A quantitative risk analysis approach to port hydrocarbon logistics

A. Ronza [a,*], S. Carol [a], V. Espejo [b], J.A. Vílchez [b], J. Arnaldos [a]

[a] *Department of Chemical Engineering, Centre d'Estudis del Risc Tecnològic (CERTEC), Universitat Politècnica de Catalunya, Diagonal 647, 08028 Barcelona, Catalonia, Spain*
[b] *Trámites, Informes y Proyectos (TIPs), C/Llenguadoc 10, 08030 Barcelona, Catalonia, Spain*

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.
© 2005 Elsevier B.V. All rights reserved.

Keywords: Ports; Accident frequencies; Hazardous materials; Hydrocarbon logistics; Quantitative risk analysis

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 Haz-Mat 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 Convention*[1], has recently issued a decree [3] in which, among other things, port authorities, marine loading

* Corresponding author. Tel.: +34 93 4016675; fax: +34 93 4011932.
  E-mail address: andrea.ronza@upc.edu (A. Ronza).

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

Nomenclature

d	pool diameter (m)
f	frequency (year^{-1})
f_a	frequency of a ship–land collision while a tanker is manoeuvring near a berth (operation^{-1})
f_b	frequency of a ship–ship collision while a tanker is (dis)charging at a terminal (operation^{-1})
F_b	frequency of a ship–ship collision while a tanker is (dis)charging at a terminal, expressed per unit time and per ship passage (operation^{-1} passage^{-1})
f_c	frequency of a ship–land collision, for a tanker moving through the port (operation^{-1})
f_d	grounding frequency, for a tanker moving through the port (operation^{-1})
f_e	frequency of a ship–ship collision, for a tanker moving through the port with another moving ship (operation^{-1})
f_f	frequency of a ship–ship collision, for a tanker moving through the port with a moored vessel (operation^{-1})
$f_{HF,l,m}$	frequency of a minor spill due to hull failure for a ship moving through the port (operation^{-1})
$f_{HF,l,M}$	frequency of a major spill due to hull failure for a ship moving through the port (operation^{-1})
$f_{HF,p,m}$	frequency of a minor spill due to hull failure in the proximity of (un)loading berth (operation^{-1})
$f_{HF,p,M}$	frequency of a major spill due to hull failure in the proximity of (un)loading berth (operation^{-1})
m	number of products bunkered in the port
n	number of hydrocarbon products traded in the port
p_m	probability of a minor spill, given the external impact on the hull
p_M	probability of a major spill, given the external impact on the hull
Q_f	release flow rate (kg/s)
R	individual risk (victims person^{-1} m^{-2} year^{-1})
RF	lethality function (victims person^{-1} m^{-2})
T	ship traffic (passages/h)
Δt	duration of (dis)charge (h)
x, y	Cartesian coordinates
x_D	fraction of double-hulled tanker traffic
x_S	fraction of single-hulled tanker traffic
y'	burning rate (kg m^{-2} s^{-1})
θ	wind direction (°)

Subscripts

p$_i$	product i
b$_j$	berth j

terminals and shipyards are required to produce a contingency plan for accidental marine hydrocarbon pollution, including a study of the effects of possible spills and of their evolution.

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;
- Trbojevic 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.

---

2. Scope of the method

Only liquid 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

---

[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.

Table 1
Chart for the collection of traffic data

	Number of (un)loading operations					
	LNG	LPG	Petrol	Gasoil + kerosene	Fuel oil	...
Berth 1						
Berth 2						
Berth 3						
Berth 4						
:						

Blanks should be filled in with the number of tanker (un)loading operations per unit time.

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_i and berth b_j might be assessed in the following way:

$$\Delta t_{p_i, b_j} = \frac{\text{total loaded and unloaded volume}_{p_i, b_j}}{\text{operational flowrate}_{p_i, b_j} \times \text{no. operations}_{p_i, b_j}}$$

