Contributions to the risk assessment of major accidents in port areas

Andrea Ronza

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Supervised by:
Joaquim Casal i Fàbrega, Ph.D.
Juan Antonio Vílchez Sánchez, Ph.D.

CERTEC - Centre d'Estudis del Risc Tecnològic
Departament d'Enginyeria Química
Escola Tècnica Superior d'Enginyers Industrials de Barcelona
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A Lara

A mamma, papà e Ela, le persone meno obiettive del mondo

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A Lara por compartir su vida con la mía. Esto tiene más mérito que diez tesis doctorales.

Resumen

Esta tesis se presenta como un conjunto de artículos (ya publicados en revistas internacionales, con la excepción del Artículo 6) precedidos por una serie de capítulos introductorios.

1. Introducción. Describe los puertos en relación al análisis del riesgo, al manejo de materias peligrosas (MMPP) y a leyes y convenciones internacionales relevantes.

2. Análisis bibliográfico. Lista trabajos sobre materias peligrosas, vertidos de hidrocarburos y análisis del riesgo de accidentes portuarios, tocando varias técnicas de evaluación del riesgo.

3. Objetivos y metodología. Esta capítulo define los objetivos de la investigación, es decir analizar los sistemas portuarios desde el punto de vista de la evaluación del riesgo de manipulación de MMPP y diseñar herramientas para evaluar dicho riesgo. Además se detallan la metodología empleada y los principales resultados para cada artículo incluido en la tesis.

4. Conclusiones.

Artículos

Artículo 1 – A Survey of Accidents in Ports (*Loss Prevention Bulletin,* 183, pp. 23-28, 2005). Presenta los resultados de un análisis histórico de 1033 accidentes, acerca de varios aspectos (tipo y causa de los accidentes, consecuencias sobre la población, etc.).

Artículo 2 – Predicting the Frequency of Accidents in Port Areas by Developing Event Trees from Historical Analysis (*Journal of Loss Prevention in the Process Industries*, 16, pp. 551-560, 2003). Se utilizó el análisis histórico −sobre una muestra parecida a la del Artículo 1− identificando secuencias accidentales, es decir árboles de eventos generales. Se determinó a continuación la frecuencia de algún típico accidente portuario, demostrando que los árboles propuestos pueden utilizarse en el análisis cuantitativo del riesgo (ACR).

Artículo 3 – Using Transportation Accident Databases to Investigate Ignition and Explosion Probabilities of Flammable Spills (*Journal of Hazardous Materials*, 146(3), pp. 106-123, 2007). Se analiza la literatura especializada sobre probabilidad de ignición y explosión. Se presentan los resultados de la investigación de varias decenas de miles de registros accidentales procedentes de dos bases de datos de vertidos/accidentes de organismos federales estadounidenses. Se proponen ecuaciones para predecir la probabilidad de ignición y explosión a partir de la cantidad y de la sustancia vertida.

Artículo 4 – A Quantitative Risk Analysis Approach to Port Hydrocarbon Logistics (*J. Haz. Mat.*, 128(1), pp. 10-24). Se presenta un método para llevar a cabo ACRs de terminales de hidrocarburos, que tiene en cuenta vertidos menores y graves. Se propone una técnica simplificada para el cálculo de la frecuencia de los accidentes y se da un ejemplo de aplicación, basado en un estudio llevado a cabo en el Puerto de Barcelona.

Artículo 5 – Consequences of Major Accidents: Assessing the Number of Injured People (*J. Haz. Mat.*, 133(1-3), pp. 46-52). El ACR requiere que se estime el número de muertos de los accidentes. El número de heridos, si bien importante, se evalúa raras veces, ya que supone un esfuerzo importante. En este artículo se utilizó un conjunto de registros accidentales para definir una relación entre el número de muertos y de heridos. Se utilizaron el análisis de los componentes principales y el *cluster analysis*, obteniendo el número verosímil de heridos en función del número de muertos.

Artículo 6 – Economic Valuation of Damages Originated by Major Accidents in Port Areas (*J. Loss Prev. Proc. Ind.*, en impresión). Se presenta un procedimiento para estimar el coste de los daños sufridos por la población, las instalaciones y el medio ambiente como consecuencia de accidentes en puertos. Se proponen niveles de compensación económica para daños a personas. Se consideran asimismo los daños al medio ambiente (atmósfera, agua, fauna). Se plantean costes de instalaciones y edificios afectados. Finalmente, se analizan las pérdidas debidas a la parada de actividades y a los costes indirectos.

Summary

This thesis is structured as a series of papers, all but one already published in international journals. A series of introductive sections precedes the papers.

1. Introduction. Port areas are described as related to risk assessment, handling of hazardous materials, accidents, relevant regulations and international conventions, and security.

2. Bibliographic survey. References are collected above all on port-HazMat topics, i.e. oil spills and risk assessment of port accidents, touching various risk assessment techniques.

3. Objectives, methodology and main results. This chapter defines the objectives of the research, i.e. to analyse port systems from the point of view of risk assessment of HazMat handling and to design proper risk assessment tools. Moreover, it lists the methodology followed and the major results obtained for each of the papers included in the thesis.

4. Conclusions.

Papers

Paper 1 – A Survey of Accidents in Ports (*Loss Prevention Bulletin*, 183, pp. 23-28, 2005). A historical analysis of 1000+ port accidents was carried out allowing for various aspects (type and cause of accidents, consequences on people, etc.). The relative importance of diverse types of accidents was studied.

Paper 2 – Predicting the Frequency of Accidents in Port Areas by Developing Event Trees from Historical Analysis (*Journal of Loss Prevention in the Process Industries*, 16, pp. 551-560, 2003). Historical analysis of a sample of port accidents similar to that of Paper 1 was used to identify accident sequences, i.e. general event trees for port accident scenarios. The frequency of some typical port accidents was then determined, showing that the event trees proposed can be used in QRA.

Paper 3 – Using Transportation Accident Databases to Investigate Ignition and Explosion Probabilities of Flammable Spills (*Journal of Hazardous Materials*, 146(3), pp. 106-123, 2007). Literature analysis of ignition and explosion probability data is performed. The results of a scrutiny of some tens of thousands of records obtained from two vast spill databases are reported. Equations are proposed to predict the ignition and explosion probability as a function of the amount and the substance spilled.

Paper 4 – A Quantitative Risk Analysis Approach to Port Hydrocarbon Logistics (*J. Haz. Mat.*, 128(1), pp. 10-24). A method is presented to perform QRA on hydrocarbon terminals. The approach accounts for minor and massive spills due to loading arm failures and hull ruptures. A shortcut approach for frequency calculation is proposed. An example application is given, based on a pilot study conducted in the Port of Barcelona.

Paper 5 – Consequences of Major Accidents: Assessing the Number of Injured People (*J. Haz. Mat.*, 133(1-3), pp. 46-52). QRA usually requires the estimation of the number of fatalities of accidents. The number of people injured, although important, is seldom evaluated, since this entails significant effort. A set of accident records were used to define a relationship between the number of people killed and the number of people injured. Principal component and clustering analyses were applied, thus obtaining expressions estimating the probable number of injured people as a function of the number of fatalities.

Paper 6 – Economic Valuation of Damages Originated by Major Accidents in Port Areas (*J. Loss Prev. Proc. Ind.*, in press). A procedure is presented to estimate the cost of damages suffered by people, equipment and the environment in consequence of port accidents. Economic compensation is proposed for damage to people, including fatal victims, injured victims and evacuees. Environmental harm is also considered, allowing for damage to the atmosphere, soil, water and fauna. Subsequently, estimates of the cost of the equipment and buildings affected are proposed. Finally, an assessment of the loss of profits due to activity breakdown and indirect costs is analysed.

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Note

While carrying out the research that brought up to this Ph.D. thesis, I had the chance of seeing six articles published on various journals. These papers report on practically all of the results obtained and research conducted in the frame of my Ph.D. activities. For this reason, my supervisors decided that it was worth presenting the document by way of those papers, instead of starting a full “book thesis” from the beginning.

The presentation of the thesis in such form complies with the Spanish legislation (Real Decreto 778/1998) and the UPC internal regulations transposing it.

The structure of the document is as follows.

First comes a general *Introduction* to the topic of risk, ports, relevant regulations and HazMat handling in port terminals.

A *Bibliographic Survey* follows, focused on various risk analysis issues related to the research. This chapter contains accounts of the literature read when I was preparing the various research activities that later lead to the compilation of the corresponding papers. Moreover, other books and articles are reviewed when this was deemed pertinent.

The chapter *Objectives, Methodology and Main Results* gives unity to the thesis: it lists the objective of the thesis –first in general and then of each article– and briefly describes the methodology followed in and the main results obtained from the research behind each article.

After the *Conclusions*, which inventory the most original findings of the thesis, each of the six papers is reported in its published form. The journal papers constitute the bulk and the most important part of the thesis. Each of them contains its own introduction, methodology, results section, discussions, conclusions and appendices. The order in which the papers are presented is not strictly chronological, partly due the inevitable differences in the duration of the editorial process of the papers, and partly due to the author’s choice of following a logical sequence rather than a chronological one, in order to demonstrate the commitment of each paper to fulfil the objectives of the thesis.

A. Ronza

List of publications

As explained in the previous *Note*, the bulk of this thesis is made up of six articles published in international journals:

Darbra, R.M.; Ronza, A.; Carol, S.; Vílchez, J.A.; Casal, J. (2005). A Survey of Accidents in Ports. *Loss Prevention Bulletin*, 183, pp. 23-28. **Referred to as Paper 1 in this thesis.**

Ronza, A.; Félez, S.; Darbra, R.M.; Carol, S.; Vílchez, J.A.; Casal, J. (2003). Predicting the Frequency of Accidents in Port Areas by Developing Event Trees from Historical Analysis. *Journal of Loss Prevention in the Process Industries*, 16(6), pp. 551-560. doi:10.1016/j.jlp.2003.08.010. **Referred to as Paper 2 in this thesis**

Ronza, A.; Vílchez, J.A.; Casal, J. (2007). Using Transportation Accident Databases to Investigate Ignition and Explosion Probabilities of Flammable Spills. *Journal of Hazardous Materials*, 146(3), pp. 106-123. doi:10.1016/j.jhazmat.2006.11.057. **Referred to as Paper 3 in this thesis**

Ronza, A.; Carol, S.; Espejo, V.; Vílchez, J.A.; Arnaldos, J. (2006). A Quantitative Risk Analysis Approach to Port Hydrocarbon Logistics. *Journal of Hazardous Materials*, 128(1), pp. 10-24. doi:10.1016/j.jhazmat.2005.07.032. **Referred to as Paper 4 in this thesis**

Ronza, A.; Muñoz, M.; Carol, S.; Casal, J. (2006). Consequences of Major Accidents: Assessing the Number of Injured People. *Journal of Hazardous Materials*, 133(1-3), pp. 46-52. doi:10.1016/j.jhazmat.2005.10.011. **Referred to as Paper 5 in this thesis**

Ronza, A.; Lázaro-Touza, L.; Carol, S.; Casal, J. (2007). Economic Valuation of Damages Originated by Major Accidents in Port Areas. *Journal of Loss Prevention in the Process Industries*, in press. **Referred to as Paper 6 in this thesis**

Furthermore, this thesis has generated other publications, mainly proceedings for conferences and congresses. These are listed below:

Darbra, R.M.; Ronza, A.; Carol, S.; Vílchez, J.A.; Casal, J. (2004). A Survey of Accidents Occurred in Ports. In: Pasman, H.J.; Škarka, J.; Babinec, F. (eds.). *11th International Symposium Loss Prevention and Safety Promotion in the Process Industries. Loss Prevention 2004. 31 May – 3 June 2004 · Praha · Czech Republic. Paper Full Texts*. Praha (etc.): CSCHI (etc.), vol. D, pp. 4305-4311. **Oral presentation and**

poster at the congress. This paper, among few others submitted at the congress, was subsequently selected for publication on the *Loss Prevention Bulletin* (see Paper 1).

Planas, E.; Ronza, A.; Casal, J. (2004). ARAMIS Project: The Risk Severity Index. In: Pasman, H.J.; Škarka, J.; Babinec, F. (eds.), *11th International Symposium Loss Prevention and Safety Promotion in the Process Industries. Loss Prevention 2004. 31 May – 3 June 2004 · Praha · Czech Republic. Paper Full Texts*. Praha (etc.): CSCHI (etc.), vol. A, pp. 1126-1132. **Oral presentation and poster at the congress.**

Ronza, A.; Darbra, R.M.; Casal, J. (2004). Anàlisi del risc en ports de mar. In: *CELC 04. II Congrés d'Enginyeria en Llengua Catalana* [CD-ROM]. Barcelona: CELC. **Oral presentation at the congress.**

de Pablo, J.; Martí, V.; Gibert, O.; Martínez, X.; Arnaldos, J.; Vílchez, J.A.; Carol, S.; Ronza, A.; Solé, X.; Vila, J.; Lluch, C. (2005). Flexris: Economical Valuation of Environmental Risks Derived from Energetic Hydrocarbon Logistics in Harbours. In: *CONSOIL 2005. Proceedings of the 9th International FZK/TNO Conference on Soil-Water Systems. 3-7 October 2005, Bordeaux,* pp. 2646-2653. **Oral presentation at the congress.**

Ronza, A.; Vílchez, J.A.; Casal, J. (2005). Estimation of Ignition Probability Data for Flammable Hydrocarbon Spills Using Historical Analysis. In: Expoquimia (ed.), *X Congreso Mediterráneo de Ingeniería Química. Ingeniería Química y Vida. Abstracts*. Barcelona: Expoquimia, p. 404. **Poster displayed at the congress.**

Ronza, A.; Vílchez, J.A.; Casal, J. (2007). Using Accident Databases to Enhance Probabilistic Risk Assessment. In: *Loss Prevention 2007. 12th International Symposium on Loss Prevention and Safety Promotion in the Process Industries* [CD-ROM]. Rugby: IChemE. **Oral presentation and poster at the congress.**

The following technical report was prepared in the frame of the FLEXRIS project:

Arnaldos, J.; Carol, S.; Manyà, J.; Ronza, A.; Vílchez, J.A.; Espejo, V. (2004). *Proyecto FLEXRIS. Nueva metodología Flexible para la valoración económica de los Riesgos ambientales. Aplicación a la logística de hidrocarburos en el Port de Barcelona. Sección 1: daños accidentales*. Barcelona: CERTEC, report prepared for Port de Barcelona

The research was selected for the “Campus de Excelencia 2005” held at Lanzarote and Fuerteventura (Canary Islands, Spain), where its results (as of May 2005) were presented orally and discussed with the participants of the congress.

List of acronyms and abbreviations

ABS	American Bureau of Shipping
ACOPS	Advisory Committee on Protection of the Sea
AGS	Adviesraad Gevaarlijke Stoffen [Dutch: Advisory Body on Dangerous Goods]
AK	Alaska
art.	article
ADIOS2	Automated Data Inquiry for Oil Spills
AIChE	American Institute of Chemical Engineers
ALOFT-FT	A Large Outdoor Fire plume Trajectory model – Flat Terrain
AMSA	Australian Maritime Safety Authority
ARAMIS	Accidental Risk Assessment Methodology for Industries in the Framework of Seveso II Directive
ARIPAR	Analisi dei Rischi Industriali e Portuali dell’Area di Ravenna [Italian: Analysis of Industrial and Port Risks in the Ravenna District]
ASA	Applied Science Associates
BASF	Badische Anilin und Soda Fabrik [German: Baden Aniline and Soda Factory]
BE	Belgium
BLEVE	boiling liquid expanding vapour explosion
BMT	British Maritime Technology
BOE	Boletín Oficial del Estado [Spanish: Official State Bulletin]
CA	California
CBS	Cyprus Bureau of Shipping
CCPS	Center for Chemical Process Safety
CD-ROM	Compact Disk – Read Only Memory
CDS	Crew Drill Score

CEDRE	Centre de Documentation, de Recherche et d'Expérimentations sur les Pollutions Accidentelles des Eaux [French: Centre for Documentation, Research and Experimentation on Accidental Water Pollution]
CHIRP	Confidential Hazardous Incident Reporting Programme
CI	Cargo Index
CLC	International Convention on Civil Liability for Oil Pollution Damage
CLH	Compañía Logística de Hidrocarburos [Spanish: Logistics Hydrocarbon Company]
CPR	Commissie Preventie van Rampen [Dutch: Commission for the Prevention of Disasters]
CSB	Chemical Safety and Hazard Investigation Board
DAMA	Databank for sikring av Maritime Operasjoner [Norwegian: Database of Safeguards for Maritime Operations]
DE	Germany
DK	Denmark
DNV	Det Norske Veritas [Norwegian: The Norwegian Veritas]
DRF	Discrepancy Risk Factor
DWT	dead weight tonnes, deadweight tonnage
EC	European Commission
ECOPORTS	Information Exchange and Impact Assessment for Enhanced Environmental Conscious Operations in European Ports and Terminals
ed.	editor
EEC	European Economic Community
EL	Greece
EMAS	Eco-management and Audit Scheme
EMS	environmental management system
ERC	Environmental Research Consulting
ES	Spain
ESC	Equivalent Safety Concept
ESPO	European Sea Ports Organisation
ETA	event trees analysis
EU	European Union
EVI	Feasibility Study on Electronic Vehicle Identification
FACTS	Failure and Accidents Technical Information System
FI	Finland
FLEXRIS	Nueva metodología Flexible para la valoración económica de los Riesgos ambientales [Spanish: New Flexible methodology for the economic valuation of Environmental risks]
FMEA	failure modes and effects analysis
FR	France
FSA	Formal Safety Assessment
FTA	fault tree analysis
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection [current name]
	Joint Group of Experts on the Scientific Aspects of Marine Pollution [former name]
GIS	geographic information system

GNOME	General NOAA Oil Modeling Environment
GP	general purpose
GT	gross tonnes, gross tonnage
HazMat	hazardous material(s)
HazOp	hazard and operability analysis
HMIRS	Hazardous Materials Incident Reporting System
HSE	Health and Safety Executive
IAPH	International Association of Ports and Harbours
IBC	intermediate bulk containers
IACS	International Association of Classification Societies
ICS	International Chamber of Shipping
IE	Ireland
IMO	International Maritime Organization
IMDG Code	International Maritime Dangerous Goods Code
IOPC	International Oil Pollution Compensation Fund
IPO	Interprovinciaal Overleg [Dutch: Interprovincial Council]
IRF	Inherent Risk Factor
IRIS	Incident Reporting Information System
ISGOTT	International Safety Guide for Oil Tankers & Terminals
ISM Code	International Safety Management Code
ISO	International Organization for Standardization
ISPS	International Ship and Port Facility Security
IT	Italy
ITOPF	International Tanker Owners Pollution Federation
LA	Louisiana
LMIS	Lloyd's Maritime Information Service
LNG	liquefied natural gas
LP	liquefied petroleum
LPG	liquefied petroleum gas
MAHB	Major-Accident Hazards Bureau
MAIB	Marine Accident Investigation Branch
MARCS	Marine Accident Risk Calculation System
MARPOL	International Convention for the Prevention of Pollution from Ships
MARS	Major Accident Reporting System [managed by MAHB]
	Marine Accident Reporting Scheme [managed by The Nautical Institute]
MCA	Maritime and Coastguard Agency [UK]
MHIDAS	Major Hazard Incident Data Service
MIC	methyl isocyanate
MINMOD	Marine Investigations Module
MISLE	Marine Information for Safety and Law Enforcement
MR	medium range
MSIS	Marine Safety Information System

MSO	Marine Safety Office
n.d.	no date
NIST	National Institute of Standards and Technology
NJ	New Jersey
NL	The Netherlands
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council *or*
	National Response Center
NTSB	National Transportation Safety Board
NY	New York
OCIMF	Oil Companies International Marine Forum
OH	Ohio
OILMAP	Oil Spill Model and Response System
OILPOL	International Convention for the Prevention of Pollution of the Sea
OPA 90	Oil Pollution Act
OPRC	International Convention on Oil Pollution Preparedness, Response and Co-operation
PA	Pennsylvania *or*
	port authority
PAJ-OSR	Petroleum Association of Japan – Oil Spill Response Department
PARI	Port Activity Risk Index
PCA	principal component analysis
PIRS	Pollution Incident Reporting System
PMG	Potomac Management Group
PrHA	preliminary hazard analysis
PrRA	preliminary risk analysis
PSI	Port Safety Index
PT	Portugal
PWS	Prince William Sound
QRA	quantitative risk analysis
RBDM	Risk-based Decision-making
RD	Real Decreto [Spanish: Royal Decree]
RSPA	Research and Special Programs Administration
SAFETI	Software for the Assessment of Flammable, Explosive and Toxic Impacts
SAFIR	Safety Information Reporting
SE	Sweden
SEALOC	Assessing concepts, systems and tools for a Safer, more Efficient And Lower Operational Cost of the maritime transport of dangerous goods
SIGTTO	Society of International Gas Tanker & Terminal Operators
SIMAP	Oil Spill Impact Model
SLORSM	SL Ross Oil Spill Fate and Behavior Model
SLR	SL Ross Environmental Research Ltd.
SOLAS	International Convention for the Safety of Life at Sea

STCW	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
TBT	tributyltin
TCDD	tetrachlorodibenzodioxin
TEU	twenty-foot equivalent units
TI	Transportation Index
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek [Dutch: Netherlands Organisation for Applied Scientific Research]
TNT	trinitrotoluene
TWASS	Transport wassergefährdender Stoffe auf Seeschiffen [German: Transport of Water-Hazardous Materials by Sea Navigation]
TX	Texas
UAE	United Arab Emirates
UK	United Kingdom
ULCC	ultra large crude carrier
UN	United Nations
US	United States of America
USA	United States of America
USCG	United States Coast Guard
UVCE	unconfined vapour cloud explosion
VI	Vessel Index
VLCC	very large crude carrier
VRF	Vessel Risk Factor
VROM	Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer [Dutch: Ministry of Housing, Spatial Planning and the Environment]
VTS	Vessel Traffic System

1 Introduction

The ship was cheered, the harbour cleared,
Merrily did we drop
Below the kirk, below the hill,
Below the lighthouse top.

