequency of accidents. When these data are not directly available, an estimate of an average duration for product \(p\) and berth \(b\) might be assessed in the following way:

\[
\Delta t_{p, b} = \frac{\text{total loaded and unloaded volume}_{p, b}}{\text{operational flowrate}_{p, b} \times \text{no. operations}_{p, b}}
\]

- Tanker hulls. As double hull tankers are much less likely to give rise to releases when they undergo a collision or grounding than single hull ships are, it is important to know, for every product, the ratio of single to double hull tankers.

Information that is not critical – but is nonetheless useful – can be gathered about past accidents (spills, fires, etc.) that have occurred in the port involving the hydrocarbons under analysis.

3.2. Scenario identification

From a general point of view, only two basic events can cause a loss of containment during the aforementioned opera-

\(^2\) From the point of view considered in this study there is no significant difference between loading and unloading operations, since the probability of a loss of containment are the same for both situations, as are the physical effects of the scenarios.
Fig. 1. Diagram of the suggested method (n = number of hydrocarbon products handled; m = number of hydrocarbon products bunkered).
tions: hull failure and loading arm/hose failure. In both cases the approach described by TNO [17] was followed. This means that, for every loss of containment, a two-fold possibility has to be considered:

- in the case of hull failure, a minor as well as a massive spill;
- for loading arms, partial and total rupture.

For bunkering operations, only two scenarios are considered (one for hull failure and one for hose rupture), as the amounts spilled are generally small. In a general application, the number of scenarios will therefore be as follows:

\[ \text{number of scenarios} = 4n + 2m \]

where \( n \) being the number of hydrocarbon products traded and \( m \) the number of products bunkered (normally \( m = 2 \), diesel oil and fuel oil being the bunkered fuels).

### 3.3 Frequency estimation

The approach that was followed is to estimate accident frequencies on the basis of both traffic data and general frequencies found in technical literature. Great efforts were made to select appropriate general frequencies for the scenarios previously described. Table 2 summarises the general frequencies that were selected and used. Many sources were consulted, but none of them proved to be actually focused on accidental events in a port environment (many are rather general, related to open sea maritime accidents; see Rømer et al. [21]). Apart from proposing data specifically intended for ports and focussing on the most recent and/or widely used frequencies, an additional criterion that was followed in the selection of data is the intention not to complicate excessively the calculations by introducing too many scenarios.

An important remark must be made here. While loading arm scenarios are of a purely punctual nature, hull ruptures are both punctual and linear. In fact the latter may be caused by any of the following:

- an external impact (ship–ship or ship–land) while the tanker is moving towards the berth or from the berth to the port entrance (linear operation);
- by an external impact (ship–land) during manoeuvres near the (un)loading berth or a ship–ship collision while the tanker is (dis)charging (punctual operation).

This dual nature must be taken into account, because, while the physical effects of the accident are practically the same, their consequences (on people and installations) may be different. If a fire or explosion takes place during the movement towards/away from the berth, it will generally have less severe consequences because the accident location is further away from the docks. For this reason, it is important to calculate separate frequencies for punctual and linear scenarios.

#### 3.3.1 Loading arm and hose failures

These events are purely punctual. Moreover, given the failure (i.e. the rupture), the probability of spillage is 1. Therefore, once proper literature data are selected, they are used directly without further calculations.

As for loading arms, we suggest using the data proposed in the Purple Book [17]. Different figures can be found in DNV Technica [22], which are used, for instance, by the Environmental Resources Management [14]. The approach followed by [22] is to consider the possibility of three spill sizes (instead of two, as in TNO’s approach). The order of magnitude of the data is the same. DNV suggests an overall failure rate of 1.94 × 10⁻⁴ operation⁻¹, approximately 76% of the spills is considered to be “small”, 18% is “medium” and 6% “large”. In order not to increase the number of scenarios, TNO data were preferred. The Rijnmond Report [23] presents some loading arm failure frequency data as well. They are smaller than those proposed by the Purple Book, and they are expressed as number of failures per hour of operation. TNO’s figures were preferred here just because they are much more recent.

For the same reason, in the case of hoses, the data found in [19] are suggested, rather than those of the Rijnmond Report.