- *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

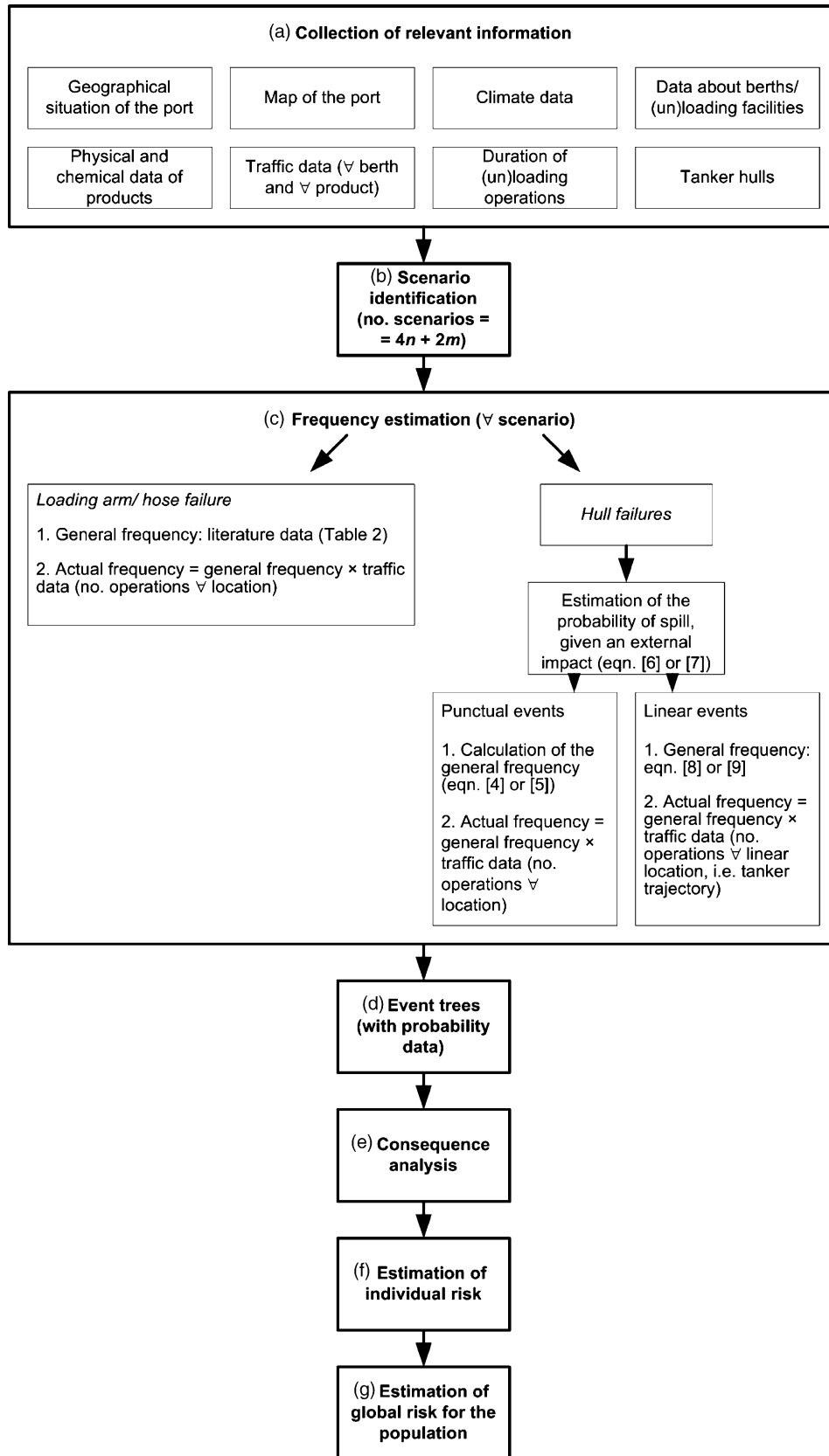From a general point of view, only two basic events can cause a loss of containment during the aforementioned opera-

(a) Collection of relevant information

| Geographical situation of the port | Map of the port | Climate data | Data about berths/ (un)loading facilities |
| Physical and chemical data of products | Traffic data ($\forall$ berth and $\forall$ product) | Duration of (un)loading operations | Tanker hulls |

(b) Scenario identification (no. scenarios = = 4n + 2m)

(c) Frequency estimation ($\forall$ scenario)

Loading arm/ hose failure

1. General frequency: literature data (Table 2)

2. Actual frequency = general frequency × traffic data (no. operations $\forall$ location)

Hull failures

Estimation of the probability of spill, given an external impact (eqn. [6] or [7])

Punctual events

1. Calculation of the general frequency (eqn. [4] or [5])

2. Actual frequency = general frequency × traffic data (no. operations $\forall$ location)

Linear events

1. General frequency: eqn. [8] or [9]

2. Actual frequency = general frequency × traffic data (no. operations $\forall$ linear location, i.e. tanker trajectory)

(d) Event trees (with probability data)

(e) Consequence analysis

(f) Estimation of individual risk

(g) Estimation of global risk for the population

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:

$$\text{number of scenarios} = 4n + 2m \qquad (1)$$

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 operations).

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:

$$f_b = F_b T \, \Delta t$$

where f_b is expressed in events per ship visit, F_b 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 Δt 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

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

- 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:

$$p_M = \begin{cases} 0.1 \text{(single hull tanker)} \\ 0.0015 \text{(double hull tanker)} \\ 0.00012 \text{(gas tanker, semi-gas tanker)} \end{cases} \quad (2)$$