The Rhyme of the Ancient Mariner

1.1 The concept of risk and the handling of hazardous materials

Every human activity entails risk. The concept of risk seems intuitive to many of us: at a first analysis risk could be defined as “a situation involving exposure to danger” or “the possibility that something unpleasant will happen”, as given in the *Concise Oxford English Dictionary* (Soanes & Stevenson, 2004). Nevertheless, modern engineering science has formalised this notion, defining risk as the arithmetical product of the *consequences* of a certain undesired event or set of undesired events (*accidents*) by the *frequency* over time of such event(s). If we can measure risk for a certain activity, we can then tell if it is worth to engage in that activity or not. In order to do that, we will compare the benefits brought about by the activity with the risk entailed.

Consequences and frequency have to be expressed in suitable units of measurement. Frequency may be given in terms of number of accidents per year, or per operation (in the case that one is referring to a device or installation), while the unit expressing consequences may vary according to the type of aftermath considered. Harm to people is usually reported in terms of number of casualties (per accident), or number of injured people; but one may choose to address risk in financial terms, and then consequences will be measured by economic loss (€ per accident).

The great variety of possible units of measurement for the consequence term depends on the great flexibility of the concept of risk, and its adaptability to a great range of systems. These include loss of human life, material loss, loss of public image (as a consequence of an accident), and environmental damage.

Risk is present everywhere: nature itself is the cause of important disasters such as earthquakes, volcanic eruptions, floods. Such events have always existed. On the other hand, economic loss and harm to people are also inherently induced by human activities, as a function of their characteristics (what is done, where it is done, with what materials, in what safety conditions). In the 20th Century, both frequency and consequences of accidents related to human activities increased significantly due to the dramatic growth of industrialisation, which brought the workers and the public in close contact with new technologies and materials. While modern industry expanded, a generalised concern for health, safety and environmental impacts began to spring up in the most advanced countries.

Over the last decades, there have been a number of emblematic disasters that have paved the way for a general awareness of the hazards of industrial activities, especially of those involving *hazardous materials* (often referred to simply as HazMat). Nuclear industry was hit by the accident of Three Mile Island (1979) and the outstanding catastrophe of Chernobyl (1986). Before them, a number of near-accidents (Hanford, 1949; Detroit, 1966) had already raised public concern about the risks entailed in the production of atomic energy. At the same time, this suddenly boosted the study of accidental frequencies and plant reliability.

Most techniques developed in the field of nuclear safety were subsequently introduced in the *process industry*. A suitable definition of the latter is

> Production Industry using (raw) materials to manufacture non-assembled products in a production process where the (raw) materials are processed in a production plant where different unit operations often take place in a fluid form and the different processes are connected in a continuous flow.
>
> (Lager, 2002)

The worst accidents in process industry tend to happen in chemical and petrochemical plants, due to the intrinsic dangerousness of the substances (HazMat) processed in those installations. Several disasters, such as massive explosions and toxic clouds, have happened during the last decades that produced enduring effects in terms of public concern about the chemical industry. This has been looked at quite suspiciously since then. Among such events one has to cite at least the following:

- At Flixborough (UK, 1974), a severe explosion in a caprolactam plant killed 28 people; this accident was of capital importance in the development of safety and loss prevention in the UK.
- Two years later a cloud of TCDD (a dioxin, extremely toxic) was released at Seveso, near Milan, Italy; this accident (which, according to the studies carried out so far, did not cause casualties) had a tremendous impact in Europe and led the European Parliament to issue the “Seveso Directive” (European Parliament and the Council of the European Union, 1982; see section 1.3.2).
- In 1984, 500 people died at San Juan Ixhuatepec, near Mexico City, as a consequence of a huge fire and a series of explosions in an LPG facility.
- In the same year, nearly 3800 people lost their life and nearly 2700 were caused permanent disability at Bhopal, India, after the accidental release of

a methyl isocyanate cloud. Bhopal is by far the worst disaster ever occurred in the chemical industry.

- In 2001, a strong impact was created by a severe ammonium nitrate explosion at Toulouse, France, which was the cause of 31 deaths.
- In 2005, the Buncefield oil depot at Hemel Hempstead (UK) almost entirely burned causing an enormous smoke plume clearly visible from tens of kilometres away and in pictures taken from space.

A specific term, *major accident*, has been coined in risk assessment engineering. The Seveso II Directive defines a major accident as

> an occurrence such as a major emission, fire, or explosion resulting from uncontrolled developments in the course of the operation of any establishment covered by this Directive, and leading to serious danger to human health and/or the environment, immediate or delayed, inside or outside the establishment, and involving one or more dangerous substances
>
> (European Parliament and the Council of the European Union, 1996)

According to the database MHIDAS (Health and Safety Executive, 2004), the worst major accidents (in terms of loss of life) happened due to HazMat handling in fixed installations are those shown in Table 1.1 and Table 1.2.

A number of novel technologies, safety devices, new building materials and innovative plant layouts have been tested and implemented during the last few decades in order to make process industry safer. More important, loss prevention and risk assessment are now taken into account in most plants, and many conceptual methods are at hand for risk identification, assessment, reduction and prevention in process plants.

Some methodologies are focused only on hazard identification (checklists, HazOp, FMEA, what-if analysis, preliminary hazard analysis), some on the frequency of accidents (fault tree analysis, event tree analysis). Many physical models have been produced to forecast the effects of fires, explosions and gas clouds; several of them have been implemented into commercial computer programs. Diverse procedures have been devised to link such effects to the individual risk, i.e. the probability of a person to die as a consequence of the exposure to a certain level of thermal radiation, overpressure or toxic concentration.

Some methods claim to be more comprehensive, embracing the evaluation of the risk entailed by a plant. Such is the Quantitative Risk Analysis (QRA), aiming at a structured estimation of the expected number of casualties per year in a given plant/area. A far more “inexpensive” technique is represented by risk ranking and risk indices. Risk ranking is generally based on the use of matrices allowing to express the risk entailed by an occurrence, according to its consequences (e.g. represented on the rows, in different severity ranges) and the frequency (on the columns). Risk indices, on the other hand, are algorithms that allow to describe the level of risk associated with a plant by means of a simple number or *score*; the input data are usually the substances involved in the process, the temperature and pressure conditions, parameters related to material handling and transfer.

HazMat are present not only in the process industry. Plants have to be constantly supplied and, at the same time, ship off their products. Growing flows of hazardous substances began to run through roads, railways, rivers, waterways, pipelines and the sea as soon as chemical industry took off during the 20th Century. HazMat transport is often less controllable than HazMat processing, because it is not set in a “rigid” plant or facility, but in a dynamic scenario, changing as rapidly as the HazMat move towards their destination. Many disasters happened during the transport of (petro)chemical products, which have left an important mark. For instance, one of the worst chemical road transport calamities occurred in Catalonia in 1978, at San Carles de la Ràpita, when 216 people died as a consequence of a propylene fireball. Rail transport has been hit by even worse accidents in recent years (Ufa, Russia, 1989; Iran, 2004; North Korea, 2004). Table 1.3 based on MHIDAS, shows some of the worst accidents in HazMat transportation.

1.2 The situation of ports

1.2.1 Ports: some definitions

A port is a facility at the edge of an ocean, river, or lake for receiving ships and transferring cargo and persons to and from them. Ports have specially-designed equipment to help in the loading and unloading of vessels. Cranes and refrigerated storage may be provided by private interests or public bodies. Often, canneries or other processing facilities are located very close by.

The term seaport is used for ports that handle ocean-going vessels, and river port is used for facilities that handle river traffic. Sometimes a port on a lake or river also has access to the ocean, and is then referred to as an inland port. A fishing port is a type of port or harbour[1] facility particularly suitable for landing and distributing fish.

Critical to the functioning of seaports and river ports are:

- Presence of deep water channels (12 m minimum) and berths;
- Protection from wind, wave, and surge;
- Access to intermodal transportation (trains and lorries).

In fact, it can be stated that a port is an intermodal node where goods (and passengers) are loaded/unloaded to/from vessels and sent to their destination, be it onshore or offshore. A port system could be thought of as a complex, often huge, environment where several transport operations are carried out, including not only maritime transport, but also (un)loading and, of course, storage of goods, along with typical process activities.

Transport includes ships and barges as well as lorries, trains, and pipelines. Process operations embrace mainly storage, which can be of different types: solid bulks in silos, stacks, warehouses, packages; liquid bulks and liquefied gases in tanks; containerised goods of any kind. Anyway, production and transformation processes can

[1] Harbours and ports are often confused. A port is a man-made coastal or riverine facility where boats and ships can load and unload. It may consist of quays, wharfs, jetties, piers and slips with cranes or ramps. A port may have magazine buildings or warehouses for storage of goods and a transport system, such as railway, road transport or pipeline transport facilities for relaying goods inland. A harbour (or haven) is a place where ships can receive shelter from the weather. Harbours can be man-made or natural. A man-made harbour will have sea walls or breakwaters. A natural harbour will be surrounded on most sides by land.

Table 1.1. Worst HazMat accidents ever happened in fixed installations, in terms of casualties (Health and Safety Executive, 2004).

MHIDAS accident number	Year[(a)]	Location	Number of deaths	Description
1098	1984	Bhopal (India)	> 2000	A cloud of MIC was released at Union Carbide pesticide plant following a runaway reaction when water entered a 45 tonnes storage tank. All four major safety systems were ineffective.
11345	2002	Ikeja (Nigeria)	1001	Series of explosions at ammunition depot.
1668	1921	Oppau (Germany)	561	An enormous explosion in an ammonium sulphonitrate bulk storage made a crater of 400 ft diameter and 90 ft deep. The cause has not been established but BASF was known to break-up its stock with explosives. 3 people were killed at Mannheim (4 miles distant).
420	1984	San Juan Ixhuatepec (Mexico)	501	An LPG leak was ignited, possibly by a gas burner. Within minutes, 2 spheres bleved simultaneously, probably causing the majority of fatalities. Numerous further BLEVEs in the next 75 min.
8418	1997	Mena Plain (Saudi Arabia)	343	Muslims on pilgrimage to Mecca fled in panic when fire engulfed 70,000 tents. The cause of fire was the explosion of a gas cylinder.
2416	1944	Port Chicago (CA, USA)	321	2 ships loading large quantities of TNT and cordite exploded.
4368	1925	Rio de Janeiro (Brazil)	300	Explosion of 3000 cases of dynamite caused a disaster. 3000 houses were destroyed.
989	1982	Tacoa (Venezuela)	154	A violent explosion occurred while a fixed roof storage tank was being gauged allowing burning oil to flow into the bund. After burning for 6 hours a massive boil-over occurred projecting the tank contents hundreds of feet in all directions.
2401	1917	Chester (PA, USA)	133	The electric wires of a vibrator were used to shake powder into shrapnel shells. A short-circuit ignited the powder giving rise to a dust explosion.
1755	1944	Cleveland (OH, USA)	131	A 4200 m^3 LNG tank ruptured spilling contents into streets and sewers. A series of violent explosions and fires followed. A second tank collapsed giving flames 800 m high.

(a): accidents happened before 1900 have not been taken into account.

Table 1.2. Worst HazMat accidents ever happened in the last decade, in terms of casualties (Health and Safety Executive, 2004).

MHIDAS accident number	Year	Location	Number of deaths	Description
11345	2002	Ikeja (Nigeria)	1001	Series of explosions at ammunition depot.
8418	1997	Mena Plain (Saudi Arabia)	343	Muslims on pilgrimage to Mecca fled in panic when fire engulfed 70,000 tents. The cause of fire was the explosion of a gas cylinder.
10298	2000	Kinshasa (Zaire)	110	A fire broke out at an airport warehouse, setting light to massive ammunition shipment in-transit.
11063	2001	Mafang (China)	101	A massive explosion left a crater where 30 houses once stood. Explosives were being stored at home after officials had shut down an illegal factory.
...				
8913	1998	Xingping (China)	50	A liquefied nitrogen pipeline exploded in a fertilizer plant.
...				
11192	2001	Toulouse (France)	30[(a)]	An explosion occurred in a silo storing off-spec ammonium nitrate. The cause is unknown. The factory site was severely damaged and windows blew out up to 2 miles away. Ammonia and chlorine were also stored on the site but were not released.

(a): the death toll later rose to 31, after a victim died at the hospital several days after the accident.

take place in port areas too, as for logistic convenience many process plants are directly sited near (un)loading facilities. This is always the case with LNG liquefaction and regasification plants; the former collect natural gas, liquefy it and dispatch it via tanker vessel to the latter, which follow the reverse chain in order to send gas to the final users through pipelines, while small quantities of LNG are also transferred to lorries. However, that is not the only case: many isolated hydrocarbon facilities, such as refineries, oil terminals, etc. may themselves be considered as port systems, as they include a marine (or river, or waterway) terminal where ships and barges berth to (un)load bulk liquids.

Fig. 1.1 is a representation of a typical port. The port has an enclosed water area, whose berthing line is normally, but not necessarily, reinforced with concrete structures. Sometimes these are artificially raised from the sea-bottom, in order to make room for wharves and storing areas (this is the case with the container terminal (a) of Fig. 1.1).

Ports are normally located near a city, unless they are isolated terminals serving a process plant or a pipeline. Many cities have in fact been founded and have grown around spots that offered shelter for fishing boats, and later, with the growth of commerce and sea-exploration, have become port-cities. The oldest part of a port, above all in the case of European ports (e.g. Barcelona), is the nearest to the core of the city. Sometimes the old terminals have been converted into marinas, cruise terminals and recreational structures (b), which is sometimes a problem, due to the proximity of leisure areas to industrial facilities. The entrance to the port is generally a narrow mouth; natural sheltering can be reinforced with long artificial breakwaters (g). Apart from being near to urban areas, ports may be adjacent to important environmental spots, like salt marshes, cliffs, beaches (h), deltas, estuaries, coral reefs, etc. Before entering

Table 1.3. Worst HazMat transportation accidents ever happened, in terms of casualties (Health and Safety Executive, 2004).

MHIDAS accident number	Year	Location	Type of transport	Number of deaths	Description
1801	1917	Halifax (Canada)	Ship	~ 2000	The ammunition ship “Mont Blanc” carrying lyddite and chlorobenzene was holed by another vessel. The chlorobenzene cargo leaked and ignited. The ship was abandoned and drifted onto a jetty where lyddite detonated in a vast explosion, breaking windows up to tens of miles away.
2394	1956	Calí (Colombia)	Road	1200	7 trucks loaded with dynamite exploded shortly after midnight while parked outside a railway terminal.
9419	1998	Apawor (Nigeria)	Pipeline	701	Blast from a leaking petrol pipeline. Vandals had caused the leak and over 1000 people gathered to collect the fuel to sell on the black market.
7172	1994	Dronka (Egypt)	Rail	581	Floods caused a rail track to subside. Two tank wagons overturned, fuel ignited and spread to other tanks. Lightning struck complex of 8 tanks with 15,000 tonnes of aircraft fuel at a military site in the flooded town.
1807	1947	Texas City (TX, USA)	Ship	576	Insufficient water was provided to extinguish fire in cargo of vessel “Grandcamp”. Fire started in a second ship carrying sulphur and ammonium nitrate, which exploded 12 hrs later.
3689	1989	Ufa (Russia)	Pipeline	501	Long distance pipeline carrying 30% gasoline and 70% LPG leaked for 4 hrs before a spark from passing trains ignited the gas cloud in massive explosion and fire.
6348	1993	Remeios (Colombia)	Pipeline	430	3000 bbl of oil spilled after some rebels dynamited a pipeline. Serious ecological damage.
157	1983	Nile river (Egypt)	Ship	317	A fire was caused by an explosion of an unauthorised cargo of bottled gas.
9882	1999	Gaisan (India)	Rail	284	An express and a local train collided head on at a station due to a signal failure. At least one train had military explosives aboard.
10409	2000	Adeje (Nigeria)	Pipeline	251	A pipeline had been punctured by some thieves intending to steal gasoline. Two days later local villagers were scavenging around the pipeline when it exploded.

the harbour to carry out loading, unloading or other operations, ships must wait for a certain period at anchorage (f) outside the port premises, until admission is given (either by the harbourmaster or the PA) and a pilot is sent. After entering the port, the ship has to be manoeuvred and berthed. In the case of large ships and tankers, tugs are used for towing (c).

Virtually, any type of vessel can enter a port:

- Ferries, for the transport of passengers and vehicles;
- Liners (or cruise ships);
- Military ships and submarines;
- Barges, i.e. flat-bottomed boats, built mainly for river and canal transport of heavy goods. Most barges are non-self-propelled and need to be moved by tugboats. Barges are very common in river and estuarine ports (like Rotterdam, Buenos Aires and many US ports);
- Fishing boats;
- Yachts and leisure boats;
- Sailing ships;
- Cargo ships.

Among the latter, there can be found the following types of watercraft:

- Bulk carriers, used to transport bulk solids such as (iron) ore, coal, coke, bauxite/alumina, food staples (rice, grain, etc.), cement, sugar, quartz, phosphate rock, fertilisers, sulphur, scrap, and similar cargo (Isbester, 1993). They can be recognized by the large box-like hatches on their deck, designed to slide outboard for loading. Bulk carriers discharge at terminals provided with proper cranes (j); ore and coal can be stored in heaps.
- Container ships. These are cargo ships that carry all of their load in containers, by a technique called containerisation. However, cargo that is too big to carry in containers can be handled using so-called flat racks, open top containers and platforms. They are designed in such a manner that no space is wasted. Their capacity is measured in TEU (twenty-foot equivalent units). This is the number of 20 ft containers that it can carry. The majority of containers used today are 40 ft in length. Above a certain size, container ships do not carry their own loading gear. Hence loading and unloading can only be done at ports with the necessary cranes. However, smaller ships with capacities up to 2900 TEUs are often equipped with their own cranes. Informally known as “box boats”, they carry the majority of the world’s dry cargo. There are large main line vessels that ply the deep sea routes, then many small “feeder” ships that supply the large ships at centralized hub ports. Most container ships are propelled by diesel engines, and have crews of between 20 and 40 people. They generally have a large accommodation block at the stern, directly above the engine room. Container ships now carry up to 8000 containers on a voyage. Container wharves (a) are now the most important source of income for port commerce; the current boom of container transportation is boosting the construction of many new terminals and the extension of the existing ones.
- Car carriers, serving specialised car terminals (i).