#### 3.3.2 Hull failures, punctual events

Two initiating events are likely to provoke accidents at the berths:

- a. a ship–land collision while the tanker is manoeuvring near the berth;
- b. a ship–ship collision during the (dis)charge, caused by a ship running adrift and colliding with the (un)loading tanker.

Literature data for these events are shown in Table 2. The frequency of both classes of initiating event must be expressed using consistent units. To do so, a frequency per unit time of ship–ship collision during (dis)charge must be estimated thus:

\[ f_s = f_s T \Delta t \]

where \( f_s \) is expressed in events per ship visit, \( f_s \) is the frequency of a ship–ship collision while a tanker is (dis)charging at a terminal, expressed per ship passage (4.0 × 10⁻⁶ ship passage⁻¹), \( T \) the ship traffic in the proximities of the berth (ship passages h⁻¹) (this can be estimated from the general traffic data for the port and the berth position), and \( \Delta t \) is the duration of the discharge. Note that this can change according to the berth and the product that is being discharged, depending on flow rates, tank dimensions, and the number of loading arms actually used.

Another aspect must be taken into consideration: given an external impact, the probability of an actual spill occurring must be identified. Several probability data have been found in the literature. They are reviewed in Table 3. We suggest to use TNO’s data [17], because:
Table 2
General frequencies for the initiating events

<table>
<thead>
<tr>
<th>Operation or scenario</th>
<th>Type of initiating event</th>
<th>Initiating event</th>
<th>General frequency</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer, loading arm (total rupture)</td>
<td>Punctual</td>
<td>External impact, mechanical failure</td>
<td>$6 \times 10^{-5}$ operation$^{-1}$</td>
<td>[17]</td>
</tr>
<tr>
<td>Transfer, loading arm (partial rupture)</td>
<td>Punctual</td>
<td>External impact, mechanical failure</td>
<td>$6 \times 10^{-4}$ operation$^{-1}$</td>
<td>[17]</td>
</tr>
<tr>
<td>Transfer, hose (total rupture)</td>
<td>Punctual</td>
<td>External impact, mechanical failure</td>
<td>$4 \times 10^{-3}$ operation$^{-1}$</td>
<td>[18], after data from [19]</td>
</tr>
<tr>
<td>Tanker manoeuvre</td>
<td>Punctual</td>
<td>Ship–land collision</td>
<td>$2.2 \times 10^{-5}$ ship visit$^{-1}$</td>
<td>[20]</td>
</tr>
<tr>
<td>Tanker (dis)charge</td>
<td>Punctual</td>
<td>Ship–ship collision (passing ship)</td>
<td>$4 \times 10^{-6}$ passage$^{-1}$</td>
<td>[20]</td>
</tr>
<tr>
<td>Tanker moving to/from berth</td>
<td>Linear</td>
<td>Ship–land collision</td>
<td>$1.5 \times 10^{-5}$ visit$^{-1}$</td>
<td>[15]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Grounding</td>
<td>$0.3 \times 10^{-5}$ visit$^{-1}$</td>
<td>[15]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ship–ship collision with passing ship</td>
<td>$2.3 \times 10^{-5}$ visit$^{-1}$</td>
<td>[15]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ship–ship collision with moored ship</td>
<td>$0.5 \times 10^{-5}$ visit$^{-1}$</td>
<td>[15]</td>
</tr>
</tbody>
</table>

- They allow for both a minor and a major spill scenario, that is, for a greater detail in scenario definition.
- In the case of liquefied gas carriers, TNO’s data are much more recent than the Canvey data [15]. Shipbuilding and vessel traffic control have changed since then (which is reflected in a decrease of spill probability by an order of magnitude).
- In the case of oil tankers, Ref. [14] recommends figures of the same order of magnitude as those of Purple Book, but makes a distinction among various circumstances (berthing impact, impact with jetty, ship–ship collision). To use these data would complicate the method, without significant improvements.