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

Event	Scope (as defined in the original source)	Probability	Source
Spill due to ship–ship collision	Ammonia carriers	0.2	[15][a]
	Oil tankers	Single hull → 0.425, double hull → 0.178	[14], pp. 14–21[b]
Spill due to berthing impact	Ammonia carriers	0.1	[15][a]
Spill due to impact with jetty	Oil tankers	Single hull → 0.425, double hull → 0.264	[14], pp. 14–22[b]
Spill due to ship–land collision (grounding)	Ammonia carriers	0.2	[15][a]
	Oil tankers	Single hull → 0.5, double hull → 0.23	[14], pp. 14–20[b]
Spill due to external impact (ship–ship *or* ship–land)	Tankers	Major spill	[17]
		Liquid tanker, single hull → 0.1	
		Liquid tanker, double hull → 0.0015	
		Gas tanker o semi-gas tanker → 0.00012	
		Minor spill	
		Liquid tanker, single hull → 0.2	
		Liquid tanker, double hull → 0.006	
		Gas tanker o semi-gas tanker → 0.025	
Continuous spill due to external impact, "given serious hull damage (very severe damages for class G ships)"	Tankers and barges in inland waterways	Single hull	[17]
		Low flow rate → 0.2	
		High flow rate → 0.1	
		Double hull or refrigerated ship	
		Low flow rate → 0.006	
		High flow rate → 0.0015	
		Gas carrier (regardless of temperature)	
		Low flow rate → 0.025	
		High flow rate → 0.00012	

[a] Referable also to LNG carriers.
[b] Data are obtained on the basis of the event trees published in this source.

$$p_m = \begin{cases} 0.2 \text{(single hull tanker)} \\ 0.006 \text{(double hull tanker)} \\ 0.025 \text{(gas tanker, semi-gas tanker)} \end{cases} \quad (3)$$

where p_M is the probability of a major spill and p_m is the probability of a minor one. This approach has been chosen for various reasons.

Therefore, for the punctual hull failures the actual general frequencies to be used are as follows:

$$f_{HF,p,M} = (f_a + F_b T \Delta t) p_M \quad (4)$$

$$f_{HF,p,m} = (f_a + F_b T \Delta t) p_m \quad (5)$$

where $f_{HF,p,M}$ is the frequency of a major spill and $f_{HF,p,m}$ is the frequency of a minor one (for the definition of major and minor spills as a function of tanker type, see Section 3.5).

In the case of liquid hydrocarbon bulk tankers, an additional remark must be made. Because a port, or even a single terminal, is normally characterised by mixed traffic of single and double hull tankers, the values of p_m and p_M must be estimated on a statistical basis. Whenever possible, data for individual terminals should be used, but if these are not available a general port ratio of single- to double-hulled tankers can be used. Internal port ship lists or general ship databases (e.g. the *Lloyd's Register of Ships*) can be referred to at this stage. For tankers (other than gas carriers) the probability of a spill will be calculated as follows:

$$p_M = 0.1 x_S + 0.0015 x_D \quad (6)$$

$$p_m = 0.2 x_S + 0.006 x_D \quad (7)$$

where x_S (x_D) is the ratio of port visits by single-hulled (double-hulled) tankers to the total of port visits by hydrocarbon bulk tankers. Obviously, $x_S + x_D = 1$.

3.3.3. Hull failures, linear events

For hydrocarbon spills, four initiating events are possible while the loaded tanker is approaching (or leaving) the berth:

c. ship–land collision;
d. grounding;
e. ship–ship collision between the tanker and another passing ship;
f. ship–ship collision between the tanker and a moored ship.

The general frequencies for these events are shown in Table 2. Ref. [24] gives a different account of frequency data for collisions and groundings. These have not been taken into account because they overlook the possibility of collisions with passing ships; moreover, they are expressed in events per nautical mile, which imply an additional complication of the calculation. As the data in Table 2 are all expressed in proper units (ship visit^{-1}), the overall frequency for linear hull failure events will simply be as follows:

$$f_{HF,l,M} = (f_c + f_d + f_e + f_f) p_M = 2.5 \times 10^{-4} \text{ visit}^{-1} p_M \quad (8)$$

$$f_{HF,l,m} = (f_c + f_d + f_e + f_f) p_m = 2.5 \times 10^{-4} \text{ visit}^{-1} p_m \quad (9)$$

Table 4 summarises the general accident frequencies that we propose.

3.3.4. Bunkering scenarios

We suggest taking into consideration the following two bunkering accidental events:

- hose failure during bunkering;
- hull failure due to external impact on the delivering boat.

The first scenario is analogous to the (un)loading accidents previously described, except that bunkering is normally carried out by way of a hose, so hose failure frequency must be used (4×10^{-3} operation^{-1}, see Table 2). This event may take place at almost any place along the berthing line of the port, as the bunkering boat generally approaches the receiving ship where the latter is moored.

A hull failure on the delivering boat must be considered in the same light as other hull failures. Because of the relatively small dimensions of the volumes transferred, only a minor spill should be taken into account. Anyway, more specific data are needed, such as whether the delivering boat (if there is only one in service at the port) is single- or double-hulled. This means that the probability of a spill is decided directly on the basis of Eq. (3) and not by means of statistics. One must also take into account the fact that this event may take place either while the delivering boat is moving towards the receiving ship, or along the berthing line while the delivering boat is carrying out the bunkering operation.