- Reefers, a type of ship typically used to transport perishable commodities, which require temperature-controlled transportation, mostly fruits, meat, fish, vegetables, dairy products and other foodstuffs.
- Tankers, usually large ships, carrying petroleum products or chemicals in bulk. Apart from pipeline transport, tankers are the only method of transporting large quantities of oil around the world. Among the chemicals transported by sea, the most important are ammonia, chlorine, methanol, ethanol, acrylonitrile, toluene, hydrochloric acid, sulphuric acid, phenol. Tankers used for liquid fuels are classified according to their capacity to carry oil:
    a) LNG tankers, relatively rare carriers for natural gas instead of oil;
    b) VLCC (very large crude carriers), over 200,000 tonnes;
    c) Suezmax, ships that can pass through the Suez Canal, 125,000 ÷ 200,000 tonnes;
    d) Aframax, 80,000 ÷ 125,000 tonnes;
    e) Panamax, ships that can pass through the Panama Canal, 50,000 ÷ 79,000 tonnes;
    f) MR (medium range) tankers, 38,000 ÷ 50,000 tonnes;
    g) GP (general purpose) tankers, under 38,000 tonnes.

  Supertankers are tanker ships built to transport very large quantities of liquids, especially crude oil. The terms VLCC (Very Large Crude Carrier) and ULCC (Ultra Large Crude Carrier) are also sometimes used. Tanker ships above 250,000 tonnes are generally considered supertankers. They are the largest ships in the world, larger even than aircraft carriers. When first introduced their size and draft prevented them from docking at many existing docks, requiring them to discharge their cargo into smaller tankers offshore (this operation is known as lightering). Some ports have developed special deep-water off-loading facilities connected to the land by pipelines. Due to their size and mass, supertankers have very poor manoeuvrability; the stopping distance of a supertanker is typically measured in miles. When operating close to the shoreline they are vulnerable to running aground, whether due to mechanical failure, human error or bad weather.

Tankers, supertankers, bulk carriers and container ships are used for the transport of huge amounts of dangerous substances (see section 1.2.4) Activities involving vessels include navigation, manoeuvre (with or without tugs), berthing and (dis)charge.

Another typical port activity is bunkering, i.e. vessel re-fuelling. In the case of boats and small vessels, bunkering is carried out from shore, using facilities similar to normal petrol stations. On the other hand, ships are bunkered from one or more dedicated barges, which can be operated by one of the oil terminals.[2] Transhipment of fuel is generally performed using hoses. The fuel bunkered is fuel oil and diesel oil.

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[2] In the Port of Barcelona, for example, ship bunkering is carried out by the barge Campero, operated by CLH, which holds a concession for an oil terminal in the port premises (CLH, n.d.).

Other port activities are carried out on land and can include:

- Dry docks, dockyards and shipyards.
- Process plants. In some situations, it can be convenient to process the raw materials unloaded directly in the port (or in an adjacent area). This is the case with soy beans and cereals, often grinded in situ to obtain flour, then stored in specialised silos. LNG regasification terminals are another example of plant performing process activities on receiving a product. In the same way, many terminals process materials before shipping them at their own jetties and wharves. These include refineries, LNG shipping terminals and chemical plants. A refinery can actually represent a port system on its own, if provided with private wharves, jetties and storage areas.
- Land transport activities, which are carried out by lorry, train and pipelines.
- Storage, either in tank parks, warehouses, container terminals, car parks, bulk solid wharves, etc.

With the exception of shipyards and dockyards, these activities are not port-specific. They are instead standard industrial operations. As well as vessel operations, these activities can involve the handling of HazMat and be affected by accidents caused by these substances.

1.2.2 The economic importance of ports and maritime transport

San Cristóbal *et al.* (1999) estimated that the Gross Added Value of the transport sector represents 5% of the Gross Domestic Product of Spain. Maritime transport is 3% of this share. It is therefore the fourth most important form of transport in Spain, after road, rail and air transport, respectively. In terms of number of employees, the order is the same. Nonetheless, maritime transport is the most important when the amount of goods transported into and out of Spain is considered. As much as 73% of the goods either enter or leave Spain by sea, while only 23% are transported by road into and out of the country.

As of 2001, 328 million persons passed through EU seaports and the total tonnage of goods handled in the EU was estimated at 3000 million tonnes. There were 261 maritime ports handling over 1 million tonnes of goods per year. 70% of all trade with third countries was channelled through the ports.

Short sea shipping, i.e. shipping along the EU’s and its neighbouring countries’ coasts, moves about one third of all goods (considering all modes) with considerable growth (Eurostat, 2003-1 and 2003-2; Zachcial, 1997). Short sea shipping is basically a form of container transportation. The main advantages promoted by this type of shipping are alleviation of congestion, decrease of air pollution, and overall cost savings to the shipper.

Ship transport is a growing sector. As a result, ports are playing an increasingly important role in world economy. For example, the crucial role played by seaports in European Union transport is evident. For quite a while, seaports have not been at the centre of common transport policy. Investment in infrastructures gradually declined between 1970 and the late 1980s. At the beginning of the 1990s however, investment in ports picked up significantly. Sustainability and intermodality are two keywords that push the Commission to take various actions aiming at better connections between ports and the rail and inland waterway networks together with improvements in the quality of seaport services. Since many years, the top five ports remain the same: Rotterdam,

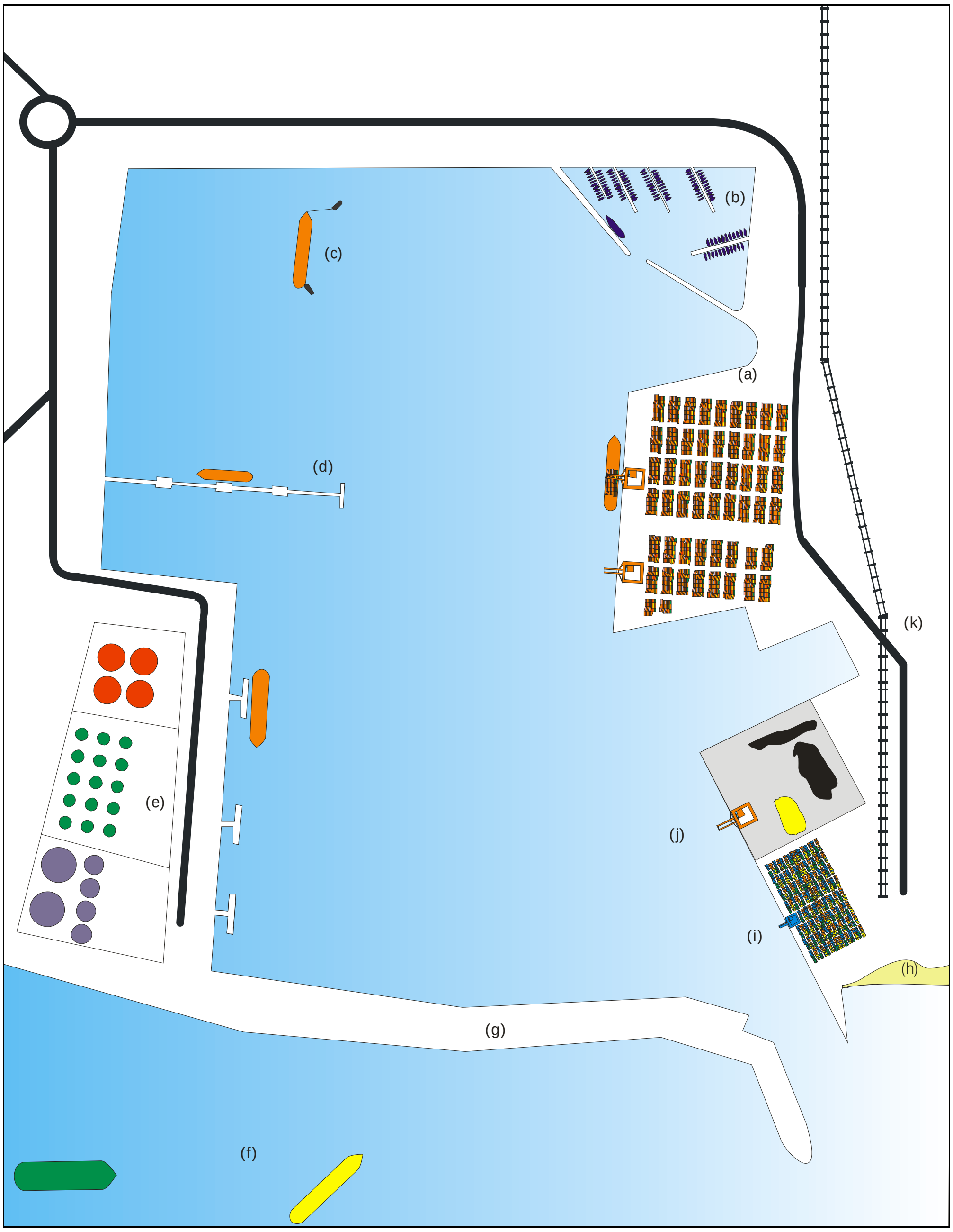

Fig. 1.1. Schematic representation of an industrial port. (a): container terminal; (b): marina; (c): ship being towed and pulled by tugs; (d): oil jetty; (e): oil depot/tank farm; (f): ships anchored outside the port waiting for admission and pilot; (g): breakwater; (h): beaches; (i): car terminal; (j): bulk ore terminal; (k): road and rail network surrounding the port.

Antwerp, Marseille, Hamburg and Le Havre.

1.2.3 The environmental impacts of port operations

Operational activities carried out in port areas are a source of pollution. Marí & Jaime (1998) describe the environmental impacts of navigation focussing above all on hydrocarbon releases. Yet this is not the only environmental impact of navigation and ports. Port activities have manifold impacts on the environment, not necessarily due to accidental events. Operational impacts of port activities include (Trozzi & Vaccaro, 2000):

- *Impacts from ships* (see also White & Molloy, 2001, for a complete account on this topic):
    a) Air pollution, due to movement and hotelling activities.
    b) Water pollution, caused by leaks of fuels and lubricants, accidental spills of liquid cargo during (un)loading, unauthorised discharge of tank washings, antifouling paints (especially TBT paints), introduction of non-indigenous species through ballast waters.
    c) Waste generation.
    d) Noise.
- *Impacts from port operations*:
    a) Air pollution, due to volatile products released during (un)loading operations, motor vehicle traffic, demolition or modifications of ships (asbestos, heavy metals, hydrocarbons, ozone depleting substances and others).
    b) Pollution of water is normally due to accidental discharges and releases; nevertheless, ports may pollute water in other ways: they are responsible for thermal pollution, eutrophication (due to stagnation) and resuspension of materials as a consequence of dredging activities.
    c) Pollution of soil, from demolition of ships, bulk handling device (oil, rubber, etc.).
    d) Waste production, from oil terminals, fuel deposits, ship demolition and maintenance.
- *Impacts from possible industrial activities*.

The EU is showing great interest in the improvement of environmental conditions of port communities. Apart from issuing a number of directives on environmental matters that affect, directly or indirectly, port areas and marine terminals, efforts have been made to urge port authorities to implement an environmental management system. These efforts are also due to the promotional effects of good environmental performance, given that EMS can be certified according to international standards like ISO 14001 (ISO, 1996) and EMAS.[3] The latter was proposed by the European Parliament and the Council of the European Union (2001).

1.2.4 HazMat accidents in ports

In the case of large ports, the majority of port business is based on the trade of chemicals, oil and hydrocarbons, i.e. HazMat. For example, a quick look at the figures of the Port of Barcelona shows that in 2003 dangerous substances, the vast majority (90%) of which were bulk liquids, represented more than one third of the total traffic of goods. On a European scale, statistics confirm this trend: bulk liquid trade (mainly

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3 Such interest has recently generated several projects that involved university research and PA expertise. In the ECOPORTS project, a number of tools has been devised, which help PAs on the way to the implementation of a complete EMS. See: Darbra *et al.* (2004-1), Darbra *et al.* (2004-2), Darbra *et al.* (2005-1).

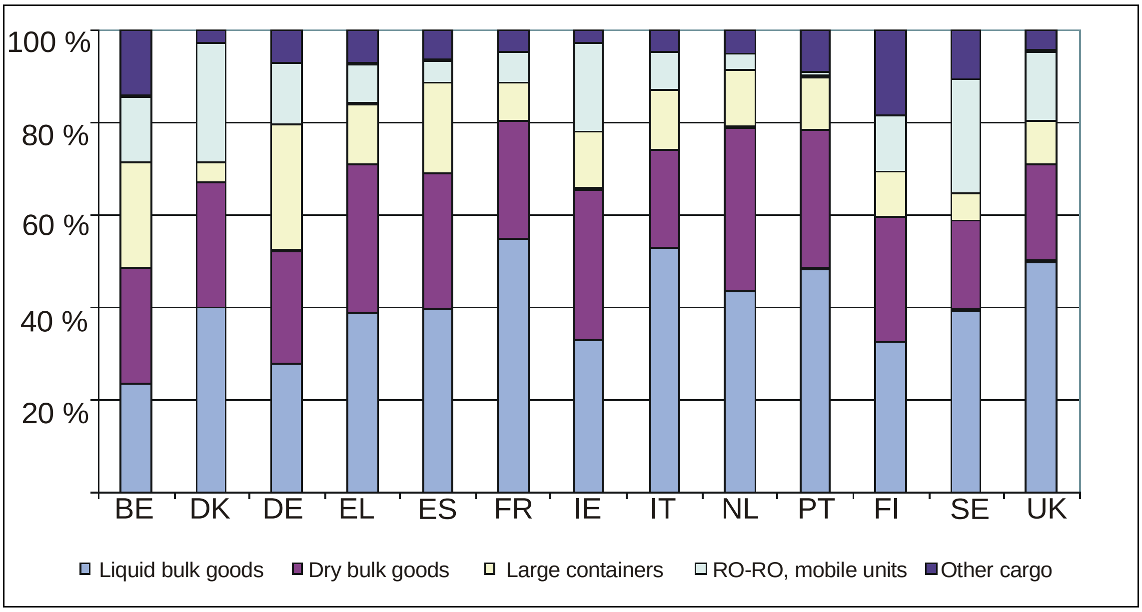


Fig. 1.2. Maritime transport in the European Union (15 countries): share of types of cargo handled (inward and outward) in main ports in 2001 (Eurostat, 2003-2).

hydrocarbons and chemicals) represents between 20% and 50% of the whole transport of goods by sea (see Fig. 1.2).

Of course, the handling and storage of huge amounts of hazardous substances has provoked and provokes accidental events in ports, the same way as it does in process plants. Moreover, depending on the geographical situation of ports, consequences may be even more dramatic. Many ports, for historical reasons, are located in the very core of urban areas; it follows that a major accident, e.g. a toxic gas cloud, could have very serious consequences on the population. Besides, the presence of water makes it easier for oil and chemical spills to spread, thus damaging the environment.

Port accidents can originate from several HazMat handling activities, such as ship approach or manoeuvre in port waters, as well as vessel (un)loading, land storage and transport. According to a list published by Rao & Raghavan (1996), hazardous events related to port operations can be classified as follows:

- Carrier accidents at sea in the vicinity of ports, including:
    a) Engine room fires and explosions;
    b) Cargo pump/compressor explosions;
    c) Chemical tank explosions;
    d) Explosions in forward part of vessel.
- Accidents during berthing at port, including:
    a) Explosions due to loading and unloading operations;
    b) Accidents due to natural causes like lightning;
    c) Fires in electrical installations on the ships/carriers;
    d) Fires during cleaning operations on cargo carriers.
- Accidents during ship-to-shore transfer of chemicals, including:
    a) Pipeline ruptures;
    b) Valve failures;

c) Accidents at port mooring-rope locker system;

d) Lightning during discharge;

e) Transfer pump fires and explosions;

f) Accidental dropping of containers.

- Accidents at cargo sheds leading to fire explosions and toxic gas/vapour discharges, including:

  a) Electrical accidents;

  b) Overfilling of storage containers;

  c) Pipe ruptures;

  d) Failure of hazard control instrumentation.

- Accidents during lifting and transportation of hazardous cargo from port premises to outside agencies, including:

  a) Transport vehicle accidents;

  b) Static electricity development;

  c) Accidental dropping of containers;

  d) Pipe ruptures and valve malfunctions.

On-board spills of highly flammable chemicals may result in large scale fires and explosions. It is very likely that a sequence of events follows that leads to the instantaneous loss of contents of a cargo vessel. Instantaneous release and immediate ignition of the liquefied hydrocarbons normally leads to a fireball with intense thermal radiation in the vicinity of the accident site. Delayed ignition of released liquefied hydrocarbons is likely to lead to unconfined vapour cloud explosions (UVCE) at distances away from the source of release. Fig. 1.3 is a representation of the possible evolution paths of port accident scenarios. Effects and damage of the accidents are charted as well.

Chemical releases from tank farms on site are the most probable. They include highly flammable and toxic chemicals. For the former, pressurized or refrigerated storage methods are employed. The latter is at approximately atmospheric pressure so that even a catastrophic failure should not result in the formation of a large flammable vapour cloud. The possible modes of catastrophic failure of pressurised storage containers are fatigue, overpressure, missile impact and nearby vapour cloud explosion. The causes for overpressure may be overheating due to a neighbouring fire, overfilling or rollover. Overfilling is a common phenomenon in storage installations and has one of the highest probabilities of occurrence values. Rollover is the phenomenon by which the liquid in the tank becomes layered, with a layer of slightly higher-density liquefied chemicals at the bottom. The two layers tend to exchange and depending upon the hydraulic head of the tank, a fraction of its mass flashes off and may momentarily overpressure the tank. Pressurized storages in Horton spheres are generally protected by the concrete containment collar plus their own insulation. The catastrophic rupture of the sphere may occur due to large thermal stresses, stress corrosion or overpressurisation by the pump. The sphere could be caused to fail by stress rupture and release its contents if it became overheated as a result of a large fire in the vicinity. Another possibility is the liquid catching fire due to a local incident or operation, which may lead to stress rupture of the sphere. Severe mechanical damage may occur from impacts from projectiles from disintegration of nearby vessels, aircraft impacts or nearby railway accident due to derailment. The tank farm storing of non-boiling liquids can be affected by pool fires and unconfined vapour cloud explosions. These spills may also result in the direct formation of a flammable vapour cloud. The latent heat required for evaporation has to be provided by the surroundings and the ground. The rate of evaporation will be initially high but decreases rapidly as the available heat from the surroundings is exhausted.

Toxic gas dispersions are also of major concern to ports. The instantaneous release of toxic gas from storage vessels can affect large areas on land and at sea.