Therefore, after the approach suggested by TNO [17], we propose the following probabilities that, given an external impact, a spill will take place:

$$p_{\text{M}} = \begin{cases} 
0.1 & \text{(single hull tanker)} \\
0.0015 & \text{(double hull tanker)} \\
0.00012 & \text{(gas tanker, semi-gas tanker)} 
\end{cases}$$

Table 3
Summary of probability data referring to spill events from tankers, as a result of an external impact

<table>
<thead>
<tr>
<th>Event</th>
<th>Scope (as defined in the original source)</th>
<th>Probability</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spill due to ship–ship collision</td>
<td>Ammonia carriers</td>
<td>0.2</td>
<td>[15]</td>
</tr>
<tr>
<td></td>
<td>Oil tankers</td>
<td>Single hull → 0.425, double hull → 0.178</td>
<td>[14], pp. 14–21$^b$</td>
</tr>
<tr>
<td>Spill due to berthing impact</td>
<td>Ammonia carriers</td>
<td>0.1</td>
<td>[15]</td>
</tr>
<tr>
<td>Spill due to impact with jetty</td>
<td>Oil tankers</td>
<td>Single hull → 0.425, double hull → 0.264</td>
<td>[14], pp. 14–22$^b$</td>
</tr>
<tr>
<td>Spill due to ship–land collision (grounding)</td>
<td>Ammonia carriers</td>
<td>0.2</td>
<td>[15]</td>
</tr>
<tr>
<td></td>
<td>Oil tankers</td>
<td>Single hull → 0.5, double hull → 0.23</td>
<td>[14], pp. 14–20$^b$</td>
</tr>
<tr>
<td>Spill due to external impact (ship–ship or ship–land)</td>
<td>Tankers</td>
<td>Major spill</td>
<td>[17]</td>
</tr>
<tr>
<td>Continuous spill due to external impact, “given serious hull damage (very severe damages for class G ships)”</td>
<td>Tankers and barges in inland waterways</td>
<td>Single hull</td>
<td>[17]</td>
</tr>
</tbody>
</table>

$^a$ Referable also to LNG carriers.

$^b$ Data are obtained on the basis of the event trees published in this source.
The general frequencies defined above shall be multiplied by the traffic data (organised according to berth and product (dis)charged, see Table 1), in order to obtain the actual scenario frequencies, i.e. specific data for the port under consideration. The result should be a further chart similar to Table 5.

3.4. Event trees and definition of probabilities

The following step of the procedure is to draw proper event trees, and assign numerical probabilities to each of their branches. As the setting is basically the same for all the scenarios (release on port waters), it is necessary to draw only \( n \) event trees, \( n \) being the number of hydrocarbon products analyzed. Whenever possible, maritime and port-specific probability data must be given priority.

In Fig. 2, an event tree for LPG spills is shown. This was actually used in the application of the method to the Port of Barcelona.

3.5. Consequence analysis

The models we used in the consequence analysis and that we suggest should be used in future applications are listed in Table 6.
Table 4
Summary of the general frequencies proposed

<table>
<thead>
<tr>
<th>Type of event</th>
<th>Scenario type</th>
<th>Dimension</th>
<th>General frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spill due to loading arm failure</td>
<td>Punctual</td>
<td>Total arm rupture</td>
<td>(j_{LF} = 6 \times 10^{-5} \text{ operation}^{-1})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Partial arm rupture</td>
<td>(j_{LF} = 6 \times 10^{-4} \text{ operation}^{-1})</td>
</tr>
<tr>
<td>Spill due to hull failure</td>
<td>Punctual</td>
<td>Major spill</td>
<td>(f_{HF,p,M} = (2.2 \times 10^{-3} \text{ visit}^{-1} + 4 \times 10^{-6} \text{ passages}^{-1}) \times T \times \Delta t \times p_M)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Minor spill</td>
<td>(f_{HF,p,M} = (2.2 \times 10^{-3} \text{ visit}^{-1} + 4 \times 10^{-6} \text{ passages}^{-1}) \times T \times \Delta t \times p_M)</td>
</tr>
<tr>
<td></td>
<td>Linear</td>
<td>Major spill</td>
<td>(f_{HF,l,M} = 2.5 \times 10^{-4} \text{ visit}^{-1} \times p_M)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Minor spill</td>
<td>(f_{HF,l,M} = 2.5 \times 10^{-4} \text{ visit}^{-1} \times p_M)</td>
</tr>
</tbody>
</table>

\* Supposing that loading arms are used. Use hose failure frequency otherwise (see Table 2).