3.3.5. Calculation of actual frequencies

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

Type of event	Scenario type	Dimension	General frequency
Spill due to loading arm failure	Punctual	Total arm rupture[a]	$f_{LAF} = 6 \times 10^{-5}$ operation^{-1}
		Partial arm rupture[a]	$f_{laf} = 6 \times 10^{-4}$ operation^{-1}
Spill due to hull failure	Punctual	Major spill	$f_{HF,p,M} = (2.2 \times 10^{-3}$ visit$^{-1} + 4 \times 10^{-6}$ passages$^{-1} \times T \times \Delta t) \times p_M$
		Minor spill	$f_{HF,p,m} = (2.2 \times 10^{-3}$ visit$^{-1} + 4 \times 10^{-6}$ passages$^{-1} \times T \times \Delta t) \times p_m$
	Linear	Major spill	$f_{HF,l,M} = 2.5 \times 10^{-4}$ visit$^{-1} \times p_M$
		Minor spill	$f_{HF,l,m} = 2.5 \times 10^{-4}$ visit$^{-1} \times p_m$

[a] 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

| Scenario	Scenario type	Actual frequencies				
		Berth 1	Berth 2	Berth 3	Berth 4	...
Loading scenario, product 1, total rupture	Punctual					
Loading scenario, product 1, partial rupture	Punctual					
Hull failure scenario, product 1, major spill	Punctual					
	Linear					
Hull failure scenario, product 1, minor spill	Punctual					
	Linear					
⋮	⋮					
⋮	⋮					
Bunkering scenario, fuel oil, hose rupture	Linear (along berthing line)					
Bunkering scenario, fuel oil, hull failure followed by minor spill	Diffuse (almost wherever in port waters)					
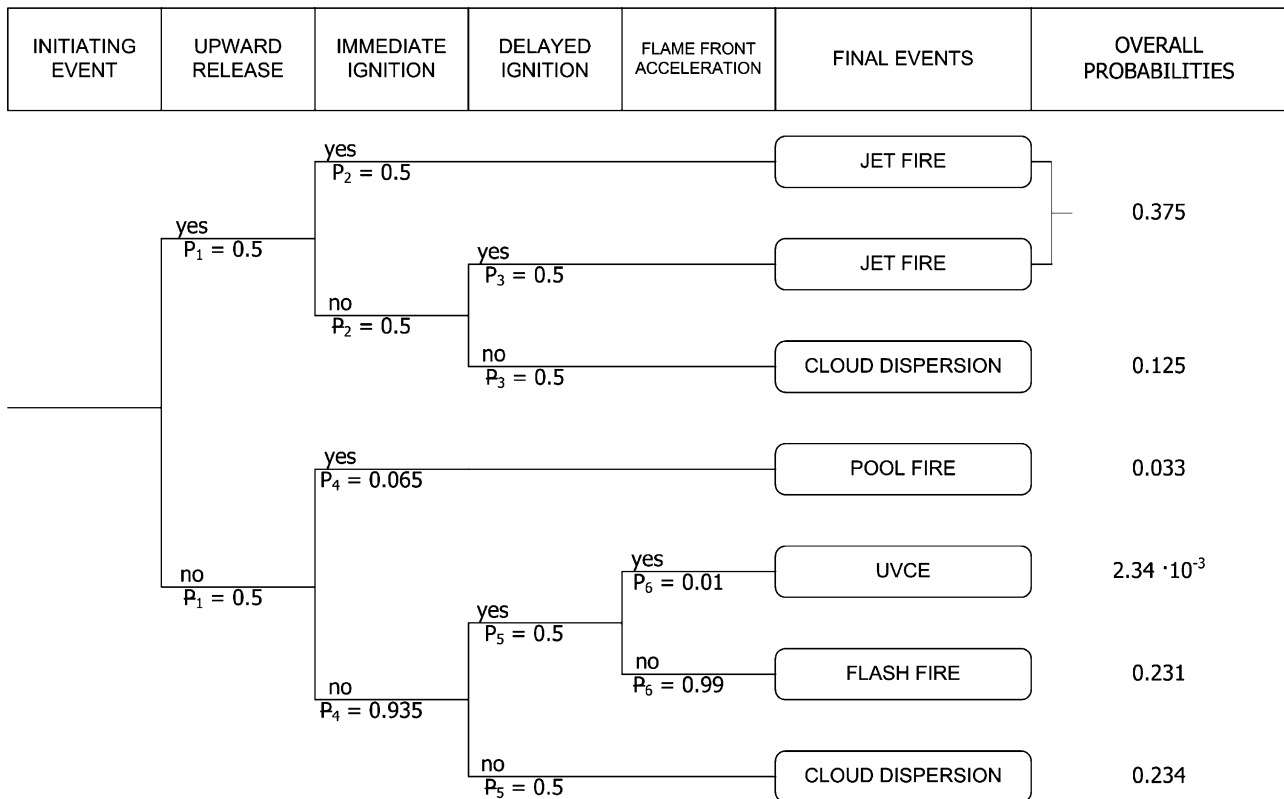
Fig. 2. Event tree for LPG. Sources: P_2, P_3, and P_5 from [17], where they are defined as the probabilities of ignition of a reactive or highly reactive gas with outflow between 10 and 100 kg/s; P_4 from [17], probability of immediate ignition of K1 class liquids (when ejected downwards and immediately ignited LPG can be considered as a liquid); P_6 from TNO's *LPG, A Study* [25].