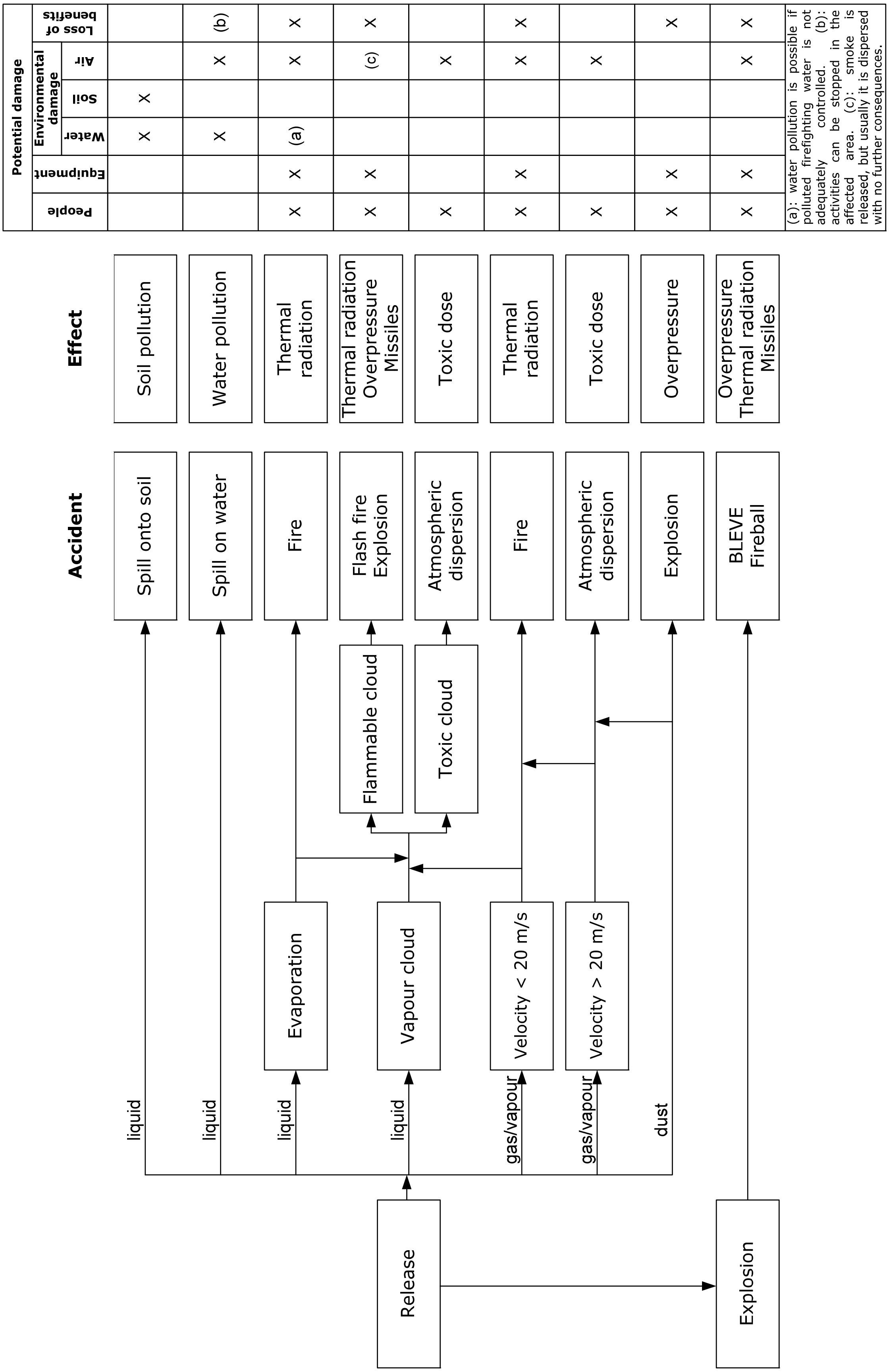
Accidental chemical release can be produced inside hazardous cargo sheds. A number of dangerous chemicals are temporarily stored in hazardous cargo sheds at the ports prior to their despatch to various destinations. Their hazard potential has to be assessed based on their inventory levels and flammability, reactivity and toxicity ratings.

Fire can involve bulk solid storage and handling operations. Self-heating or spontaneous combustion of a solid material is a process of slow oxidation. This is applicable to coal stored in heaps at port. Prevention of accidents due to self-heating depends on recognizing the hazards and taking appropriate measures. Good housekeeping can reduce self-heating caused by items such as waste paper/rags or dust layers. Employment of smaller heaps and their periodic remixing can to a large extent reduce the self-heating process in coal dumps. A smouldering fire in a ship's hold could immobilise the whole ship. In such cases, it may be necessary to dig the material out. This involves a number of hazards and suitable precautions should be taken against them. The operations should be conducted in such a way as not to raise a dust cloud.

Table 1.4 presents a list of the worst accidents ever happened in port areas. The list gives an idea of the accidental scenarios that can affect port areas. Examining this table, the following can be said:

- The six worst accidents (Halifax, Bombay, Port Chicago, Havana, Bone, Bahrain) all happened with explosives and ammunitions, and all before 1965;
- Apart from explosives, the most recurrent substance is crude oil;
- The majority of accidents in Table 1.4 occurred in developing countries.

In addition to fatal accidents, deriving from explosions, fires and toxic clouds, many tremendous tanker spills have happened on ships approaching or leaving a port. Any oil spill at sea as far as about 10 ÷ 15 km away from port installations will create a major emergency at the port due to the serious pollution and flammability effects of oil slicks (Rao & Raghavan, 1996). The infamous accident of the “Exxon Valdez”, which occurred on a tanker's leaving the Valdez terminal at Bligh Reef (AK) in 1989, is probably the most outstanding, due to its huge environmental consequences and the fact that it affected such an influential country as the United States; in fact the US government reacted to the “Exxon Valdez” spill with a number of measures that were to change the international perspectives on the safety of oil tankers at sea (see section 1.3). Of all the spills happened in ports, or in their vicinities, the biggest in terms of volume spilled, is nevertheless the “Urquiola” accident, happened at La Coruña, Spain, in 1976. It is important to stress that spills (mostly oil spills) that happen in ports can be as catastrophic as those occurring in the open sea, even if booms, skimmers and response facilities are sometimes at hand. Some important port oil spills are reported in Table 1.5.



Accident	Effect	Potential damage: People	Equipment	Environmental damage: Water	Soil	Air	Loss of benefits
Spill onto soil	Soil pollution			×	×		
Spill on water	Water pollution			×		×	(b)
Fire	Thermal radiation	×	×	(a)		×	×
Flash fire, Explosion	Thermal radiation, Overpressure, Missiles	×	×			(c)	×
Atmospheric dispersion	Toxic dose	×				×	
Fire	Thermal radiation	×	×			×	×
Atmospheric dispersion	Toxic dose	×				×	
Explosion	Overpressure	×	×				×
BLEVE, Fireball	Overpressure, Thermal radiation, Missiles	×	×			×	×

(a): water pollution is possible if polluted firefighting water is not adequately controlled. (b): activities can be stopped in the affected area. (c): smoke is released, but usually it is dispersed with no further consequences.

Fig. 1.3. Sequence of possible port accidental scenarios.

Table 1.4. Worst accidents in port areas in terms of number of deaths (after Health and Safety Executive, 2004).

MHIDAS accident number	Year	Location	Number of deaths	Description	Substance(s) involved
1801	1917	Halifax (Canada)	~ 2000	The ammunition ship “Mont Blanc” carrying lyddite and chlorobenzene was holed by another vessel. The chlorobenzene cargo leaked and ignited. The ship was abandoned and drifted onto a jetty where lyddite detonated in a vast explosion, breaking windows up to tens of miles away.	chlorobenzene; lyddite
2091	1944	Bombay (India)	1377	A fire of unknown origin started in ships hold, containing mixed cargo of cotton, scrap metal, fish manure, and ammunitions. After 2 days, a massive explosion devastated the dock, damaged hundreds of buildings and sent pieces of scrap metal flying into the city.	dynamite
2416	1944	Port Chicago (CA, USA)	321	2 ships loading large quantities of TNT and cordite exploded.	TNT
2408	1960	Havana (Cuba)	100	The unloading of ammunition ship “La Coubre” was nearly completed when an explosion ignited the remaining cargo.	ammunitions
2395	1964	Bone (Algeria)	85	Detonation on board “Star of Alexandria”.	explosives
168	1958	Bahrain	57	A ship with a fire in hold was put into port to have explosives removed.	explosives
8721	1997	Visakhapatnam (India)	56	A vessel was unloading LPG into a storage tank when a leaking pipe caught fire. The fire spread to other storage tanks containing kerosene, crude oil and petroleum products.	crude oil; kerosene; LPG; petroleum products

Table 1.4. (continued)

MHIDAS accident number	Year	Location	Number of deaths	Description	Substance(s) involved
1132	1979	Istanbul (Turkey)	52	A tanker exploded after colliding with a Greek freighter near docks. 3 weeks later the ship was still burning. Further explosions sent flames 300 m high and burning debris rained on shore (see also Table 1.5).	crude oil
484	1979	Bantry Bay (Eire)	50	Small explosion on tanker "Betelgeuse" discharging oil at terminal. A second blast, followed by a fire-ball, was produced some time later. Missiles thrown at a very large distance.	crude oil
2122	1966	New York Harbour (NY, USA)	33	The "Alva Cape" was struck by a tanker. Naphtha gushed out forming a large pool on the water. A tug ignited the vapour cloud causing a large fire. 12 days later 4 more men died in an explosion while trying to inert an empty gas tank.	naphtha
1851	1975	Marcus Hook (PA, USA)	26	A 200 m chemical tanker tried to u-turn but lost control and rammed a 230 m tanker unloading crude oil. Flames were 150 m high + oil spread 4 km across a river. Fire on other tanker loaded with 11,000 tonnes of phenol.	crude oil; phenol
3345	1945	Port Arthur (Canada)	22	An explosion occurred during loading of refuse screenings onto a ship.	grain dust
1882	1947	Brest (France)	21	The discharge of 3300 tonnes of ammonium nitrate from the "Ocean Liberty" began on July 24. Yellow smoke was seen 3 days later. Steam and water were injected into the hold. The ship was evacuated and towed 600 m offshore. Nevertheless, it exploded damaging Brest buildings.	ammonium nitrate

Table 1.4. (continued)

MHIDAS accident number	Year	Location	Number of deaths	Description	Substance(s) involved
2772	1974	Sumatra (Indonesia)	15	A series of explosions were produced as fire engulfed the oil tanker “Palma” during loading of 40,000 tonnes of crude oil.	crude oil
2851	1987	Manila (Philippines)	15	A tanker was unloading 750 tonnes of methyl methacrylate into two barges when a worker lit a cigarette and ignited the vapours.	methyl methacrylate
2677	1974	Fort Miffin (PA, USA)	13	The tanker “Elias” berthed at Atlantic Richfield Co. terminal was wrecked by a series of explosions. Burning oil spread into the river and onto the pier.	crude oil
2783	1987	Porto San Vitale (Italy)	13	Explosion + fire during maintenance work on LPG carrier “Elisabetta Montanari”. Dead were trapped in confined space in vessel’s double bottom that was filled with smoke.	LPG
5618	1992	Port Kelang (Malaysia)	13	Explosions and huge fire on chemical tanker at depot during a cargo test of 400 tonnes of xylene. 1st test rejected cargo. The vessel still contained traces of previous toluene.	toluene; xylene
6946	1994	Bandar Khomeini (Iran)	13	Explosion and fire at wheat silo. Electrical short circuit suspected.	wheat
893	1979	Good Hope (LA, USA)	12	Collision of a cargo vessel with a loading butane barge on Mississippi river. A fireball hundreds of feet high was formed and lasted 1 minute. 12 hrs were necessary to extinguish secondary fires.	butane

Table 1.5. Most representative marine oil spills within ports or in their close vicinity.

Year	Accident	Location	Ship	Outflow	Description and source
1965	Collision of the “Heim Vard” against a quay	Within the port of Muroran (Japan)	“Heim Vard” (35,355 GT)		The ship loaded with 27,283 m^3 of crude oil entered the port and collided against a quay by an error in ship manoeuvring while it was advancing toward the shore. The oil caught fire and exploded immediately. It went on burning for as many as 28 days (PAJ-OSR, n.d.).
1971	Stranding of the “Juliana”	Outside of the port of Niigata (Japan)	“Juliana” (11,684 GT)	7200 m^3 of Oman crude oil	While anchoring in stormy weather, the ship stranded after being driven by the wind and the waves. The vessel split in two, and crude oil flowed out (PAJ-OSR, n.d.).
1974	Oil spill accident at Mizushima Oil Refinery, Mitsubishi Oil Co., Ltd.	Port of Mizushima (Japan)		7,500 m^3 of heavy oil	The bottom plate of an heavy oil storage tank cracked. Heavy oil spilled out and diffused all the way to the southern area of the Sea of Bisanseto and the Sea of Harima (PAJ-OSR, n.d.).
1975	“Jacob Maersk”	Leixoes (Portugal)	“Jacob Maersk” (48,252 GT)	88,000 tonnes of crude oil	The Danish tanker “Jacob Maersk”, carrying 88,000 tonnes of oil, ran aground whilst docking. Subsequent explosion and release of oil into water caused injuries and a heavy oil slick to cover the bay. Toxic fumes were emitted by the burning slick (Health and Safety Executive, 2004).
1976	“Urquiola”	Entrance to the port of La Coruña (Spain)	“Urquiola” (59,723 GT)	102,000 tonnes of crude oil	The tanker “Urquiola” struck an uncharted rock on approaching the harbour. Authorities ordered to put the ship to sea. The vessel was holed again. Subsequent series of fires and explosions sank the ship, spilling 102,000 tonnes of oil (Health and Safety Executive, 2004).
1979	“Independenta”	Istanbul (Turkey)	Independenta (88,690 GT) & Evriyali (59,723 GT)	95,000 tonnes partially burnt	A tanker exploded after a collision with a Greek freighter near the docks. Burning oil in harbour was brought under control. 3 weeks later ship was still burning and further explosions sent flames 300 m high; burning debris rained onshore (Health and Safety Executive, 2004).

Table 1.5. (continued)

Year	Accident	Location	Ship	Outflow	Description and source
1989	Stranding of the “Exxon Valdez”	Prince William Sound (AK, USA)	“Exxon Valdez” (94,999 GT)	41,000 m^3 of crude oil	En route to Long Beach, California, the ship loaded with about 200,000 m^3 of North Slope crude oil grounded on the Bligh Reef in the Prince William Sound, and stranded due to a manoeuvring error. Eight out of eleven tanks were damaged, and 41,000 m^3 (about 20% of the cargo) flowed out in 5 hrs. The oil from the ship contaminated a total area of 1100 miles along the coast of Alaska, which ended up in the greatest oil spill accident in the US (PAJ-OSR, n.d.).
1990	Linden	Linden (NJ, USA)	a barge	15,000 tonnes of heating oil	A barge exploded and caught fire just after leaving the dock. It drifted down the channel until it was trapped against the shore by a tug so that fire services could tackle the blaze with water and foam. Attempts were made to confine the spill using booms (Health and Safety Executive, 2004).
1992	Stranding of the “Aegean Sea”	Entrance to the Bay of La Coruña (Spain)	“Aegean Sea”	73,000 tonnes of crude oil	The “Aegean Sea” was entering the port of La Coruña when she stranded at the entrance of the Bay by an error in ship manoeuvring in stormy weather; then, lightning struck the ship, which exploded and was destroyed by fire. A great deal of oil flowed out into the sea. The oil contamination extended over an area of 100 km on the beaches. However, damage was relatively minor because most of the spilled oil was burned up, diffused, and evaporated (PAJ-OSR, n.d.).
1993	Outflow of asphalt from the Showa Shell asphalt storage tank	Port of Kushiro (Japan)		246 m^3 of asphalt	An onshore asphalt storage tank was cracked by an earthquake off the coast of Kushiro. Part of the spilled asphalt flowed into the drain system and then out into the sea. The asphalt floating on the sea was smashed into pieces by a crane ship, and was collected by a working ship. The asphalt deposited on the bottom of the sea was collected with a fishing gear (PAJ-OSR, n.d.).
1995	“Chung Mu”	Access channel to Zhanjiang’s harbour (China)	“Chung Mu” (3500 GT) and “Chon Stone”	230 tonnes of styrene monomer	On March 9, 1995, the “Chon Stone N°1”, a cargo boat, collided with the “Chung Mu N°1”, a chemical tanker built in 1994, loaded with styrene monomer in the access channel to Zhanjiang’s harbour (Southern China). When the ships collided, 230 tonnes of styrene monomer were spilled at sea (CEDRE, 2000-2).

Table 1.5. (continued)

Year	Accident	Location	Ship	Outflow	Description and source
1995	Stranding of the "Sea Prince"	Southeast shore of Shori Island off the port of Yosu (South Korea)	"Sea Prince" (275,469 DWT)	96,000 m^3 of Arabian oil	The "Sea Prince" stopped unloading crude oil at the refinery of the port of Reisui. It drifted to Shori Island, where it stranded. Later, a fire broke out in the engine room, which was followed by an explosion in the cargo tank. As a result, fuel oil and crude oil flowed out. Serious damage to the fishing industry (PAJ-OSR, n.d.).
1996	Stranding of the "Sea Empress"	Entrance to Milford Haven (Wales, England)	"Sea Empress" (133,855 DWT)	72,000 tonnes of crude oil	En route to the Texaco terminal at Milford Haven, the ship stranded. Later, the ship left a reef and got stranded again in stormy weather tide (PAJ-OSR, n.d.).
1997	Oil spill accident of the "Diamond Grace"	Near the Nakanose Route about 6 km away from the Honmaki Quay, Naka-ward, Yokohama (Japan)	"Diamond Grace" (147,012 GT)	1550 m^3 of crude oil	En route to the Kawasaki plant of Mitsubishi Oil Co., Ltd. from the UAE, the "Diamond Grace", operated by Nihon Yusen K.K., whose cargo was 305,000 m^3 of crude oil, wrecked on a reef and oil flowed out (PAJ-OSR, n.d.).
1997	"Katja"	Port of Le Havre (France)	"Katja" (52,067 GT)	187 tonnes of fuel oil	This spill occurred after a berthing error in the Port of Le Havre. The "Katja" is a VLCC with an overall length of 232 m built in 1995 according to new construction standards requiring a double hull, after recent US legislation (Oil Pollution Act). Nevertheless, one bunker tank was holed; according to US legislation a double hull was not required for this section of the vessel. Consequently, 187 tonnes of bunker C were released into oil wharf number 3 (CEDRE, 1997).
2000	"Coral Bulker"	Port of Viana do Castelo (Portugal)	"Coral Bulker" (28,454 GT)	100 ÷ 150 tonnes of heavy fuel and oil	On December 25, 2000, in heavy sea, the bulk carrier "Coral Bulker" was waiting at anchor in front of Viana do Castelo harbour for the master's office to grant it a place alongside the quay, as it came from Tallinn. (CEDRE, 2003).
2003	"Tasman Spirit"	Outside Karachi harbour (Pakistan)	"Tasman Spirit" (45,603 GT)	28,000 tonnes of crude oil	The tanker "Tasman Spirit", loaded with 67,000 tonnes of Iranian crude, grounded in the access channel to Karachi harbour. The hull was perforated and around 28,000 tonnes of crude were spilled. Lightering operations allowed to recover 13,000 tonnes of oil, after which bad meteorological conditions interrupted operations and split the vessel into two parts (CEDRE, 2004-2).

1.2.5 Safety issues regarding tankers, cargo ships and port terminals

This section deals with the most important safety problems posed by the maritime transportation of hazardous materials into and out of ports. Safety matters concerning non-port-specific operations like storage, process and land transport will not be dealt with, since this work is devoted to the specificity of port systems. Anyway several references are provided in Chapter 2 – Bibliographical Survey, which cover aspects such process plant, storage and land transport safety, whenever these activities are approached from the point of view of ports.

The Oil Companies International Marine Forum has prepared in the last two decades a number of Safety Guidelines covering a wide range of operations with hydrocarbons. The *International Safety Guide for Oil Tankers & Terminals* (or ISGOTT; ICS *et al.*, 1996) concerns oil transportation into and out of port terminals. The *Safety Guide for Terminals Handling Ships Carrying Liquefied Gases in Bulk* (OCIMF, 1982), as well as McGuire & White (2000) on behalf of SIGTTO, are devoted to the transhipment of liquefied gases. ICS (2002) published a similar set of guidelines dealing with the transport of chemicals.