Table 5
Chart showing frequencies for the scenarios of a given product

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario type</th>
<th>Actual frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading scenario, product 1, total rupture</td>
<td>Punctual</td>
<td></td>
</tr>
<tr>
<td>Loading scenario, product 1, partial rupture</td>
<td>Punctual</td>
<td></td>
</tr>
<tr>
<td>Hull failure scenario, product 1, major spill</td>
<td>Punctual</td>
<td></td>
</tr>
<tr>
<td>Hull failure scenario, product 1, minor spill</td>
<td>Linear</td>
<td></td>
</tr>
<tr>
<td>Bunkering scenario, fuel oil, hose rupture</td>
<td>Linear</td>
<td></td>
</tr>
<tr>
<td>Bunkering scenario, fuel oil, hull failure followed by minor spill</td>
<td>Diffuse (almost wherever in port waters)</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Event tree for LPG. Sources: \(P_2, P_3, \text{ and } P_5\) from [17], where they are defined as the probabilities of ignition of a reactive or highly reactive gas without outflow between 10 and 100 kg/s, \(P_4\) from [17], probability of immediate ignition of K1 class liquids (when ejected downwards and immediately ignited LPG can be considered as a liquid); \(P_6\) from TNO’s LPG, A Study [25].
Individual risk was assessed using the vulnerability correlations found in [27]. An additional criterion was adopted that is currently widely accepted: in the case of flash fires, 100% lethality was assumed for the area occupied by the portion of gas cloud in which the concentration is greater than the lower flammability limit, while outside that zone, lethality is assumed to be zero.

For the definition of the amounts of liquids spilled from damaged tankers, the guidelines suggested in the Purple Book are to be followed. Therefore, whenever a tanker spill is calculated, a major spill is considered to be a continuous release of the following:

- 30 m$^3$ over 1800 s in the case of single-hulled liquid bulk tankers,
- 32 m$^3$ over 1800 s in the case of semi-gas carriers,
- 90 m$^3$ over 1800 s in the case of gas carriers,
- 20 m$^3$ over 1800 s in the case of double-hulled liquid bulk tankers,
- 20 m$^3$ over 1800 s in the case of semi-gas carriers,
- 180 m$^3$ over 1800 s in the case of double-hulled liquid bulk tankers.

While a minor spill is considered to be a release of the following:

- 126 m$^3$ over 1800 s in the case of semi-gas carriers,
- 75 m$^3$ over 1800 s in the case of liquid bulk tankers,
- 220 evacuees for each fatality.

The data used to obtain these figures are a subset of the 1033 port-area accidents analysed in [11]. Of these accidents, only the 428 that occurred during bulk hydrocarbon (un)loading and tanker movement/manoeuvres were retained. The data are taken from the MHIDAS database [28], in which three fields are devoted to gauging the consequences of the accidents on humans: KR, IR and ER, which represent the number of people that were killed, injured and evacuated as a consequence of the accident. Unfortunately, these fields do not always give positive information. This means that KR may be 0 or more or it might not be defined at all. The same happens with IR and ER. In order to estimate the number of injured and evacuated people, historical data have been used. The average ratios of injured people/evacuees to fatalities have been estimated to be the following:

- 2.21 injured people for each fatality;
- 220 evacuees for each fatality.

Societal risk was estimated by building on the general procedure described by Pietersen and van het Veld [11]. TNO’s software RISKCURVES, which implements this procedure, was also used. The individual risk at a point (x, y) is expressed by the following equation:

$$ R(x, y) = \frac{\int_{\theta = 0}^{\theta = \pi} \sum_{k=1}^{8} \left( \int_{\theta=0}^{\theta=\pi} \sum_{j=1}^{6} R_{F,\phi}(x, y) p(\theta) p_k d\theta \right)}{R_{F,\phi}(x, y) p(\theta) p_k d\theta} $$

where $\theta$ represents the wind direction, $k$ stands for stability class, $f$ is the accident frequency, $R_{F,\phi}(x, y)$ the lethality function estimated on the basis of the vulnerability criteria, $p(\theta)$ the probability that the wind will blow in the direction $\theta$ and $p_k$ is the probability of the class of stability $k$.