Table 6
Models and sources used in the project

Phenomena or quantities to be modelled	Models used and sources
Liquid releases	Software: EFFECTS by TNO (models contained in the *Yellow Book* [26]) and Shell FRED
Evaporation rates	Software: EFFECTS by TNO (models contained in the *Yellow Book* [26])
Burning rates	Software: EFFECTS by TNO (models contained in the *Yellow Book* [26]) and LNGFIRE by Gas Technology Institute (for LNG)
Pool fire radiation	Software: EFFECTS by TNO (models from [26]) and Shell FRED (for LNG, LPG)
Jet fire radiation (LPG)	Shell FRED
Cloud dispersion and UVCE (LPG)	Shell FRED
Oil spill evolution	ADIOS 2.0 by NOAA

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* [17] are to be followed. Therefore, whenever a tanker spill is calculated, a major spill is considered to be a continuous release of the following:

- $180\,m^3$ over 1800 s in the case of gas carriers,
- $126\,m^3$ over 1800 s in the case of semi-gas carriers,
- $75\,m^3$ over 1800 s in the case of liquid bulk tankers,

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

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

For loading arm failure, the spill duration was considered to be 120 s. For partial ruptures, it was postulated that the orifice section is 10% of the pipe section. Both of these criteria are proposed by [17].

Several controversial issues are raised by the application of the models. One of these is the estimation of the rate of evaporation of petrol from layers deposited on water, which presented some difficulties related to the major influence of certain variables, such as water temperature and wind speed.

3.6. Estimation of individual risk

Societal risk was estimated by building on the general procedure described by Pietersen and van het Veld [1]. 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:

$$R(x, y) = \int_{\theta=0}^{2\pi} \sum_{k=1}^{6} f\, RF_{k,\theta}(x, y) p(\theta) p_k\, d\theta \qquad (10)$$

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

3.7. 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

Table 7
IR/KR and ER/KR ratios for different accident data subsets

Accident subset	No. accidents	IR/KR	ER/KR
(Un)loading accidents	261	3.09	358
Tankers approaching or manoeuvring	167	0.67	1.66
General	428	2.21	220

unlikely 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 accident. 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 reconverted 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 8
List of scenarios for the Port of Barcelona

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

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 hazardousness 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.

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
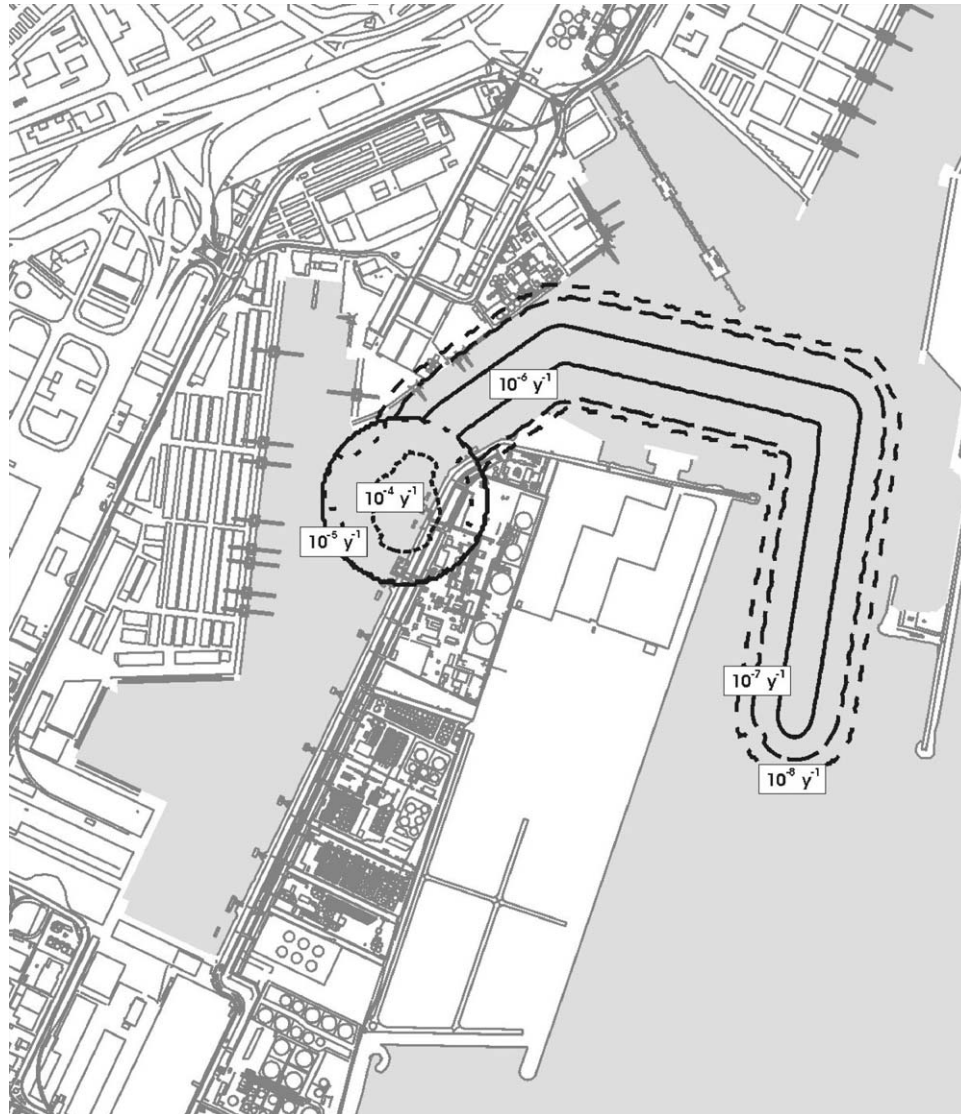
Fig. 3. Iso-individual risk curves for scenario no. 1 (major LNG spill from cargo tank rupture).