The major safety concerns regarding the transport of bulk liquids, be they oil, liquefied gases or chemicals, can be summarised as follows:

- A series of specific precautions must be taken *on board the tanker*, in order to avoid the presence of any ignition sources, ignitable or toxic atmospheres and spills. Naked lights and smoking are strictly forbidden, the crew must exercise caution when working with lamps and electrical equipment. Hot work on board must be carried out under strict safety conditions. When using tools, crew must be aware they are a potential source of sparks. Special attention has to be paid when working in pump, engine and boiler rooms and when entering enclosed spaces.
- At *arrival in port*, relevant technical and safety information has to be exchanged between the tanker, the terminal and the competent authority (i.e. the PA and/or the harbourmaster). Relevant information includes vessel data (name, country of registration, overall length, draught and beam, estimated time of arrival, nature of cargo, UN number of cargo, flashpoint of cargo, distribution of cargo on board, whether the vessel is fitted with an inert gas system, oxygen content of cargo tanks, manifold details) and terminal data (depth of water at the berth at low water and range of salinity that can be expected, availability of tugs and mooring craft, mooring lines and accessories present at the terminal, which side of the vessel has to be moored alongside, number and size of hose connections, loading arms and manifolds, maximum allowable speed and angle of approach, etc.). Mooring is a critical operation. Wind can cause the rupture of poorly operated and/or designed mooring lines.
- While *at berth*, tanker fire hoses have to be connected to the ship's fire main. Fire fighting equipments have to be ready for use, both on board and ashore. The tanker's boilers, main engines, steering machinery and other equipment essential for manoeuvring have normally to be maintained in a condition that will permit the ship to move away from the berth at short notice. Smoking is strictly forbidden, any task to be performed with the aid of electrical equipment is required a special permit, as well as any hot work activity, including welding and burning.

- While *preparing for loading* (or unloading), the tanker and the terminal have to agree on a loading plan (or a discharge plan), including information on the amount and nature of the product to be (un)loaded, the sequence of the operation, the initial and maximum loading rates, the method of tank venting, and the emergency stop procedure. Where possible, an inspection of ship's tanks before loading cargo should be made without entering the tanks. The ISGOTT Guidelines, as well as the liquefied gases and the chemical bulk tanker guidelines, provide a thorough Ship/Shore Safety Checklist, which should be completed on behalf of both the tanker and the terminal. The check list was originally endorsed by the IMO. The terminal must provide hoses in good condition. Hoses have always to be handled with care; they should not be dragged over a surface or rolled in a manner that twists their body. As to metal loading arms, it must be ensured that they are free to move with the motion of the ship. Excessive vibration should be avoided. In order to provide protection against arcing during connection and disconnection, the terminal operator should ensure that cargo hose strings and metal arms are fitted with an insulating flange.
- While *(dis)charging*, the following safeguards must be maintained: a responsible officer must be on watch; a senior terminal representative must be on duty and communications between him and the responsible officer continuously maintained; a competent member of the terminal should be on continuous duty in the vicinity of the ship to shore connections.
- *Double hull* ships, which provide a higher safety level at sea, need additional safety checks when at berth, due to problems of stability and the presence of additional enclosed spaces (those in between the two hulls), which have to be properly inerted.
- Possible operations involving *tank cleaning and gas freeing* are critical to the safety of oil tankers.

As to bulk solid transportation, the major reference in matters of safety is the *Code of Safe Practice for Solid Bulk Cargoes* (IMO, 2001). Apart from focussing on the correct ways of stowing cargo in holds, this Code is above all concerned with the perils of coal, the most important hazardous bulk solid cargo transported by sea. Economists distinguish two main types of coal: steam or thermal coal, which is used for power generation and domestic heating, and coking or metallurgical coal (Isbester, 1993). A number of hazards are associated with the carriage of coal. The most important, at a large scale, is fire, sometimes produced in conditions of spontaneous heating. Other hazards include the spontaneous production of hydrogen and methane, which can ultimately lead to explosion. The sulphur in coal can produce sulphuric acid if it is combined with moisture. The relevant provisions of the abovementioned *Code* are the following:

- *Before loading* coal must be separated from other categories of hazardous cargo and must not be stowed adjacent to hot areas. The shipper should provide the master with a written cargo declaration of the cargo's contracted moisture content, sulphur content and size, and whether it will be liable to emit methane, or to self-heat. Holds and bilge wells should be thoroughly cleaned. Coal cargoes having a moisture content in excess of the transportable moisture limit must not be carried. All electrical circuits in holds and adjacent compartments must be isolated. The ship should carry on board appropriate instruments for measuring concentration of methane, oxygen and carbon monoxide, pH of cargo hold bilge samples and temperature of cargo, without requiring entry of personnel into the cargo space.

- *During transport* self-contained breathing apparatus must be kept available, smoking and naked flames should be prohibited; burning, cutting and welding should be performed only when strictly necessary and under safe conditions.
- *Before discharging* precautions must be taken against sparks, especially when opening the hatch covers.

Container transportation is probably the most controversial from the point of view of safety. In fact, whilst tankers and bulk carriers are loaded with no more than two different HazMat at a time, a container ship can carry tenths of different HazMat, together with the most diverse types of other cargoes. Containers include portable tanks, carrying any kind of bulk liquid, including liquefied gases and hazardous chemicals. In the case of seaborne container transportation, safety regulations are currently under development. IMO's *IMDG Code* is the basic reference as to regulations as well as safe practices with containers (see section 1.3.1). A number of relevant regulations were issued in the mark of the Real Decreto 145/1989 (BOE, 1989; see section 1.3.2 and Merino *et al.*, 1994). Containerised dangerous goods shall be strictly segregated, as they had been stowed in bulk. In general, containers carrying HazMat shall be stowed on the deck and as far as possible from the area where the crew live. Sources of ignition, like refrigerated containers, shall be disposed at a proper distance. Containers carrying HazMat shall bear proper labels to indicate the nature and hazardousness of their content. HazMat shall be disposed inside the container with care, providing there is no possibility for spills and releases (Palacio, 2001; Costa, 1987).

1.3 Laws and regulations affecting sea HazMat transportation

1.3.1 Non-port-specific laws and regulations

In this section the most important laws and treaties will be cited and described, which concern safety at sea when transportation of hazardous materials is involved. These regulations mainly affect tankers. They have been enacted in the last decades as reactive, rather than proactive, measures against the "no. 1" threat to the safety of the seas: oil spills (especially massive ones, like the "Exxon Valdez" or "Prestige" spills). The previous section has specifically focused on this topic from different points of view, mainly risk-related. In the present section we present a brief review of the most important international treaties concerning (oil) tanker safety.

Over the course of the past three decades the international shipping industry has undergone significant transformation from virtual self-regulation to increasingly prescriptive rules and regulations from international bodies and national governments. Major spill events have served as a catalyst for heightened oversight and regulation. History has consistently supported acceptance of "freedom of the high seas" as a basic tenet governing the operation of vessels. This has served the shipping industry well over time, as it has largely shielded this industry, unlike other transportation sectors, from significant government involvement or intervention. The International Maritime

Organization (IMO) was established under the auspices of the United Nations to provide a forum for promoting shipping through uniform standards (Lentz & Felleman, 2003).

The first response to the problem of oil spills by the international community was not to regulate shipping for prevention of spills, but rather, to limit the liability of ship owners, by providing a mechanism to pay for cleanup and damages that would not create a financial burden on the industry. Nevertheless, the Torrey Canyon spill of 1967 provided the impetus for the international community to address liability and compensation for accidental spills of oil for the first time.

The international community's first consideration of oil pollution was reflected in the International Convention for the Prevention of Pollution of the Sea (OILPOL) in 1954. The purpose of this Convention was to reduce intentional "operational" discharges of oil from routine ballasting and tank cleaning operations. It did not address the problem of accidental spills.

In November 1969, IMO adopted the International Convention on Civil Liability for Oil Pollution Damage (CLC). The purpose of the CLC was to ensure compensation for victims of oil spills by adopting uniform standards for establishing liability and compensation. Under the CLC, a ship owner is "strictly" liable for damages caused by the spill. This means that, regardless of fault, a ship owner must compensate the victims. In 1971, the International Oil Pollution Compensation Fund (IOPC Fund) was established to provide compensation for damages from spills, which are not fully compensated under the CLC. Both the CLC and Fund Conventions are now gradually being superseded by revised versions of the Conventions, known as the 1992 Protocols, which entered into force in 1996. In fact, increasing costs of spill cleanup and damages has necessitated an increase in both ship owner liability limits and Fund claim limits (IMO, 1996).

The IMO convention that addresses most directly the issue of accidental pollution from ships is MARPOL 73/78. While the original focus of MARPOL was intentional "operational" discharges of oil, over time, concern for accidental spills has been translated into amendments specifically intended to prevent such accidental incidents.

MARPOL meant a substantial reduction of operational spills (Puértolas, 1993, chapter 24). In the 1980s a modest decline in the number and severity of spills is evident in the statistics. However, during this time, better understanding by the scientific community of the destruction of natural resources and the expanding claims for economic loss sustained ongoing concerns about the adequacy of preventive measures. In other words accidental spills became the new target for spill reduction.

However, it was not until the "Exxon Valdez" incident that the international community was forced to take significant steps to further improve upon prevention. The "Exxon Valdez" incident in March of 1989 roused deep concern within the United States about the environmental and economic consequences of oil spills. The US Congress acted quickly to adopt the Oil Pollution Act of 1990. A key provision of that new law was a requirement that ships entering US ports be fitted with a double hull. This requirement was to be phased in over time.

The unilateral North American intervention included very important aspects such as: a) the liability is unlimited in case of accidents, so shipowners have to provide a 1000 million € guarantee, as well as to appoint a representative in the affected territory to whom to demand civil liabilities in case of an accident; b) a list of ports was drawn up to give refuge to those vessels with less safety conditions; these safe-haven ports have the suitable infrastructures and means to act if necessary; c) the safety measures for vessels were increased and strengthened. A subsequent analysis on the enactment of this regulation shows that there have not been more oil spills of the first magnitude since the implementation of this legislation.

As a result, the US set out to convince the international community to adopt similar requirements. The United States was successful in doing so, and MARPOL was once again amended. Specifically, Regulation 13F of MARPOL was amended to provide that tankers contracted on or after July 6, 1993, of 600 deadweight tonnes (DWT) capacity or more be equipped with double hulls. Those between 600 and 5000 DWT are to be fitted with double hulls and double sides, and the capacity of each cargo tank is restricted. Every oil tanker of more than 5000 DWT is required to have a double hull (double bottom and double sides), a middeck with double sides, or an alternative arrangement specifically approved by IMO that provides protection equivalent to the double-hull design. Regulation 13G of MARPOL addresses existing single hull ships. It provides that tankers (> 20,000 DWT) and oil product carriers (> 30,000 DWT) be retrofitted with double hulls or their equivalent according to an established schedule. They must also be subject to operational measures providing added protection, or be retired 25-30 years after delivery.

Unlike in the US, in Europe the institutional framework related to oil slicks has been quite limited and vague until the “Erika” and “Prestige” accidents (happened off Brittany and Galician coasts in 1999 and 2002, respectively), before which the existing instruments for the regulation of maritime activities showed a very narrow scope (González *et al.*, 2005). The control of maritime traffic, the inspection of the characteristics of vessels carrying dangerous goods, the conditions to enter European ports, the knowledge of operators, or the responsibilities regarding compensations, are examples of this secondary and vague role that the European institutions adopted.

The European Union reacted positively after the “Erika” accident (1999) and started to elaborate new sets of regulations to improve maritime safety, the so-called Erika I and Erika II sets of measures. They included new inspections and controls for both vessels and classification societies, and they verified the conditions of maritime traffic. However, the European reaction was less exigent and decisive than the US procedures after the “Exxon Valdez” accident (1989).

Apart from the previous codes, mainly related to the concern of oil spills and other sources of pollution of ships, the IMO released in 1965 the International Maritime Dangerous Goods Code, or IMDG Code (IMO, 2002-2). The development of the IMDG Code dates back to the 1960 Safety of Life at Sea Conference, which recommended that Governments should adopt a uniform international code for the transport of dangerous goods by sea to supplement the regulations contained in the 1960 International Convention for the Safety of Life at Sea (SOLAS).

The Code is meant to cover such matters as packing, container traffic and stowage, with particular reference to the segregation of incompatible substances. It lays down basic principles; detailed recommendations for individual substances, materials and articles, and a number of recommendations for good operational practice including advice on terminology, packing, labelling, stowage, segregation and handling, and emergency response action. It is divided into the following parts:

- General provisions, definitions, training;
- Classification;

- Packing and tank provisions;
- Consignment procedures;
- Construction and testing of packagings, IBCs, large packagings, portable tanks and road tank vehicles;
- Transport operations;
- The *Dangerous Goods List*, presented in tabular format.

Since its adoption by the fourth IMO Assembly in 1965, the IMDG Code has undergone many changes, both in appearance and content to keep pace with the ever changing needs of industry.

Amendments to SOLAS chapter VII (Carriage of Dangerous Goods) adopted in May 2002 make the IMDG Code mandatory from 1 January 2004. Also in May 2002, IMO adopted the IMDG Code in a mandatory form, known as Amendment 31.

1.3.2 Port-specific laws and regulations

As ports are located in territorial waters, port authorities are not subject to international conventions.[4] In general, it can be said that, for administrative and technical matters, a port is managed by a *port authority* as far as the shoreline, while navigation affairs are under the competence of a *harbourmaster's office*. Port authorities and harbourmaster's offices are either under control of local authorities or national governments. This depends on the country and on the size of the port. For an overview of port ownership and management organisation in Europe, see Puertos del Estado – Boletín información mensual (1999-1, 1999-2, 1999-3) and ESPO (2005). In Puertos del Estado – Boletín información mensual (2000) an outline is presented of who is in charge of the management of port services (piloting, towing, berthing, stevedoring, shipyards) in several European countries.

These organisational differences are reflected in those codes and laws specifically concerning the handling of dangerous goods. However, under the influence of IMO and other supranational organisations (e.g. the European Union), uniformity of approach is being progressively achieved. It would take too long to make a survey of relevant international –or even only European– codes and legislation, so in this section some insights will be given on the legal aspects of the handling of dangerous goods in Spain.

From the administrative point of view, Spanish PAs and harbourmaster's offices fall under the "Ley 27/1992, de 24 de noviembre, de Puertos del Estado y de la Marina Mercante" (BOE, 1992). This comprehensive law sets in order a complex system of acts and statutes previously issued. In particular it defines the competences of port authorities and harbourmaster's offices. Furthermore it states that major ports are under the jurisdiction of special Port Authorities directly managed by an institution (Puertos del Estado) belonging to the state ministry of economic promotion.

The most important Spanish act regulating port HazMat handling is the "Real Decreto 145/1989, de 20 de enero, por el que se aprueba el Reglamento Nacional de

[4] As long as some specific operational aspect of ships coming from or heading to international waters are not concerned. For example the MARPOL convention, which Spain enforced, requires port authorities to provide ship operators with installations for the collection of oil residues.

Admisión, Manipulación y Almacenamiento de mercancías peligrosas en los puertos” (BOE, 1989). The RD 145/1989 has to be enforced in any Spanish port where operations with dangerous goods are carried out. Dangerous goods (*mercancías peligrosas*) are defined as those products listed in the article 12 of the IMDG Code. The act does not apply to bunker fuels (this matter is now covered by BOE, 2004; see below).

Section I-3 of the act (“Faculties of the Port Authorities”) states that:

- The harbourmaster is responsible for admitting ships carrying dangerous goods into the port, while the director of the port authority is responsible for the admission of any dangerous product into service areas (art. 4).
- The (un)loading of dangerous goods is under the control of the harbourmaster (art. 7).
- Ports must have an emergency control centre for dealing with any dangerous goods emergency (art. 12); among other things, the control centre will be provided with:
    a) Sufficient communication facilities (towards PA, harbourmaster, ship masters, dock operators, etc.).
    b) A safety study (*estudio de seguridad*), in order to study the risk of admitting, handling and storing dangerous goods in the port and their possible consequences for the surroundings of the terminals and the entire port; it is later specified (art. 123) that the safety study has to include a risk assessment for fires, explosions and spills, as well as maritime pollution if necessary.
    c) An interior emergency plan (*plan de emergencia interior*), specifically designed for the port, together with the respective exterior emergency plan.

Section I-5 states that ports must set aside special areas for the (un)loading, handling and storage of dangerous goods (art. 18). These areas must be located as far as possible from urban areas and are subject to particular safety requirements (art. 20). Art. 21 lists a series of facilities these special areas have to be provided with. Among them, the following fire fighting facilities are specified: 1) hydrants and hoses, sufficient to cover the entire (un)loading dock/hazardous goods area; water pressure is never to be less than 7 atm; 2) fire extinguishers (foam, dry powder and/or CO_2). The port must also set separate anchorage areas for dangerous goods ships waiting to berth and (dis)charge (art. 22).

Sections I-6 and I-7 concern the requirements for ships carrying dangerous goods into or out of the port. Section I-8 is addressed to terminal and dock operators. Section I-10 regards land transport (by train and lorry) of dangerous goods.

Section II (“Classification and labelling of dangerous goods”) describes the obligations for all the transportation stakeholders in the port to label dangerous goods according to the classification of the *IMDG Code*, which is based on nine classes:

- Class 1: explosives;
- Class 2: gases;
- Class 3: flammable liquids;
- Class 4: flammable solids;

- Class 5: oxidising agents and organic peroxides;
- Class 6: poisonous (toxic) and infectious substances
- Class 7: radioactive substances;
- Class 8: corrosive substances;
- Class 9: miscellaneous dangerous substances.

Section III lists detailed instructions and obligations on how to handle dangerous goods, for each of the abovementioned classes. Special directions are given on hydrocarbons, liquefied gases and bulk chemicals in section III-10. Art. 101 (a very detailed one) describes the correct practice of handling bulk liquids. Paragraph 1.1 of this article institutes a ship/terminal checklist (reproduced in the Appendix VI of the law). Art. 108 relates some basic actions to take in case of spill. These have been later expanded and better specified in a new Real Decreto (BOE, 2004; see below).

Section IV affects container, road tanker and rail tanker handling. Section V is about the storage of non-bulk goods.

Section VI ("Emergency and self-protection plans") specifies that ports handling dangerous goods are affected by the Spanish directive on civil defence (BOE, 1985). For this reason ports have to be provided with a safety plan and an interior emergency plan (see above, art. 12). Art. 123 resolves a possible conflict with the European Seveso directive (European Parliament and the Council of the European Union, 1982; now replaced by the Seveso II directive). This directive (see below) affects those establishments where certain amounts of hazardous materials are processed or stored. Many port terminals fall under this directive and are thus required to have a HazMat accident risk assessment report and an emergency plan of their own. Art. 123 of RD 145/1989 states that this obligation does have to be accomplished and that it is the responsibility of the PA and of the harbourmaster to harmonise the different documents and plans. Art. 132 is a concise list of resources the port must be supplied with in order to cope with emergency situations.

Finally, section VII regards training of personnel.

In 2004 a new decree was issued, which regards HazMat matters in port areas, as well as at private and public terminals. The RD 253/2004 (BOE, 2004), first presented as a project of RD in 2003 (Ministerio de Fomento – Subsecretaría Dirección General de la Marina Mercante, 2003), opens with an introduction that makes explicit reference to the OPRC Convention (1990).[5] The main requirements of the OPRC are:

- That ports and terminals interested by hydrocarbon commerce, transport, transfer etc. be provided with an interior emergency plan;
- That such ports and terminals have at least a minimum set of equipments in place in order to fight and prevent hydrocarbon pollution.

This RD does not concern HazMat accidents as a whole, but is rather focused on accidental hydrocarbon spills. Its scope is extended to bunkering operations, which were

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[5] The OPRC Convention was issued by the IMO in 1990. The 1998 OPRC Regulations are now the principal legislation on counter pollution from a harbour authority and oil handling facility perspective. The UK Maritime and Coastguard Agency developed guidelines for ports to comply with the OPRC (MCA, 2002).

excluded from the reach of RD 145/1989. Actually, all Spanish marine installation handling hydrocarbons (including offshore platforms and loading buoys) are covered by this act.