Eq. (10) is solved by commercial software that discretises the integral by way of a summation of 8, 12 or 16 radial directions.

### 3.6. Estimation of individual risk

Individual risk was assessed using the vulnerability correlations found in [27]. An additional criterion was adopted that is currently widely accepted: in the case of flash fires, 100% lethality was assumed for the area occupied by the portion of gas cloud in which the concentration is greater than the lower flammability limit, while outside that zone, lethality is assumed to be zero.

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- 220 evacuees for each fatality.

### 3.7. Estimation of overall risk for the population

By integrating the product of $R$ by the local population density over spatial coordinates, the global risk for a given accident scenario is obtained: By adding up the several $R$ functions (one for each scenario), a global risk function is obtained. In order to estimate the number of injured and evacuated people, historical data have been used. The average ratios of injured people/evacuees to fatalities have been estimated to be the following:

- 2.21 injured people for each fatality;
- 220 evacuees for each fatality.

The data used to obtain these figures are a subset of the 1033 port-area accidents analysed in [11]. Of these accidents, only the 428 that occurred during bulk hydrocarbon (un)loading and tanker movement/manoeuvres were retained. The data are taken from the MHIDAS database [28], in which three fields are devoted to gauging the consequences of the accidents on humans: KR, IR and ER, which represent the number of people that were killed, injured and evacuated as a consequence of the accident. Unfortunately, these fields do not always give positive information. This means that KR may be 0 or more or it might not be defined at all. The same happens with IR and ER. In order to estimate the above IR/KR and ER/KR ratios, the following assumptions were made:

1. whenever KR and ER are not defined, they are assumed to be 0;
2. to obtain the IR/KR rate, only the accidents for which IR is defined were used.

In fact, it is highly probable that an undefined KR (ER) simply means that there have not been any victims (evacuees) as a consequence of an accident. This is certainly not true for IR data, since many accidents have a high KR record while the number of injured people remains undefined. It is very...
likely that these accidents have not caused some people to be affected other than fatally, so the average rate IR/KR was estimated solely on the basis of the records for which a positively defined IR was available.

Apart from the above rates (IR/KR = 2.21 and ER/KR = 220), which are general, averaged for all the accidents, more specific rates can also be estimated, as a function of the operation that was carried out during the accidents. The values are shown in Table 7.

It is interesting to note how both IR to KR and ER to KR ratios decrease dramatically when it comes to accidents that occurred during the approach or manoeuvre of a tanker (on average, IR is even smaller than KR in these circumstances). This means that manoeuvre/approach do not have significant aftermaths other than in terms of human life loss. The reason why the injured to killed ratio is so low is that these accidents mainly involve tanker crews, who are often so close to the accident that they are more likely to suffer death than non-fatal injuries. Likewise, ER/KR is low because these accidents normally happen farther from working and residential areas, and are consequently of less concern in terms of people to be evacuated.

The general ratios should be used whenever the present QRA conceptual approach is applied to a port, because the scenarios, as they have been designed and structured, entail both (un)loading and ship manoeuvre/approach operations. Nevertheless, the operation-specific values can be used for studies that focus on a particular stage in port hydrocarbon logistics. Note that, however useful it is to estimate the consequences of accident for humans, the figures in Table 7 only represent historical averaged data.

### 4. Case study: the Port of Barcelona

The Port of Barcelona is one of the largest Mediterranean ports in terms of the number of tonnes traded, and the largest in Spain. Bulk liquid trade amounts to about 25% of the total traded goods. Almost 9 million tonnes of bulk liquid energetic hydrocarbons were transported out of and (mainly) into the port during 2003 [29], which constitutes the main part of the hazardous material flux through the harbour.

The port is quite close to the city. The oldest, downtown terminals have been converted in the last decade and are now a tourist and commercial district. The main hydrocarbon terminals are located in a separate section of the port (“Moll d’Inflamables”, Flammable Product Wharf), which is more than 2 km away from the nearest residential area.