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 m³/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):

$$f_{HF,p,M} = (f_a + F_b T \Delta t)p_M = (2.2 \times 10^{-3} \text{ visit}^{-1} + 4.0$$
$$\times 10^{-6} \times 3.74 \times 13.2) \times 0.00012$$
$$= 2.88 \times 10^{-7} \text{ operation}^{-1}$$

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:

$$f_{HF,l,M} = 2.5 \times 10^{-4} \times 0.00012 = 3.0 \times 10^{-8} \text{ visit}^{-1}$$

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 2.5×10^{-6} deaths/year.
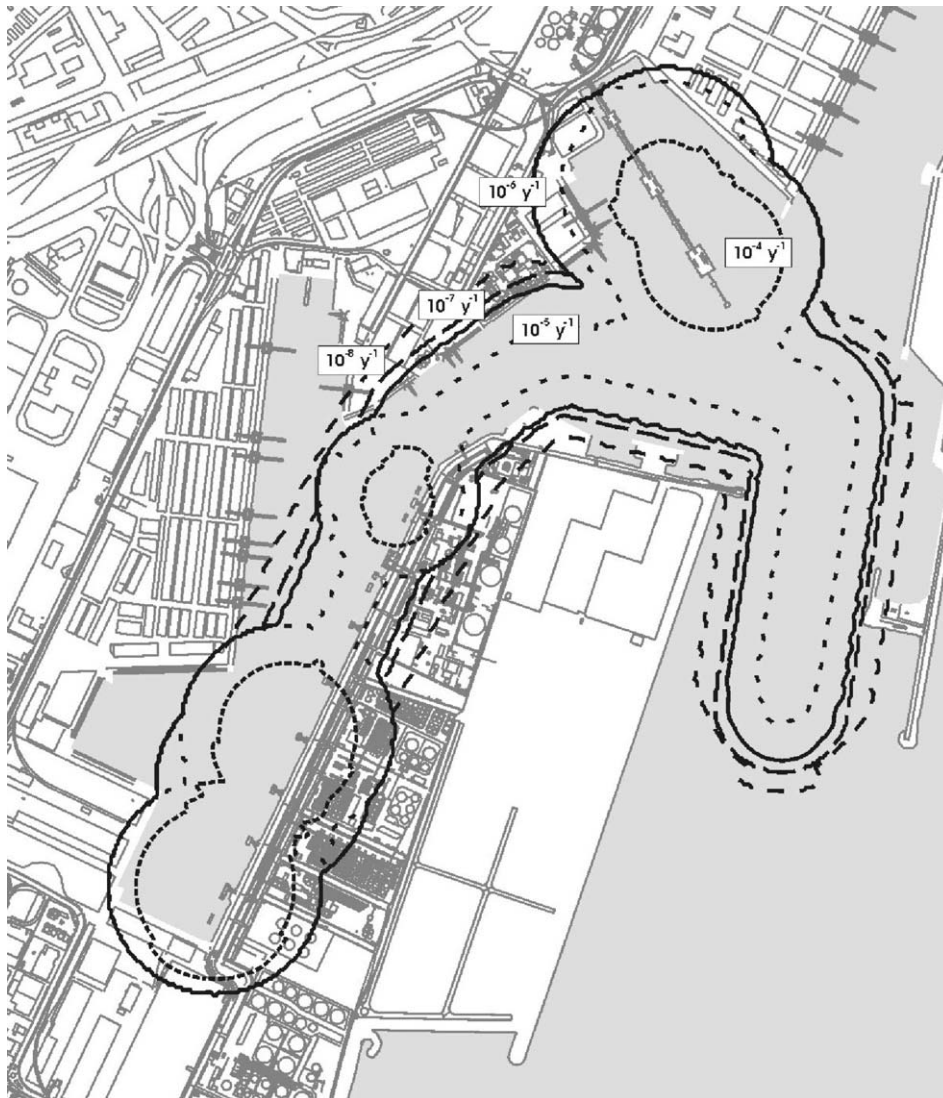