Chapter 1 deals with measures for preventing and fighting against marine pollution due to accidents during transfer and handling of hydrocarbons.[6] Hydrocarbon ports/terminals have to produce two documents:

- An interior contingency plan for accidental maritime pollution (*Plan Interior de Contingencias por Contaminación Marina Accidental*), the structure of which is described in Annex I; the main issues of such plan are: composition/functions of the directive bodies, how to actuate in case of emergency, inventory of the means of intervention, etc.
- A study of environmental conditions (*Estudio de condiciones ambientales*), the structure of which is described in Annex II; this is both a description of the characteristics of the surroundings of the installation (from different points of view: oceanographic, physical, meteorological, social, etc.) and a study of the possible effects of a hydrocarbon spill. In particular, an identification of possible accidental spills and a determination of spill trajectories must be included in the study.

Details are provided on document processing and approval (differences are made between ports/terminals on state land, on private land and offshore installations). In the Planes Interiores de Contingencias por Contaminación Marina Accidental, ports/installations have to show evidence they are provided with, at least, the following equipments:

- Booms;
- Physical recollection systems for hydrocarbons;
- Fire hoses properly directed and oriented;
- Emergency boats, for the disposal of booms and for the recollection;
- An effective communication system between land and ship.

Also buoy and monobuoy fields have similar restrictions as to emergency equipments. Ports/terminals have the right to inspect ships suspected not to be in safe conditions.

Special, lighter measures are to be taken in the case of bunkering terminals and facilities; even lighter ones in the case the bunkered fuel is diesel oil (Chapter 2).

Apart from the abovementioned decrees, it is worth noting that terminals, storing companies and stevedoring plants may be subject to another, very important directive, i.e. the European directive “Seveso II”.

The “Seveso” directive made its first appearance in 1982 (European Parliament and the Council of the European Union, 1982). It was issued by the European Council

[6] The definition of hydrocarbon adopted by RD 253/2004 is the one first given in the International Convention on Civil Liability for Oil Pollution Damage (CLC), which is: crude, fuel oil, diesel oil, and lubricating oil. Gasoline and kerosene are excluded, probably because of their high volatility.

after the Seveso accident in 1976 had provoked great public shock. The Directive affected sites and establishments where certain dangerous substances were stored and/or handled in amounts exceeding specified levels. The aim of the directive was to improve prevention practices against the occurrence of major accidents involving HazMat. The directive was slightly modified twice (European Parliament and the Council of the European Union, 1987; European Parliament and the Council of the European Union, 1988). It was implemented gradually by all the members of the EU (then EEC); Spain enforced it in 1988 (BOE, 1988).

In 1996 the European Council issued a new version of the directive, which substituted the previous one (European Parliament and the Council of the European Union, 1996). This directive, commonly known as "Seveso II", was again modified in 2003 to take into account new substances (European Parliament and the Council of the European Union, 2003). Spain enforced the "Seveso II" in 1999 (BOE, 1999).[7]

The requirements to which an establishment may be subject vary according to the amount of HazMat stored/processed. In fact, two "tiers" of establishments are defined. Establishments belonging to the first tier, with relatively low amounts of dangerous goods treated or stored, are only required to send a notification to the competent authority, containing basic information on the activity carried out and the HazMat involved; moreover, they have to demonstrate they have an interior contingency plan accounting for the risks entailed by the dangerous goods handles and stored. The second tier, i.e. those establishments where dangerous goods are present in large amounts, is subject to stricter requirements. In particular, a complete Safety Report has to be produced, together with detailed Emergency plans. Furthermore, "Seveso" operators have to supply to the authorities specific information after a major accident occurs in their premises.

The "Seveso" directive does not apply to ports as industrial districts. In fact it does not cover transport operations and loading and unloading of goods. In the preface to the text of the directive, it is stated that

> Member States may retain or adopt appropriate measures for transport-related activities at docks, wharves and marshalling yards, which are excluded from this Directive, in order to ensure a level of safety equivalent to that established by this Directive
>
> (European Parliament and the Council of the European Union, 1996)

while in art. 4 (c) it is asserted that

> **Exclusions.** This Directive shall not apply to the following: […] (c) the transport of dangerous substances and intermediate temporary storage by road, rail, internal waterways, sea or air, outside the establishments covered by this Directive, including loading and unloading and transport to and from another means of transport at docks, wharves or marshalling yards;
>
> (*ibid.*)

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[7] In several EU member states, the "Seveso" directive has been provided with a further decree, detailing practical and technical aspects. In Spain a first version of this *Directriz básica* had been published in 1991 (BOE, 1991). Following the issuing of the "Seveso II", a new *Directriz* was brought out (BOE, 2003).

This exclusion has had an important influence in keeping port operations out of the mainstream risk analysis policies and research in the last years. The possible inclusion of port areas (and marshalling yards) into the scope of the directive has been the subject of debate in the European Council (Mitchison, 1999; Mitchison & Caprioli, 1998). It should be noted, by the way, that the exclusion only applies to transport-related activities; the Directive applies to other activities within the establishments, for example specialised storage establishments within ports. Port terminals are often subject to the directive, since they are responsible not only for the (un)loading operations, but also for temporary storage of goods (not to mention those terminals that process, either chemically or physically, raw materials inside the port premises; e.g. LNG reception terminals are often regasification plants).

Port authorities must harmonise their safety studies and emergency plans with those of the terminals. In the case of Spain, for instance, this is regulated by the text of RD 1254/1999 (BOE, 1999), ordaining that:

- PAs (as well as the Comunidades Autónomas) are responsible for: 1) the reception of the notification, the document stating the policy of prevention of major accidents, the safety report and the emergency plan of those establishments located in public ports; 2) the adoption of measures of protection through the collaboration with the Comunidad Autónoma in the preparation of the external emergency plan, taking into consideration the “Seveso” documentation provided by port terminals.
- The harbourmaster’s offices are responsible for fighting marine pollution in Spanish territorial waters, in agreement with the act of State Ports (BOE, 1992).

1.3.3 Port security: a new frontier

If safety is defined as “protecting the environment against the risk of a system”, the quasi-synonym *security* can be labelled “protecting a system from the risks arising in the surrounding environment” (EVI Project Consortium, 2003). Security in ports means basically protecting ships and facilities from sabotages and terrorist attacks. Major concern about the possibility of large scale terrorist acts in port areas developed in the wake of the 9/11 attack in the US, due both to the strategic role of ports in the logistics chain and to the high concentration of HazMat in port areas (either on board tankers or on shore). These preoccupations are focussed, for instance, on LNG regasification plants, since in their premises very large quantities of gas are stored in a small number of huge tanks, with volumes in the order of 10^5 m^3 and more.[8]

In a Conference, held at its London headquarters, the IMO adopted a number of amendments to SOLAS 1974 (IMO, 2002-1), the most far-reaching of which enshrines

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[8] The US federal government is currently planning the construction of a number of onshore LNG regasification plants, e.g. in California (Marks *et al.*, 2003), Louisiana and Texas. Public reactions are being quite negative, all of them making direct reference to the possibility of terrorist attacks. See Caputo (2005), Wittmeyer (2005) and Living on Earth (2005). Parfomak (2003) provided the US Congress with a document for discussion which focuses on the main hazards of LNG, including the possibility that LNG onshore regasification plants be the target of terrorist attacks; the benefits of LNG are also highlighted. Other recent research efforts in the frame of LNG safety include the Sandia report by Hightower *et al.* (2004).

the new International Ship and Port Facility Security Code (ISPS Code). As the ISPS Code is part of SOLAS, compliance is mandatory for the 148 Contracting Parties to SOLAS. The Code entered into force in July 2004. This regulation contains detailed security related requirements for Governments, PAs and shipping companies in a mandatory section (Part A), together with a series of guidelines about how to meet these requirements in a second, non-mandatory section (Part B). In summary the ISPS Code:

- Enables the detection and deterrence of security threats within an international framework;
- Establishes roles and responsibilities;
- Enables collection and exchange of security information;
- Provides a methodology for assessing security;
- Ensures that adequate security measures are in place.

It requires ship and port facility staff to:

- Gather and assess information;
- Maintain communication protocols;
- Restrict access; prevent the introduction of unauthorised weapons, etc.;
- Provide the means to raise alarms;
- Put in place vessel and port security plans; and ensure training and drills are conducted.

Each Contracting Government has to ensure completion of a *Port Facility Security Assessment* for each port facility within its territory that serves ships engaged on international voyages. The Port Facility Security Assessment is fundamentally a risk analysis of all aspects of a port facility's operation in order to determine which parts of it are more susceptible, and/or more likely, to be the subject of attack. Security risk is seen as a function of the threat of an attack coupled with the vulnerability of the target and the consequences of an attack.

On completion of the analysis, it will be possible to produce an overall assessment of the level of risk. The Port Facility Security Assessment will help determine which port facilities are required to appoint a Port Facility Security Officer and prepare a *Port Facility Security Plan*. This plan should indicate the operational and physical security measures the port facility should take to ensure that it always operates at "security level 1". The plan should also indicate the additional, or intensified, security measures the port facility can take to move to and operate at "security level 2" when instructed to do so. It should also indicate the possible preparatory actions the port facility could take to allow prompt response to the instructions that may be issued at "security level 3".

Ships using port facilities may be subject to *port State control* (see section 1.2.1.i), inspections and additional control measures. The relevant authorities may request the provision of information regarding the ship, its cargo, passengers and ship's personnel prior to the ship's entry into port. There may be circumstances in which entry into port could be denied (Ariel Pinto & Talley, 2006).

1.4 Port areas and risk analysis: a gap to fill

Regarding risk analysis methodologies, an important difference can be observed between the situation of fixed chemical plants and land transport (both by road and rail) on one side and port areas on the other.

In the case of plants and land transport, the use of traditional risk analysis techniques has been a standard for many years. A wide range of probability and accident frequency data are available for these settings, which help in performing quantitative risk analysis.

This specific information is often missing in the case of ports. Leaving aside certain port storage or process installations, which must meet the requirements and/or fall under the regulations mentioned in section 1.3, the rest of operations carried out in port areas are not included in the scope of the Seveso directive. Nevertheless, some of these operations entail significant hazards, as for example do loading and unloading activities, with their high spill and accident rates.

As a consequence, a solid, reliable collection of data is missing that would make it possible to carry out quantitative risk assessments with a certain accuracy. These shortcomings have been demonstrated in recent years, whenever risk analysis methods were applied to port areas.

Consequently, it is evident that there is need for a research effort helping carry out port risk assessments as reliable as those of the process industry and HazMat transportation environments.

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2 Bibliographic survey

This chapter is devoted to an extensive overview of recent bibliography on the issue of risk in port settings. References are collected and commented above all on HazMat topics, but some literature regarding general safety problems in ports is mentioned as well, if it is relevant to the contents of this thesis.

Fig. 2.1 shows that the chapter is organised in two main sections. Section 2.1. is devoted to the topic of oil spills, which deserves a separate treatment due to the exceptional importance of this accidental scenario in maritime and port settings. The great public interest raised by oil spills has boosted over the past years a greater amount of research than had been done by other types of hazard affecting maritime transport. Maritime oil spills are, so to say, the quintessential maritime accident, always causing important impact on the public, because of the widespread and highly visible environmental consequences they have. Several aspects of oil spill safety have been accounted for, which are listed in Fig. 2.1.

Section 2.2. is instead dedicated to the risk assessment of other types of accidents to be expected in port areas, like spills of hazardous materials other than oil products, explosions, fires and toxic gas clouds.

Finally, section 2.3 summarises the relevant results of the bibliographic survey. In particular, in that section we stress the near absence of studies on the topic of the economic valuation of the consequences of HazMat accidents in ports (save for oil spills).

Non-HazMat focused and non-port specific references are cited only if they contain significant elements that can be applied to the risk assessment of hazardous

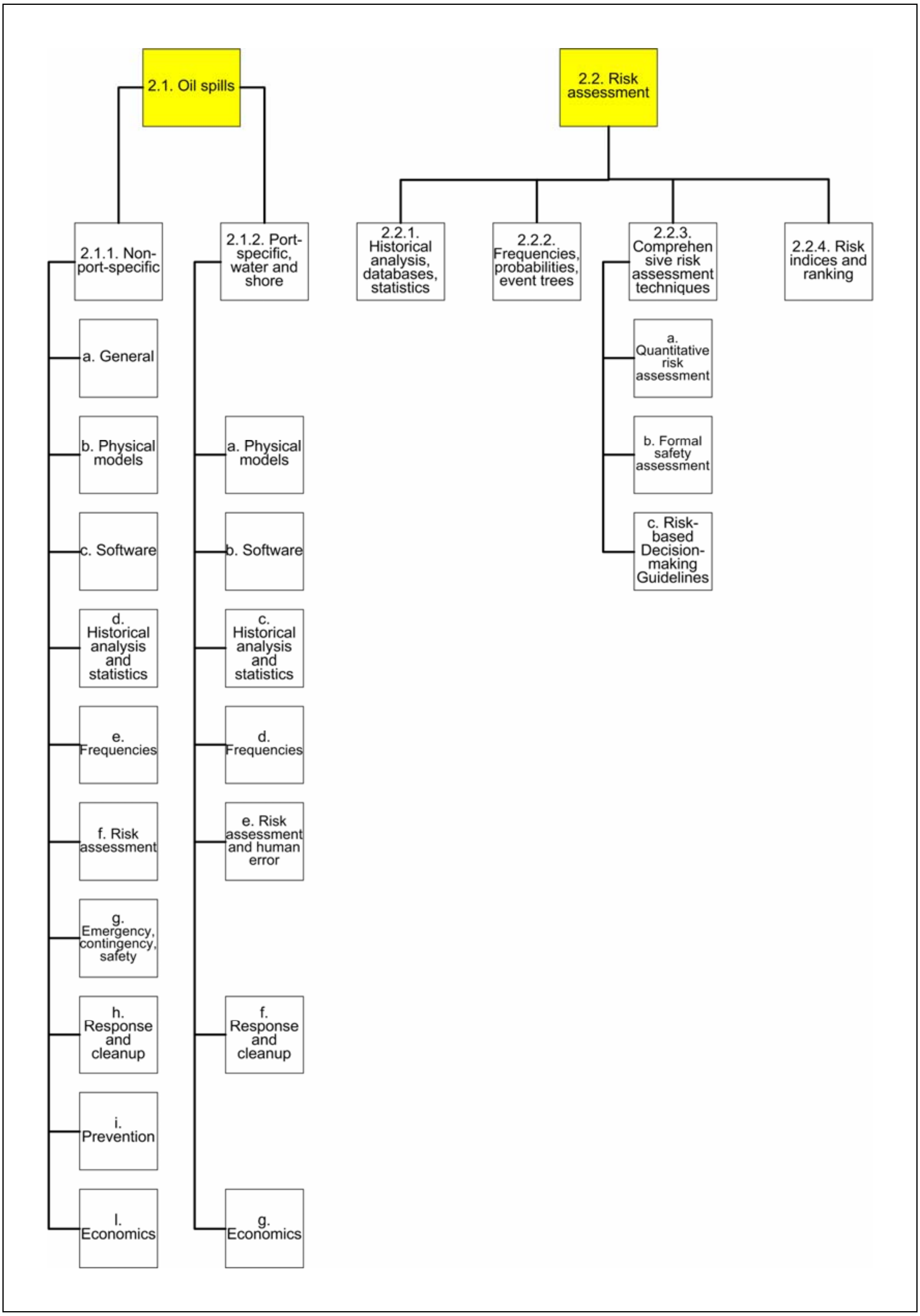

Fig. 2.1. Layout of this chapter.

materials scenarios in ports.[1] In such cases, the reason why the paper or book is referenced is explained.

2.1 Oil spills

2.1.1 Non-port-specific papers and reports about oil spills

Literature about maritime oil spills is incredibly abundant. This section discusses several documents that, while not being necessarily related to port settings, contain interesting insights and may ultimately be used for spill risk assessment in ports.

a. General concerns. As a result of the Exxon Valdez spill in 1989, the United States Congress issued the Oil Pollution Act (OPA 90). One of the provisions of this act was the institution of an Interagency Coordinating Committee on Oil Pollution Research. In 1997 the Committee produced an *Oil Pollution Research and Technology Plan*, a quite complete overview of oil spill related issues (Interagency Coordinating Commitee on Oil Pollution Research, 1997).

Another interesting, if brief, outline of spill problems is the yearly *ITOPF Handbook*, issued by the International Tanker Owners Pollution Federation (ITOPF, 2004-1).

b. Physical models. When oil is spilled at sea it spreads and moves on the surface while undergoing a number of chemical and physical changes, collectively termed weathering (see Fig. 2.2). Most of the processes, such as evaporation, dispersion, dissolution and sedimentation, lead to the disappearance of oil from the surface of the sea, whereas others, particularly the formation of water-in-oil emulsions (mousse) and the accompanying increase in viscosity, promote its persistence. The speed and relative importance of the processes depend on factors such as the quantity and type of oil, the prevailing weather and sea conditions, and whether the oil remains at sea or is washed ashore. Ultimately, the marine environment assimilates spilled oil through the long-term process of biodegradation.

The main properties that govern the behaviour of spilled oil at sea are specific gravity (its density relative to pure water, often expressed in ºAPI); distillation characteristics (its volatility); viscosity (its resistance to flow); and pour point (the temperature below which it will not flow). Since the interactions between the various weathering processes are not well understood, reliance is often placed on empirical models based upon the properties of different oil types (ITOPF, 2004-1).

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[1] Throughout this chapter the expressions “dangerous goods” and “hazardous materials”, as well as the abbreviation of the latter, i.e. “HazMat”, are used more or less interchangeably. Both expressions indicate substances (solids, liquids, or gases) that are dangerous to the well-being of humans, animals, or the environment. Nevertheless, there is a difference between the two terms: “dangerous goods” refers to hazardous materials being sold/transported as *products*, while “hazardous materials” and “HazMat” are more comprehensive expressions and can indicate any substance, either a product (good) or a raw material.

A great deal of research has been conducted on this topic. Several parameters have been researched. Equations have been proposed for the rate of spread, emulsification, evaporation, dispersion, and the maximum area affected by the spill.

Two pioneering works were published by Fay (1969) and Fannelop & Waldman (1972). These have virtually been at the base of all the subsequent research during the next three decades, which is resumed by Brebbia (2001).

The PhD thesis by Mestres (2002) describes the development, validation and application of a three-dimensional numerical model for pollution transport (including oil spills) in coastal waters. The model can be used in a variety of situations, of which marine oil spills are just an example.

Fay (2003-1) has recently published a paper in which a complete model for predicting the dynamics of spills from LNG and oil product tankers. The model is constructed from fluid mechanics principles and empirical properties of oil and LNG spills on water. This has to be considered among the most up-to-date and interesting contributions on the topic of oil spill physical models.

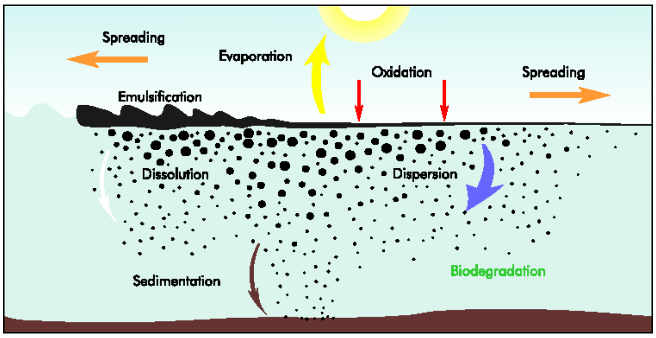

Fig. 2.2. Weathering of a marine oil spill (ITOPF, 2004-1).

c. Software programmes. A variety of commercial software programmes are available that implement the aforementioned physical models. The majority of these programmes have been produced in the US, either by federal agencies, like NOAA, or private software or consultancy companies. These products are listed and discussed in a circular by IMO (2000) and in a report by NOAA (2002-2). Some of the most commonly used are the following:

- GNOME (NOAA, 2002-1) by NOAA. This is a publicly available oil-spill trajectory model. GNOME plots the predicted evolution of spill positions from relevant oceanographic, atmospheric, and spill information. It also uses weathering algorithms to make simple predictions about the changes the oil will undergo while it is exposed to the environment (Fig. 2.2). It works at port scale.
- ADIOS2 by NOAA, an oil weathering model that incorporates an extensive database of crude oils and petroleum products. It is publicly available.
- SLORSM (Belore, n.d.) by SL Ross, based on the mathematical models by Fay (see above). It works at a larger scale than GNOME (tens of kilometres).
- OILMAP by Applied Science Associates (ASA, n.d.-1), working at a medium-small scale.
- SIMAP by ASA (n.d.-2), focused on forecast of spill response, natural resource damage assessment and contingency planning.