#### Table 7

<table>
<thead>
<tr>
<th>Accident subset</th>
<th>No. accidents</th>
<th>IR/KR</th>
<th>ER/KR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un/Loading accidents</td>
<td>261</td>
<td>3.09</td>
<td>358</td>
</tr>
<tr>
<td>Tankers approaching or manoeuvring</td>
<td>167</td>
<td>0.67</td>
<td>1.66</td>
</tr>
<tr>
<td>General</td>
<td>428</td>
<td>2.21</td>
<td>220</td>
</tr>
</tbody>
</table>

The following bulk hydrocarbon products are traded:

- LNG
- LPG
- petrol
- kerosene and diesel oil
- fuel oil

Crude oil is virtually absent as a bulk liquid. For practical purposes, kerosene and diesel oil were grouped together, as they present similar characteristics with regard to flammability and general hazard issues.

The harbour, like most Mediterranean ports, is compact, and not scattered over multiple locations. Nine private companies carry out bulk liquid trade activities. Five of them perform energetic liquid hydrocarbon stevedoring, one of which is exclusively devoted to the unloading and distribution of LNG cargo, and another trades in LPG. All the companies but one are located on the Flammable Product Wharf, where they make use of the berths and unloading facilities located therein. One company currently holds the concession for a separate bulk liquid jetty.

The bunkering service is performed by a specialised barge held by one of the companies. As a result (see Eq. (1)), 24 scenarios were considered during the study, which are itemised in Table 8.

#### Table 8

<table>
<thead>
<tr>
<th>Scenario no.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Major LNG spill from cargo tank rupture</td>
</tr>
<tr>
<td>2</td>
<td>Minor LNG spill from cargo tank rupture</td>
</tr>
<tr>
<td>3</td>
<td>Major LNG loading arm failure</td>
</tr>
<tr>
<td>4</td>
<td>Minor LNG loading arm failure</td>
</tr>
<tr>
<td>5</td>
<td>Major LPG spill from cargo tank rupture</td>
</tr>
<tr>
<td>6</td>
<td>Minor LPG spill from cargo tank rupture</td>
</tr>
<tr>
<td>7</td>
<td>Major LPG loading arm failure</td>
</tr>
<tr>
<td>8</td>
<td>Minor LPG loading arm failure</td>
</tr>
<tr>
<td>9</td>
<td>Major petrol spill from cargo tank rupture</td>
</tr>
<tr>
<td>10</td>
<td>Minor petrol spill from cargo tank rupture</td>
</tr>
<tr>
<td>11</td>
<td>Major petrol loading arm failure</td>
</tr>
<tr>
<td>12</td>
<td>Minor petrol loading arm failure</td>
</tr>
<tr>
<td>13</td>
<td>Major diesel oil/kerosene spill from cargo tank rupture</td>
</tr>
<tr>
<td>14</td>
<td>Minor diesel oil/kerosene spill from cargo tank rupture</td>
</tr>
<tr>
<td>15</td>
<td>Major diesel oil/kerosene loading arm failure</td>
</tr>
<tr>
<td>16</td>
<td>Minor diesel oil/kerosene loading arm failure</td>
</tr>
<tr>
<td>17</td>
<td>Major fuel oil spill from cargo tank rupture</td>
</tr>
<tr>
<td>18</td>
<td>Minor fuel oil spill from cargo tank rupture</td>
</tr>
<tr>
<td>19</td>
<td>Major fuel oil loading arm failure</td>
</tr>
<tr>
<td>20</td>
<td>Minor fuel oil loading arm failure</td>
</tr>
<tr>
<td>21</td>
<td>Fuel oil spill from cargo tank during bunkering operations</td>
</tr>
<tr>
<td>22</td>
<td>Fuel oil hose failure during bunkering operations</td>
</tr>
<tr>
<td>23</td>
<td>Diesel oil spill from cargo tank during bunkering operations</td>
</tr>
<tr>
<td>24</td>
<td>Diesel oil hose failure during bunkering operations</td>
</tr>
</tbody>
</table>

By way of example, Scenario 1 (a major LNG spill from cargo tank rupture) is presented and discussed below as a particular application of the method.