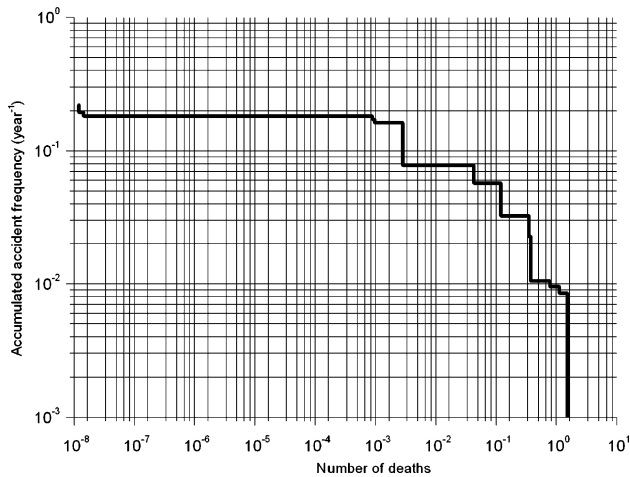Fig. 4. Iso-individual risk curves for all the scenarios.

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[3].

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 materials in port environments would be made available.

Acknowledgements

The authors wish to acknowledge the collaboration of the APB (Port Authority of Barcelona).

References

[1] C.M. Pietersen, B.F.P. van het Veld, Risk assessment and risk contour mapping, J. Loss Prevent. Process Ind. 5 (1992) 60–63.

[2] European Parliament and the Council of the European Union, Council Directive 96/82/EC on the control of major-accident hazards involving dangerous substances. Official Journal of the European Communities, L 010, 14/01/1997, 13–33, available online at: <http://europa.eu.int/smartapi/cgi/sga_doc?smartapi!celexapi!prod!CELEXnumdoc&lg=EN&numdoc=31996L0082&model=guichett> [consulted 18 December 2003].

[3] Boletín Oficial del Estado, Real Decreto 253/2004, de 13 de febrero, por el que se establecen medidas de prevención y lucha contra la contaminación en las operaciones de carga, descarga y manipulación de hidrocarburos en el ámbito marítimo y portuario, Boletín Oficial del Estado, 39 (14/02/2004), available online at: <http://www.boe.es/boe/dias/2004-02-14/pdfs/A06878-06883.pdf> [consulted 14 July 2004].

[4] P.G. Rao, K.V. Raghavan, Hazard and risk potential of chemical handling at ports, J. Loss Prevent. Process Ind. 9 (1996) 199–204.

[5] P. Thomas, MSO Jacksonville's risk toolkit, Proc. Marine Safety Council, 56 (1999) 11–14, available online at: <http://www.uscg.mil/hq/g-m/nmc/pubs/proceed/q3-99.pdf> [consulted 12 December 2003].

[6] C. Hartley, MSO/Group LA/LB Port activity risk index – an adaptation of MSO Jacksonville's tool, Proc. Marine Safety Council 56 (1999) 15–18, available online at: http://www.uscg.mil/hq/g-m/nmc/pubs/proceed/q3-99.pdf [consulted 12 December 2003].

[7] H.L. Kite-Powell, Di Jin, J. Jebsen, V. Papakonstantinou, N.M. Patrikalakis, Investigation of potential risk factors for groundings of commercial vessels in U.S. ports, Int. J. Offshore Polar Eng. 9 (1999) 16–21, available online at: <http://deslab.mit.edu/DesignLab/ij.pdf> [consulted 18 July 2003].

[8] V.M. Trbojevic, B.J. Carr, Risk based methodology for safety improvements in ports, J. Hazard. Mater. 71 (2000) 467–480.

[9] L.K. Cunningham, Risk assessment methodology for marine terminals, in: Ports 2001 Conference: America's Ports – Gateway to the Global Economy [CD-ROM], ASCE, Reston, VA, 2001, available online at <http://www.han-padron.com/papers/LK01.pdf> [consulted 02 March 2004].

[10] A. Ronza, S. Félez, R.M. Darbra, S. Carol, J.A. Vílchez, J. Casal, Predicting the frequency of accidents in port areas by developing event trees from historical analysis, J. Loss Prevent. Process Ind. 16 (2003) 551–560.

[11] R.M. Darbra, A. Ronza, S. Carol, J.A. Vílchez, J. Casal, A survey of accidents occurred in ports, in: Proceedings of the 11th International Symposium Loss Prevention and Safety Promotion in the Process Industries. Loss Prevention 2004, Praha Czech Republic. Paper Full Texts, CSCHI, vol. D, May 31–June 3, 2004, pp. 4305–4311.