- ALOFT-FT by NIST, predicting the downwind distribution of smoke particulate and combustion products from large outdoor fires. ALOFT-FT was developed to aid in the planning process for the intentional burning of crude oils spills on water. It is publicly available.

d. Historical analysis and statistics. Historical analysis (see section 2.2.1) is a tool widely used in the field of risk analysis and accident investigation for various purposes. In the case of oil spills, it is mainly used to determine statistical trends capable of describing the factors most likely to cause an accidental spill, as well as the most frequent locations and consequences of the accidents. Many institutions, such as the ITOPF, publish regular bulletins of oil spill statistics based on internal or public databases.

An early example of application of a database taking into account maritime HazMat transportation is described by Heinecke & Golchert (1989). This is limited to the transport of dangerous goods through the territorial waters of the then Federal Republic of Germany.

The Interagency Coordinating Commitee on Oil Pollution Research, established in the US by the OPA 90 convention (see section 1.3.1) published an interesting report (Interagency Coordinating Commitee on Oil Pollution Research, 1997) where extensive historical data and tables based on USCG data (previous to 1993) are presented and discussed. Appendix B of this report is a comparison of seven oil spill accident databases.

The ITOPF (International Tanker Owners Pollution Federation) updates yearly a brief but very interesting statistical bulletin about maritime oil spills from tankers, barges and carriers (ITOPF, 2004-2). Statistics are based on an in-house oil spill database, which is not available to the public. Spills are classified into 3 categories, according to their size: < 7 tonnes; > 7 tonnes and < 700 tonnes; > 700 tonnes. ITOPF states that information on spills > 7 tonnes is complete and reliable, while the number of small spills is just estimated. Fig. 2.3 shows the number of medium and large spills per year in the last decades according to ITOPF. The diagram shows an evident decrease in the number of spills after 1980, probably as a result of the new international directives promulgated in the 1970s (see section 1.3.1). Fig. 2.4 enumerates the amount of oil spilled per year: besides a generalised reduction of the quantities spilled after 1980, it can be observed that catastrophic accidents, such as those occurred to the "Atlantic Empress", the "Castillo de Bellver", the "ABT Summer" and, more recently, the "Prestige", have a dramatic impact over the yearly balance of spills. For instance, the year 1983 would have been quite in line with the general improvement of the early 1980s, had it not been for the huge spill of the "Castillo de Bellver".

A valuable source of information is represented by the annual reports by ACOPS, the UK Advisory Committee on Protection of the Sea (for example: ACOPS, 2003; ACOPS, 2004). The reports include detailed annual lists of spills occurred in British territorial waters.

McMahon Anderson & LaBelle (1994) performed a historical analysis in order to infer frequency data for oil spills (see section 2.1.1.e). The analysis involves both US and worldwide offshore platforms, pipelines and oil tankers accidents.

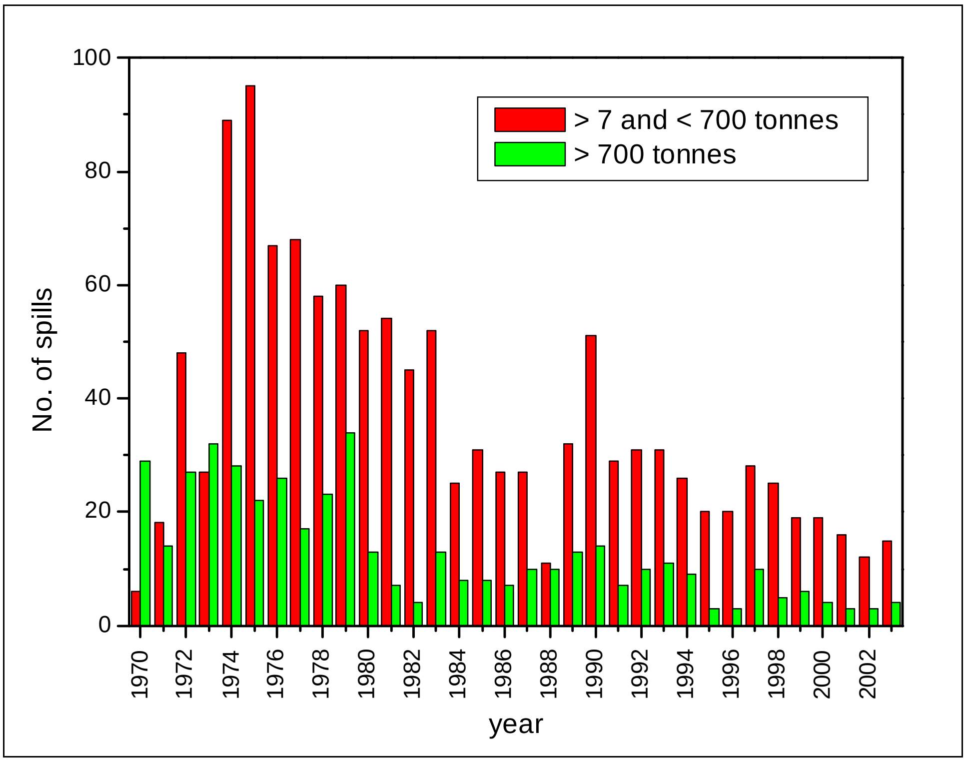

Fig. 2.3. Number of medium and large oil spills per year during the last three decades (after ITOPF, 2004-2).

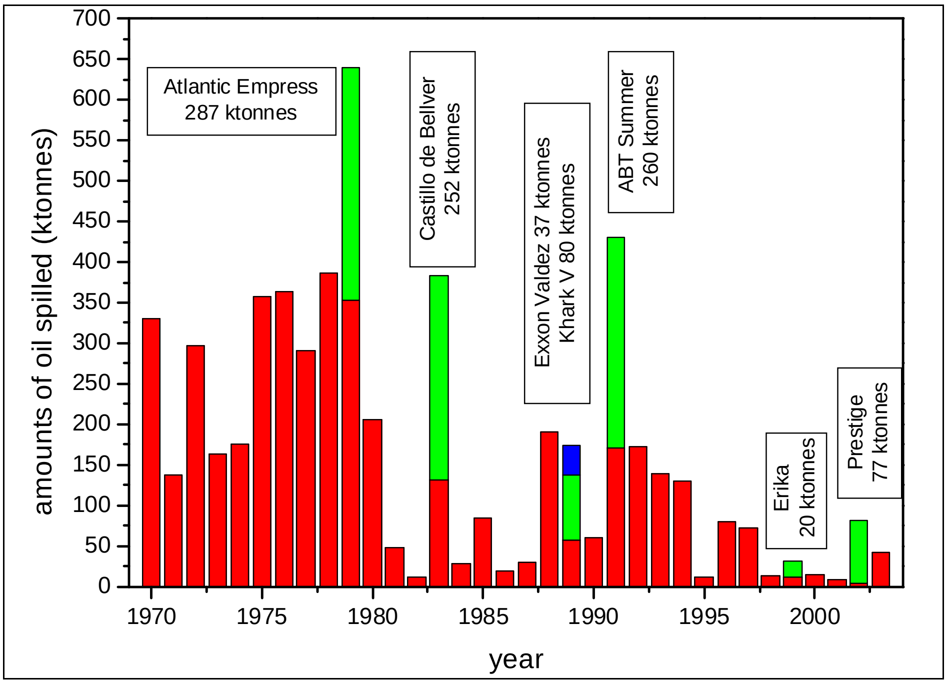

Fig. 2.4. Amounts of oil spilled into the sea by year (ITOPF, 2004-2).

Ketkar & Babu (1997) examine the size distribution of oil spills in the US from 1980 to 1990. The analysis confirms that an increase in the size of vessels has increased the risk of larger oil spills in US waters.

Several papers and communications by Dagmar Schmidt Etkin present the results of an extensive historical analysis. Etkin is a member of GESAMP (Joint Group of

Experts on the Scientific Aspects of Marine Environmental Protection), a board of authorities in the field of maritime pollution, sponsored, among others, by the IMO.

Etkin & Welch (1997) is the first paper published by this author on the topic of accidental oil spill statistics. It contains a description of the *Oil Spill Intelligence Report* International Oil Spill Database, which reports (as of 1997) more than 4100 accidents happened worldwide and involving at least 10,000 gallons of released product.

Etkin *et al.* (1998) is a declaration of the future work to be carried out by the Working Group 32 of the GESAMP, focused on the collection of information regarding the pollution of sea waters due to sea-based activities. Etkin *et al.* (1999) and Etkin (1999-2) present the first results of such research, which were later updated in Etkin (2001-1). Some results are further summarised in Burns *et al.* (2002). GESAMP data do not differ significantly from those provided by ITOPF. The authors state that, contrary to popular perception after recent catastrophic events, oil spill frequencies and total spillage have decreased significantly over the last two decades, particularly in the last few years, despite an overall increase in oil movement. The decrease in oil spills worldwide (but in the United States in particular), may be attributed to a variety of factors. Etkin states that the influence of the OPA 90 has been widely positive and has had an important impact on this reduction. Nevertheless, she warns that, while the statistics show encouraging downward trends, there is no room for complacency. An ill-timed oil spill that occurs in a sensitive location, regardless of spill size, can cause devastating damage to natural environments, property, and business, and, occasionally, to human lives.

Finally, Lentz & Felleman (2003) present more historical data in a comprehensive overview of past spills. The research is performed on a database owned by ERC (Environmental Research Consulting) and agrees with those previously mentioned.

e. Accidental frequencies for marine oil spills. Accidental frequencies are an essential aspect of risk assessment (see sections 1.1 and 2.2.2). Evaluating the frequency factor is sometimes more important than gauging the consequences of accidental scenarios, especially if the latter are expected to be particularly severe. This is the case with massive marine oil spills. Therefore, a certain number of studies have been specifically dedicated to estimate the rate of oil spills, building mainly on historical studies (see section 2.1.1.e). For an overview of references dealing with frequencies of maritime accidents in general, see section 2.2.2.

McMahon Anderson & LaBelle (1990) estimated the occurrence rates of accidental oil spills on the US outer continental shelf. Years later, this work was improved and extended (McMahon Anderson & LaBelle, 1994; McMahon Anderson & LaBelle, 2000). The ultimate estimate proposed in these analyses were 0.90 and 0.40 tanker spills greater than 1000 bbl (= 159 m^3) for every 1.0×10^9 bbl transported by tanker. Specific figures were proposed for platform and maritime pipeline spills as well, but in this case data were limited to the US outer continental shelf. Data from these papers were used to build a complete oil spill risk analysis model (Price *et al.*, 2003).

f. Oil spill risk assessment. The elements analysed so far (physical models, software, historical analysis, databases, etc.) must be taken into consideration all at once when performing an oil spill risk assessment. Non-port-specific oil spill risk assessments are very ambitious studies. Their geographical scope is often very vast, whereas they tend to use the traditional tools of risk assessment (e.g. probabilistic instruments like fault and event trees), which are maybe too formal to cope with such large areas. As a result, findings are often of a qualitative kind. Sometimes they are simply unsatisfactory.[2]

Risk assessment surveys are mostly focused on environmental damage. Among the many factors usually taken into account are found:

- Environmental sensitivity;
- The industry sectors (e.g. fishing, tourism) most affected by spills;
- Commercial cargo shipping size, frequency, trading patterns and amounts of oil carried as bunker fuel;
- Oil/chemical tanker frequency, sizes, shipping patterns and quantities shipped;
- Properties of oil/chemicals shipped as cargo;
- Type, density and movement of shipping including concentration of fishing vessels and tourist vessels;
- Areas that pose a high level of difficulty to safe navigation.

Brown & Amrozowicz (1996) and Amrozowicz *et al.* (1997) perform a probabilistic risk assessment of tanker groundings. Their work is mainly based on fault trees specifically designed to describe tanker groundings and allows for human error, which is investigated in detail.

Rawson *et al.* (1998) developed an index for the evaluation of the environmental performance of tankers in accidental groundings and collisions. Another risk index was devised by Forsyth *et al.* (1997) for the lower Mississippi River. After constructing a "mile database" where each mile of the river is catalogued according to a series of risk factors characterising either the river itself or vessel traffic, weights are assigned to the factors and a simple algorithm is used to obtain the relative risk ranking. Among the river features taken into account are width, turns, anchorages, bridges, junctions, ferry crossings, currents, etc.

The Committee on Oil Spill Risks from Tank Vessel Lightering *et al.* (1998) produced an extensive risk assessment report for lightering operations in the Gulf of Mexico. Lightering is a procedure carried out at a certain distance from the coast, where a vessel transfers its cargo (or part of it) to another vessel, smaller than the first. This operation is made necessary in areas like the Gulf of Mexico where most supertankers from the Middle East arrive with their cargo of crude oil and petroleum products, but are unable to enter the ports of destination because they are too wide and/or deep.[3] The study is mainly based on past safety records and historical data and eventually proposes good levels of risk for lightering operations.

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[2] "The most significant weaknesses of the PWS Study are: (1) the lack of an overarching framework to ensure the consistency and logic of the analyses; […] (4) the treatment of human and organizational error; and (5) the appearance that conclusions are precise and logical, when in fact, they are neither" (Committee on Risk Assessment and Management of Marine Systems *et al.*, 1998).

[3] Lightering is in fact similar to ship-to-ship bunkering, except that cargo is transferred instead of bunkers (hence amounts transferred are normally higher in the case of lightering). Moreover, bunkering is normally carried out in a port, whereas lightering is performed offshore.

The accident of the “Exxon Valdez” in March 1989 developed a wider awareness of the environmental risks entailed by maritime transportation of petroleum products. One of the major effects was the issue of the US OPA 90 (see section 1.3.1). Another result was the sudden increase of the efforts in the field of oil spill risk assessment. The end product of such endeavours is the report by the Committee on Risk Assessment and Management of Marine Systems *et al.* (1998). This is a short account of the massive “PWS Study” (where PWS stands for Prince William Sound, the tanker-busy sea inlet affected by the “Exxon Valdez” oil spill). The PWS Study uses three modelling approaches: MARCS (Marine Accident Risk Calculation System), fault trees, and simulation. MARCS is a method devised by Det Norske Veritas. MARCS treats all ships alike and assumes that they stay in assigned shipping lanes, using Gaussian probability distribution of a ship’s distance from the centre of the lane. The MARCS model calculates the probability of collisions and powered groundings using fault trees based on expert judgement for collisions of vessels that pass within a ship’s length of each other. The model can include weather and other environmental factors, such as currents, sea states, and wind, as well as geographical features. Oil outflow models and expert judgement questionnaires were used as well, coupled with each of the aforementioned approaches. Results of the PWS Study are somehow questioned by the steering committee and, ultimately, by its authors, who admit that the scope of the analysis was too large in comparison with the refinement of the tools employed.

Recently, the federal and regional governments of Australia (AMSA, 2001; Queensland Transport & Great Barrier Reef Marine Park Authority, 2000), have commissioned important risk assessment studies, above all in view of the development of a comprehensive national oil pollution plan, capable of protecting both the seashore environments and the invaluable coral reefs. These studies are mainly based on DNV’s in-house experience (e.g. MARCS). One of the final results is that the overall frequency of spills > 10 tonnes in ports is three times that of offshore spills.

g. Emergency, contingency, safety. The design of comprehensive contingency and safety plans for the organisation of the response to oil spills is currently a hot topic. Regional and national governments as well as international institutions are making great efforts in order to avoid that disasters such as the “Exxon Valdez” and the “Prestige” accidents happen again.

The example set by past accidents has been used to predict the most likely oil spill scenarios for emergency and contingency designing purposes. Etkin (2003) and Etkin (2004) perform a statistical analysis of the ERC’s in-house database of tanker oil spills and infer that:

- 95% grounding spills are expected not to exceed 2.5×10^6 gal (= 9500 m^3);
- 50% grounding spills are expected not to exceed 2.7×10^5 gal (= 1020 m^3).

A typical example of national contingency plan for oil spills response is the Australian “National Plan to Combat Pollution of the Sea by Oil and Other Noxious and Hazardous Substances” (AMSA, 2001). This plan, in place since 1973 and regularly revised, commits the port authorities and the regional governments to harmonise their efforts and resources with the aim of effectively fighting oil spill spread and carrying out fast recovery in the case of accidents. The Plan holds a wide range of response equipment at 37 locations around the Australian coast, including all major ports. Types of equipment include oil spill control booms of varying dimensions, self-propelled oil recovery vessels, static oil recovery devices and sorbents. This is complemented by equipment held by port authorities, individual oil and chemical companies and by the Australian Marine Oil Spill Centre stockpile. The Plan is based on a risk assessment study.

h. Response and cleanup. ITOPF (2004-1) describes the cleanup techniques currently available for oil spill recovery. A cleanup response is not always necessary. Often the oil remains offshore, where it is dissipated and eventually degraded naturally without affecting coastal resources or wildlife. In such cases, monitoring the movement and fate of the floating slicks to confirm the predictions may be sufficient. On this basis, some of the largest spills over the last 30 years have not required a cleanup response. In contrast, even a small spill, especially of a very persistent crude or heavy fuel oil, may call for a major response effort, especially if sensitive resources are threatened. Response can be performed at sea or onshore. Possibly, the most obvious means of intervening at sea is making use of *booms* and *skimmers*. The use of booms to contain and concentrate floating oil prior to its recovery by specialised skimmers is often seen as the ideal solution since, if effective, it would remove the oil from the marine environment. Unfortunately, this approach suffers from a number of problems, not least of which is the fact that it is in direct opposition to the natural tendency of the oil to spread, fragment and disperse under the influence of wind, waves and currents. Because of this, it is rare that, even in ideal conditions, more than a relatively small proportion (10-15%) of the spilled oil is recovered. Another option is represented by *in-situ burning*: because of the logistical difficulties of picking up oil from the sea surface and storing it prior to final disposal on land, an alternative approach involves concentrating the oil in special fireproof booms and setting it alight. In practice, this technique is unlikely to be viable in most ship-source spills, due to the difficulty of collecting and maintaining sufficient thickness of oil to burn. As the most flammable components of the spilled oil evaporate quickly, ignition can also be difficult. Residues from burning may sink, with potential long-term effects on sea bed ecology and fisheries. *Dispersant chemicals*, instead, work by enhancing the natural dispersion of the oil into the sea. The oil is broken down into tiny droplets that are dispersed into the water column, where they are diluted by currents and eventually break down naturally. Dispersants can be sprayed from boats, planes and helicopters. With good operational support, large quantities of oil spread over a wide area can be treated quickly and effectively. The controlled use of dispersants can reduce the overall impact of an oil spill on the environmental and economic resources. However, since the use of dispersants results in the oil being transferred from the sea surface into the water column, it is necessary to evaluate the relative risk to potentially sensitive resources in different parts of the marine environment.

On the other hand, once oil has reached coastlines, response efforts should first focus on areas that have the heaviest concentrations of mobile oil, which could otherwise lead to further pollution of surrounding areas. *Shoreline cleanup* is often performed through a combination of techniques, including manual and mechanical removal, flushing or washing with water at high or low temperatures and pressures, and even wiping with rags and sorbent materials. *Bioremediation* is another alternative: the application of oil-degrading bacteria and nutrients to contaminated shorelines to enhance the process of natural degradation has generated considerable interest for more than two decades. So far, however, it has not proved technologically feasible nor beneficial for large-scale restoration projects.

Finally, *disposal* of the oil recovered has to be carried out. At-sea recovery and shoreline cleanup generate substantial amounts of oil and oily waste that need to be transported, temporarily stored and ultimately disposed of in an environmentally acceptable manner. Such operations often continue long after the cleanup phase is over. Liquid oil and oily water may be reprocessed at a refinery. Oily material can be used as a low-grade feedstock in some industrial processes and it may also be stabilised for use in construction projects, as a low-cost secondary raw material. More traditional disposal routes include incineration and landfill.