Firstly, relevant data are collected for the scenario in step (a). Apart from the physical conditions of LNG being stored in the tankers (112 K, 120 kPa), it is necessary to consider...
the traffic flow of LNG tankers and the duration of unloading operations, considering that the Port of Barcelona, when this work was being carried out, had only one LNG unloading berth, which is situated almost at the entrance of the port. It was estimated that, on average, 169 LNG tankers entered the Port of Barcelona in a 1-year period to discharge. A single discharge operation, considering the average dimensions of the LNG tankers usually in service at the Port, the number of loading arms (two), and their operational flow rate (3000 m$^3$/h), lasts 13.2 h on average. It is also necessary to estimate the average number of ships passing the LNG tanker while it is discharging; considering the position of the LNG berth and the overall traffic data of the Port of Barcelona, it is estimated that 3.7 ships pass that spot every hour.

The frequency of LNG spill events due to hull failure is then estimated in (b). Because it is both a “linear” and a “punctual” scenario, two frequencies must be taken into account. The frequency of the accidents that are likely to happen in the proximity of the berth is calculated using Eq. (4):

\[
\frac{H_{P,M}}{f} = \left( f_{a} + F_{b}T/D_{T} \right) p_{M} = (2.2 \times 10^{-3} \text{ visit}^{-1} + 4.0 \times 10^{-6} \times 3.74 \times 13.2) \times 0.00012 = 2.88 \times 10^{-7} \text{ operation}^{-1}
\]

where the probability of spill $p_{M}$ is specific to gas carriers, in compliance with Eq. (2). Thus, the actual frequency of a spill, considering the yearly LNG tanker traffic, is as follows:

\[
f = 2.88 \times 10^{-7} \times 169 = 4.87 \times 10^{-5} \text{ year}^{-1}
\]

For the linear phenomenon, Eq. (8) must be used:

\[
\frac{H_{L,M}}{f} = 2.5 \times 10^{-4} \times 0.00012 = 3.0 \times 10^{-8} \text{ visit}^{-1}
\]

which implies a frequency of

\[
f = 3.0 \times 10^{-8} \times 169 = 5.07 \times 10^{-6} \text{ year}^{-1}
\]
An event tree is drawn out (step c) in which it is made clear that the spill can give rise to a pool fire, a flash fire followed by a pool fire or simply to the dispersion of a gas cloud. The probabilities of these events are 0.065, 0.037 and 0.898, respectively.

The consequences for people of each of these sub-events (apart from cloud dispersion, which does not cause harmful effects) must be calculated (step e).

When, for example, a pool fire is considered, the steps to be taken in order to calculate the radiated power are the following:

• calculation of the released flow rate,
• estimation of pool diameter:

\[ d = 2\sqrt{\frac{Q_f}{\pi y'}} \]

where \( y' \) is the mass combustion rate, which can be estimated using the LNGFIRE commercial software devised by the Gas Technology Institute. Subsequently, the heat radiated by the pool fire can be estimated, using programmes such as Shell FRED, and eventually mortality percentages are obtained through the probit equation by Eisenberg et al. [27].

Individual risk was then calculated for this scenario (step f). This is shown by way of isorisk curves in Fig. 3 (which not only takes into account pool fires but all the final events possibly caused by an LNG spill). Two risk areas are clearly visible in the figure: a circular one, which expresses the risk of “punctual” accidents occurring in the proximities of the berth, and an elongated one, which follows the trajectory of the LNG tankers from the port entrance to the berth and expresses the risk of hull failures while the ship is moving. The calculation of the overall risk for this scenario (g) leads to a number of casualties of \( 2.5 \times 10^{-6} \) deaths/year.

Fig. 4. Iso-individual risk curves for all the scenarios.
to be calculated separately for punctual and linear events; every scenario type. For tanker hull failures, frequencies have Table 4 represent a shortcut for estimating frequency data for through an extensive bibliographical survey. The equations in ship.

collision with a passing ship and ship collision with a moored port waters: these are ship–land collision, grounding, ship

events are linear, as they can affect a tanker moving through vessels can strike the berthing line. Contrarily, four initiating events were classified for these scenarios. To be specific, six take place during (dis)charge, the latter can affect a tanker (un)loading bulk hydrocarbons.

tankers. Eqs. (6) and (7) must be used, prior to the frequency calculation.