[12] D. Egidi, F.P. Foraboschi, G. Spadoni, A. Amendola, The ARIPAR project: analysis of the major accident risks connected with industrial and transportation activities in the Ravenna area, Reliabil. Eng. Syst. Safety 49 (1995) 75–89.

[13] R. Leedham, J. Riding, Operational Risk Assessment of Port of London 1999 – 2001. Report Number 00NR110, May 2001, prepared for Port of London Authority, MARICO Marine, Southampton, 2001, available online at: <http://www.portoflondon.co.uk/pdfs/NavSMSDoc.pdf> [consulted 19 May 2003].

[14] Environmental Resources Management, Marine terminal – accidental events and incidents, in: BTC Project EIA, Final EIA, ERM, London, 2002, vol. 3, pp. 14-1–14-53, available online at: <http://www.caspiandevelopmentandexport.com/Files/BTC/English/ESIAs/Amended%20Turkey%20EIA%20(Final%20incorporating%20comments)/Content/BTC%20EIA%20Volume%203%20Section%2014.pdf> [consulted 7 July 2004].

[15] Health and Safety Executive, Canvey: An Investigation of Potential Hazards from Operations in the Canvey Island/Thurrock Area, HM Stationary Office, London, 1978.

[16] Health and Safety Executive, Canvey: A Second Report. A Review of the Potential Hazard from Operations in the Canvey Island/Thurrock Area Three Years after Publication of the Canvey Report, HM Stationery Office, London, 1981.

[17] TNO, Guidelines for Quantitative Risk Assessment, CPR18E. Purple Book, TNO, Apeldoorn, 1999.

[18] Det Norske Veritas, Frequency Analysis of Accidental Oil Releases from FPSO Operations in the Gulf of Mexico. Final Report, prepared for Ecology & Environment, Inc., Talahassee, Florida, under contract to Minerals Management Service Gulf of Mexico OCS Region, New Orleans, Louisiana, MMS Contract 1435-01-99-CT-30962, Det Norske Veritas, Houston, 2001, available online at: <http://www.gomr.mms.gov/homepg/offshore/fpso/Risk_Assessment.pdf> [consulted 18 January 2004].

[19] Committee on Oil Spill Risks from Tank Vessel Lightering, Oil Spill Risks from Tank Vessel Lightering, National Academy Press, Washington, DC, 1998.

[20] Health and Safety Commission. Advisory Committee on Dangerous Substances, Major Hazard Aspects of the Transport of Dangerous Substances, HM Stationary Office, London, 1991.

[21] H. Rømer, H.J.S. Styhr Petersen, P. Haastrup, Marine accident frequencies – review and recent empirical results, J. Navig. 48 (1995) 410–424.

[22] DNV Technica, Port Risks in Great Britain from Marine Transport of Dangerous Substances in Bulk. A Risk Assessment for the Health and Safety Executive, Report No. C1216 (October 1990), DNV Technica, London, 1990.

[23] Rijnmond Public Authority, Risk Analysis of Six Potentially Hazardous Industrial Objects in the Rijnmond Area, A Pilot Study, Reidel, Dordrecht, 1982.

[24] SEALOC project, Final Report for Publication. SEALOC. TR1193, Expertel Consulting, Paris, 1998, available online at: <http://europa.eu.int/comm/transport/extra/final_reports/waterborne/sealoc.pdf> [consulted 6 October 2003].

[25] TNO, LPG, A Study. A Comparative Analysis of the Risk Inherent in the Storage, Transhipment, Transport and Use of LPG and Motor Spirit. 00 General Report, TNO, Apeldoorn, 1983.

[26] TNO, Methods for the Calculation of Physical Effects Due to Releases of Hazardous Materials (Liquid and Gases). CPR 14E. Yellow Book, 3rd ed., TNO, Apeldoorn, 1997.

[27] N.A. Eisenberg, C.J. Lynch, R.J. Breeding, Vulnerability Model – A Simulation System for Assessing Damage Resulting from Marine Spills, Report No. CG-D-136-75, NTIS AD-015-245, US Coast Guard, Office of Research and Development, Springfield, VA, 1975.

[28] Health and Safety Executive, MHIDAS. October 2003 [CD-ROM], Health and Safety Executive, London, 2003.

[29] Port de Barcelona, Traffic Statistics. Period January - December 2003. Monthly Statistical Report No. 12/2003 (Report Date: 25/02/2004), Autoritat Portuària de Barcelona, Barcelona, 2004, available online at: <http://www.apb.es/en/APB/Statistics/Statistics_2003> [consulted 2 November 2004].

[30] H.L. Kite-Powell, N.M. Patrikalakis, Di Jin, S.L. Abrams, J. Jebsen, V. Papakonstantinou, Shu-chiang Lin. Formulation of a Model for Ship Transit Risk: Final Project Report, MIT Sea Grant College Program Report No. 98-7, 1998.