Fig. 5. f–N curves referred to the accidents included in the scope of the project.

Fig. 4 shows the overall risk of all 22 scenarios. Again, risk is clearly concentrated along tanker port routes and near (un)loading berths. Fig. 5 shows the f–N curves for the scenarios identified in the Port of Barcelona. The limited number of casualties is due to the low population density in the port area and because the effects of the accident scenarios never reach beyond the confines of the port terminals.

5. Discussion and conclusions

A methodology was designed that allows the analysis of the risk arising from bulk hydrocarbon accident scenarios at ports. The scope of the method is restricted to tanker (un)loading operations, hull failures for tankers navigating through port waters and bunkering accidents.

A series of typical accident scenarios were identified. Basically, four scenario types must be considered: major and minor spills for loading arm failure, and major and minor spills for tanker hull failure. While the first two can only take place during (dis)charge, the latter can affect a tanker both when it is navigating and when it is at berth. Initiating events were classified for these scenarios. To be specific, six can be identified for hull failure accidents. Two are punctual events: when a tanker is (dis)charging, it can be hit and punctured by a passing ship, while during the manoeuvre vessels can strike the berthing line. Contrarily, four initiating events are linear, as they can affect a tanker moving through port waters: these are ship-land collision, grounding, ship collision with a passing ship and ship collision with a moored ship.

Frequencies were estimated for all the initiating events through an extensive bibliographical survey. The equations in Table 4 represent a shortcut for estimating frequency data for every scenario type. For tanker hull failures, frequencies have to be calculated separately for punctual and linear events; punctual initiating events are roughly 10 times more frequent than linear ones.

Sensitivity and uncertainty of the model are not different from the case of other QRA approaches, given that vulnerability and physical effects models are not new. Punctual and linear events have an individual risk of the same order of magnitude, but in general punctual events have a higher societal risk, because their effects can have a significant impact ashore, where the population density is higher. The critical step regarding both sensitivity and uncertainty is frequency estimation. As to hose/loading arm failures, the influence of the frequency data is quite obvious: choosing data other than those of Table 2 changes the risk of those scenarios in a proportional way. For tanker navigation accidents, it must be observed that the frequency of ship–land collision during tanker manoeuvre is higher than the sum of all the frequencies regarding ship collisions/groundings occurring when the ship is moving towards/from the berth. This tendency is confirmed by some historical data [30] estimated for some US ports. However, studies such as [30] should be carried out with data referring to more ports and to larger time spans, in order to provide more refined frequency data.

The case study provided results that are consistent with classic quantitative risk analyses as applied to chemical plants and storage areas. Some inconsistencies were found in delayed ignition flash fires, especially for the 2F atmospheric class of stability. It is very likely that in these conditions results are overestimated. However, overall the estimation of the consequences derived from the accidents presented no significant difficulties, provided that the accident scenarios had been properly defined (amount spilled, maximum area of the spill, loading arm sections, etc.), as well as other conditions such as water temperature, spilled product temperature and wind speed. The results obtained were always found to be consistent with those of a conventional QRA.

Another aspect that was addressed is how to take into account the presence of both single- and double-hulled liquid tankers. Eqs. (6) and (7) must be used, prior to the frequency calculation.

In addition, a shortcut was suggested for calculating the number of injured people and evacuees, given the number of accidental deaths. This method was based on an analysis of 428 accidents, which occurred in ports while transporting or (un)loading bulk hydrocarbons.

Moreover, the method can help locate newly projected terminals as well as allow port authorities to build an objective basis for making decisions about conditions to be required of hydrocarbon terminal dealers, in order to guarantee safety.

The method presented and discussed in this paper can be easily extended to other product types, such as general bulk chemicals and toxic products, with only slight modifications (mainly concerning the calculation of effects). It would be

3 This figure is confirmed by historical data. Taking in consideration the aforementioned set of 428 hydrocarbon port accidents, it was seen that the ratio of linear to punctual accidents is 1.5:10.
interesting to adapt the method to the transport and handling of containerised goods, by identifying proper frequencies and consequence estimation models. By doing so, a complete risk assessment scheme for the manipulation of hazardous mate-
rials in port environments would be made available.

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References