Needless to say, all this operations are not free. The cost of oil spill response has been investigated by D.S. Etkin (1999-1), who later focused on shoreline cleanup costs (Etkin, 2001-3) and at-sea response (Etkin, 2001-2; see section 2.1.1.j)

i. Spill prevention. Lentz & Felleman (2003) summarise the development of the major international measures taken to address the prevention of vessel oil spills:

- Prevention of oil spills begins with ship design requirements. Thanks to Regulation 13F of MARPOL, of 1993 (see section 1.3.1), new tankers have be equipped with a *double hull*, a device consistently found to be effective in the prevention and mitigation of spills. Not until the year 2020 is the entire world fleet scheduled to be converted to double hulls. The US Coast Guard's Programmatic Regulatory Assessment found that double hull requirements will reduce the number of spills for tankers and barges by 13% and 16% respectively, and the volume of oil spilled by 21% and 22% respectively in the future (PMG, 2001). Double hulls were found to be even more effective in an analysis of vessels in US waterways, which demonstrated that for collisions, groundings and allisions there is an order of magnitude reduction in spill volume that can be attributed to the double hull/double bottom designs. While there is general agreement that double hulls play an important role in the prevention of oil spills, there is some debate on the cost effectiveness of this measure, with a number of experts submitting that it is a costly measure in relation to its effectiveness. This assessment can be largely attributed to the failure of most cost-benefit analyses to fully account for the true value of environmental benefits associated with the prevention of spills.
- Other design requirements that should be incorporated in international standards (but so far have not) are: redundancy, alarm, and automatic changeover for steering gear in event of single failure; increased powering; emergency or redundant propulsion; improved longitudinal bending moments; restricted use of high tensile steel to internal structures; requirement for inherent positive stability throughout cargo and ballast handling.
- *ISM Code*. Beyond the actual design of a ship, the extent to which spills might be prevented depends in large part on the standards set and maintained by those responsible for managing ship operations. The International Safety Management (ISM) Code was adopted in 1998 to provide an international standard for the safe management and operation of ships. The ISM Code requires a documented management system designed to provide for the prevention of accidents involving ships and personnel, casualties and damage to the marine environment.
- The *International Convention on Standards of Training, Certification and Watchkeeping for Seafarers* (STCW), 1978, as amended, sets qualification

standards for masters, officers and watch personnel on seagoing merchant ships. The Convention was amended in 1995, largely in response to the major spills of the "Braer" (1993), the "Aegean Sea" (1992) and the "Scandinavian Star" (1990).

- *Port state control*. Historically, the primary responsibility for ensuring that ships comply with international regulations has rested with the flag state that issues the necessary certifications attesting to such compliance. Unfortunately, certain flag States, for various reasons, fail to fulfil their obligations to ensure ships' compliance with internationally agreed standards. As a result, some ships operate in a substandard condition, threatening crew safety and posing serious risks to the marine environment. Port states have become increasingly impatient with the failure of flag states to meet their obligations. These circumstances have motivated port states to undertake efforts within IMO under Resolution 632 to increase supervision and broaden the scope of authority of port states for inspection and detention of vessels. More importantly, a number of regional Memoranda of Understanding have developed over the years to improve port state control in particular areas of the world. The first of these Memoranda was signed in Paris in 1982 among 13 EU countries. Nowadays, virtually any port state has signed a regional Memorandum.
- A key ingredient for effective "preventive salvage" is the availability of *safe havens* or *ports of refuge* for vessels in distress, where salvage and/or repair efforts can be safely undertaken in a more controlled environment. The enormity of this problem was demonstrated in the case of the "Castor". This ship, laden with gasoline, developed a deck crack. The responding salvagers were forced to tow the casualty over 2000 miles around the Western Mediterranean as they sought shelter to perform a ship-to-ship cargo transfer. Government after government refused their requests for shelter. IMO responded to the Castor incident by agreeing to develop guidelines for coastal states for identifying places of refuge, including ports, sheltered waters and safe anchorages. In addition, guidelines will be prepared for the evaluation of risks posed by casualties and for advice to masters in emergency situations.

Another problem that has to be addressed in the framework of oil spill prevention is the *human factor*. The US *Oil Pollution Research and Technology Plan* (Interagency Coordinating Committee on Oil Pollution Research, 1997) thoroughly insists on this point, which was later tackled by Harrald *et al.* (1998) in the context of the PWS Risk Assessment (see section 2.1.1.f). The authors state that studying human error based on historical data is virtually impossible, because of the lack of valuable information, though the development of maritime simulators can help to capture human error data.

j. Economics of oil spills. In the last few decades, in the wake of disastrous marine oil spills, environmental scientists and economists have joined efforts to model the costs caused by the accidents, as well as the economic benefits deriving from prevention policies and strategies (Field, 1994).

The costs of an oil spill are multifarious. Basically, it can be said that on the one hand there are direct costs, which are essentially *cleanup costs*, while on the other hand social and environmental costs have to be accounted for. The latter strongly depend on the oil spill location. The damaged coastline can be rich in biodiversity/highly sensitive or, instead, lack substantial environmental value, the socio-economic setting can be strongly dependent on sea-related activities (fishery, aquaculture, tourism) or practically independent of it. As a result, studies have often focused on cleanup costs only, which can be traced back to a number of physical variables (though in a not straightforward, unambiguous way). Studies on the benefits of spill prevention and cost benefit analyses are also scarce.[4]

There is general agreement (Interagency Coordinating Committee on Oil Pollution Research, 1997; Etkin, 1999-1; White & Molloy, 2003) that the main technical factors influencing the cost of oil spills are:

- *Type of oil*. Basically, light oils and light refined products disperse more readily, which means lower cleanup costs. Nevertheless, sometimes they constitute a fire/explosion hazard if spilled in confined situations, leading to potential closure of ports and industrial districts. In addition, light products tend to be more toxic than heavier oils and they can lead to mortality of marine plants and animals, as well as to tainting of edible fish, shellfish and other marine products. On the other hand, heavy oils, besides normally requiring higher cleanup costs because of poor dispersion, constitute a threat to seabirds and other wildlife.
- *Physical, biological and economic characteristics of the spill location*. A spill occurring far from the coast tends to cause little or no damage, as oil will be dispersed before reaching the shore. The “Atlantic Empress” accident off the coast of Tobago (1979, West Indies) represents so far the world record in terms of amount spilled (280,000 t), but caused little damage and costs (also due to favourable wind and weather conditions; see CEDRE, 2000-1). Similarly the vulnerability of different shoreline types, the extent to which they are self-cleaning, the feasibility of manual cleanup, the availability of local labour and facilities influence the cost of spill cleanup.
- *Weather and sea conditions*.
- *Amount spilled*. There is an obvious relation between the costs of a spill and the amount spilled. In general, larger spills imply higher costs. Yet, such relation is not linear, as proved by Etkin (1999-1), who showed that the cleanup costs on a per tonne basis decrease significantly with increasing amounts of oil spilled. White & Molloy (2003) insist on the fact that it is not possible to design an equation capable of predicting the cost of a spill on the sole basis of volume spilled. The other factors mentioned in this list are equally important, if not more so (in the case of ports, this is not always true; see section 2.1.2.h). See also Sirkar *et al.* (1997) that take into account the environmental performance of tankers.

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[4] Of the scant number of studies dealing with this subject, it is worth mentioning at least Cohen (1986). In order to perform a cost benefit analysis, the author first describes the costs of preventing oil spills (see section 1.2.1.i), then tries to estimate the benefits of prevention. Total benefits consist of three components: reduced cleanup costs, reduced environmental damages, and the value of oil not spilled. However, the author admits it is not possible to estimate a benefit function, other than for the value of the non-spilled oil (for which oil price is the only information required).

- *Time of the year*.
- *Effectiveness of clean-up*. Quite understandably, good management and rapidity of response (see section 2.1.1.h) are fundamental to limit spill costs.
- *Pattern of spillage*. Some spills last months instead of few days. This makes necessary to maintain a comprehensive cleanup response (oil collection, chemical dispersal, booming, beach cleanup) for a long time, which leads to cost shoot up. This was the case of the accident of the tanker “Betelgeuse” (1979, South-West Ireland; CEDRE, 2004-1).

How all these factors relate to one another is shown in Fig. 2.5.

One of the early studies on oil spill costs was performed by Cohen (1986), who ultimately proposes this correlation for the cost of the recovery of the oil spilt:

$$C_{cl} = \alpha_0 V^{\alpha_1} f^{\alpha_2} \qquad [2.1]$$

where C_{cl} is the cleanup cost, V the volume spilled, f = 0.83 and α_0 = 5.346, α_1 = 0.439 and α_2 = - 0.798 (for ports). The relation is based on data owned by the USCG, collected between 1973 and 1981 and regarding 95 accidents. It accounts for the recovery of the spillage.[5]

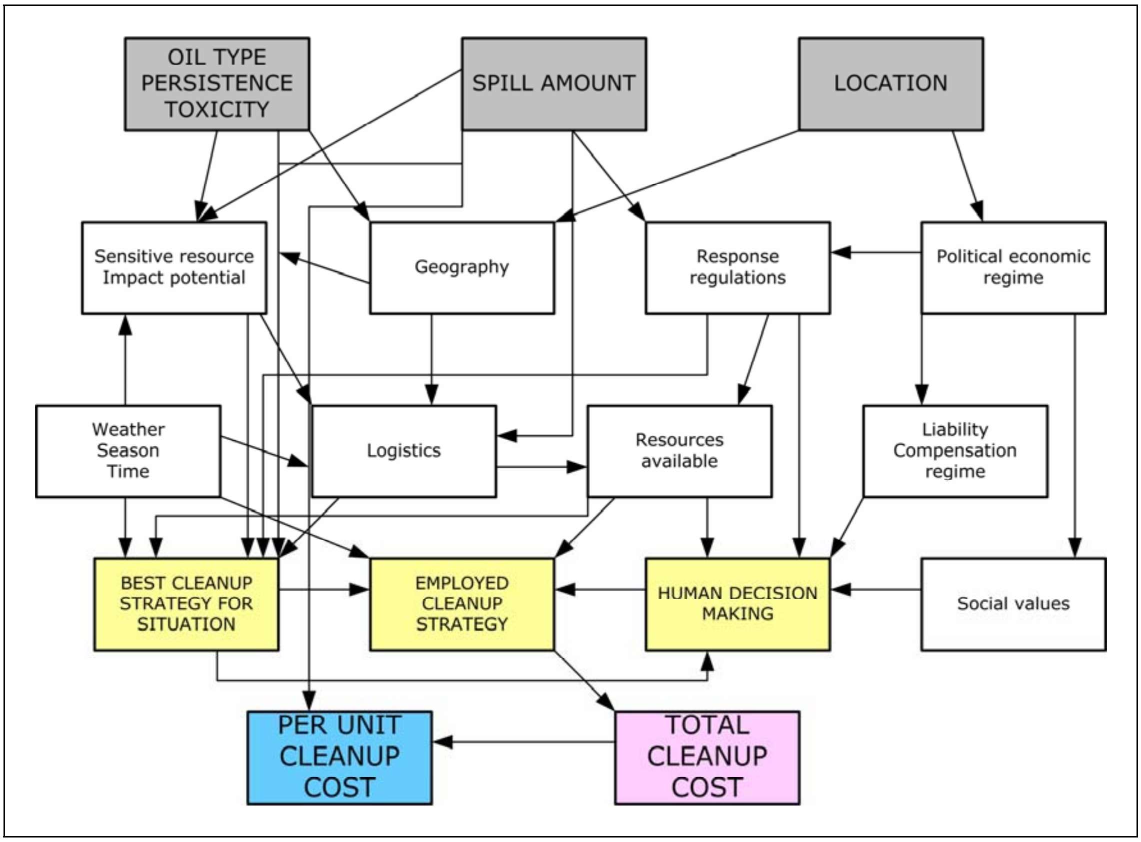

Fig. 2.5. Interaction among the factors influencing the cost of oil spill cleanup (Etkin, 1999-1).

[5] For more details on Cohen’s correlation, see Paper 6 (“Economic valuation of damages originated by major accidents in port areas”).

Later Etkin (1999-1) significantly improved –and complicated– the model. She devised a method for estimating cleanup costs (per tonne of oil recovered) based on five variables: location, shoreline oiling, oil type, cleanup strategy and amount spilled. Etkin (2000) further refined the model by adding two important independent variables:

- Specific location, allowing for three types of spills: offshore, coastal, and *port spills* (see section 2.1.2.g).
- Country location. In fact, the previous study (Etkin, 1999-1) was based on US spills only, while in this new analysis a number of historical spills happened worldwide is used for the estimations. The influence of country location is decisive: average cleanup costs, on a per tonne basis, vary by at least one order of magnitude (they are in the order of 1000 $ 2000 in the Middle East and 20,000 $ 2001 in North America).

Etkin (2001-2) validates this model with satisfactory results. Finally, Etkin (2001-3) deals specifically with *shoreline* cleanup costs.

2.1.2 Port-specific papers and reports about oil spills

a. Physical models. The models cited in section 2.1.1.b are generally valid for the enclosed waters of a harbour. Kung *et al.* (2001) propose the combination of various models found in the literature to give a comprehensive explanation of the various oil weathering phenomena and shoreline deposition. The authors then validate the model, testing it in a spill scenario designed for the Taiwanese Mai-Liau Harbour.

b. Software programmes. Only few of the programmes mentioned in section 2.1.1.c can be used to model oil spill weathering and trajectory. One of these is GNOME by NOAA (NOAA, 2002-1).

Bruzzone *et al.* (2000) devised a programme implementing models allowing for chemical risk in port areas, including a module for the estimation of oil spill trajectories. This takes into account the possible use of response facilities, like skimmers and booms.

Kung *et al.* (2001; see section 2.1.2.a) implemented their model in a programme with graphic animations of the oil spill trajectory.

c. Historical analysis, databases, statistics. Many of the studies cited in section 2.1.1.d present statistics that are related to offshore as well as port spills. In particular ITOPF reports are highly recommendable (see Fig. 2.3 and Fig. 2.4). ITOPF (2004-2) presents interesting data about the origin of the spills (Table 2.1 and Fig. 2.6). The following considerations can be made:

- Most spills from tankers result from routine operations such as loading, discharging and bunkering, which normally occur in ports or at oil terminals.
- The majority of these operational spills are small. 91% involve less than 7 tonnes; only 30 out of 335 major spills happened during (un)loading operations, while 95 and 114 were due to a collision or a grounding, respectively.
- Accidents involving collisions and groundings generally give rise to large spills, with almost a fifth involving quantities in excess of 700 tonnes.

Table 2.1. Number of spills by cause, 1974-2003 (ITOPF, 2004-2).

	< 7 tonnes	7-700 tonnes	> 700 tonnes	Total
Operations				
(Un)loading	2812	326	30	3168
Bunkering	548	26	0	574
Other routine operations	1177	55	0	1232
Accidents				
Collisions	167	274	95	536
Groundings	228	212	114	554
Hull failures	572	88	43	703
Fires and explosions	85	11	29	125
Other/unknown	2175	143	24	2342
TOTAL	7764	1135	335	9234

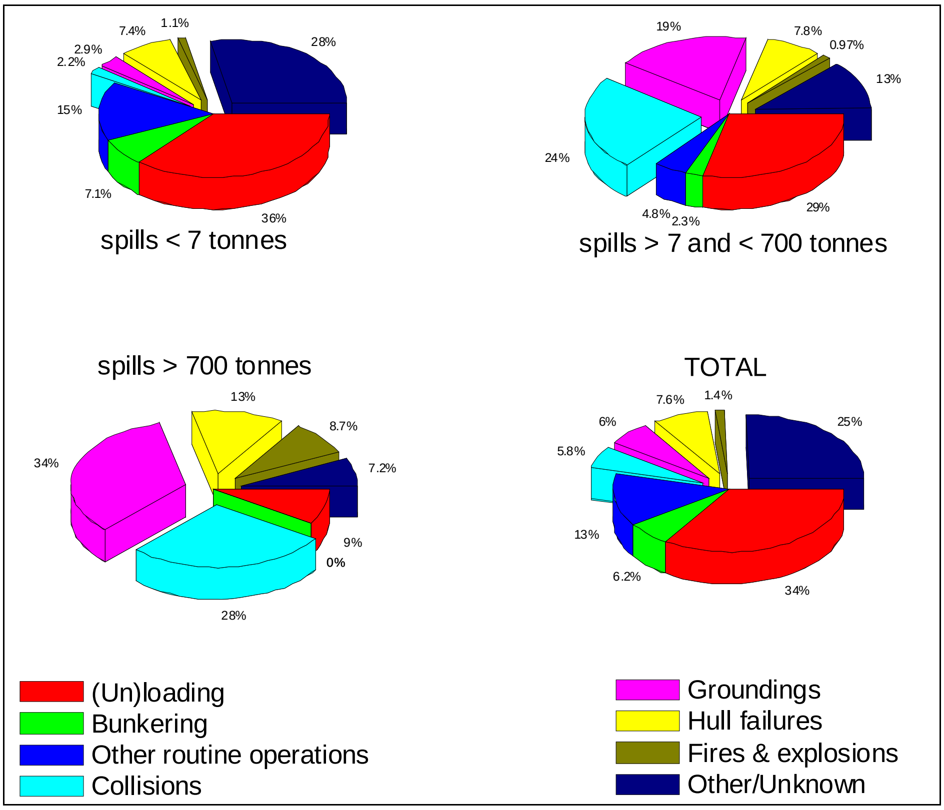

Fig. 2.6. Causes of oil spills, as a function of spill size. Routine operations, like (un)loading and bunkering, which are mainly carried out in ports and marine terminals, are predominant in the case of small spills, while maritime accidents like groundings and collisions are more important for larger spills.

The National Research Council (2002) has published several data that tend to confirm the above conclusions (Table 2.2). The NRC states that in the period 1990-1999, coastal facilities were responsible of 8.5% of the number of spills and 98.3% of the total spilled volume.

The already mentioned study by Lentz & Felleman (2003) analyses the often overlooked topic of land-based sources. These are of two types: non-point sources, like urban/coastal runoff and atmospheric input, and land-based facilities (tanks, pipelines, other onshore facilities). In general, non-point sources are neither port-based nor incidental. On the other hand, land-based facilities are mostly found in port settings. Many releases are actually originated from spills made during delivery. Spills usually result from human error during tank filling. Overfills can result in large volumes of oil spilled.

d. Frequencies. It is clear that tanker spills occur more frequently in ports than at sea, (and that consequences tend to be less severe, due to the immediate presence of booms, skimmers and other facilities and to the fact that ports are almost confined spaces). Nevertheless frequency data are not easily found in literature. The only reference worth citing is SLR (2000), where a brief outline of predicted spill frequencies for US ports is given (although with no theoretical rationale).

e. Risk assessment and human error. A simple example of oil spill risk assessment is included in Howard (2001), whose probabilistic approach is based on ITOPF data. The already cited work by the Australian Maritime Safety Authority (AMSA, 2001) contains the results of a six-month study carried out by Det Norske Veritas to produce a risk assessment of oil and chemical spills in Australian ports and waters.

Walker (2000-1), in the frame of the US Coast Guard's efforts to standardise its maritime risk assessment procedures (see section 2.2.3), presents the results of a HazOp (hazard and operability analysis) of a small (un)loading hydrocarbon terminal for barges. The analysis is successful, above all on account of the small size of the system under analysis. Otherwise, HazOp is not an easy technique to use with port systems.

Harrald *et al.* (1998; see section 2.1.1.i) and Bruzzone *et al.* (2000) focus on human error as the specific cause of port spills.

Table 2.2. Spills from land based facilities to US coastal and marine waters (National Research Council, 2002).

Spill source	**No. of spills 1990-1999**	**Total amount spilled 1990-1999 (tonnes)**	**Average amount spilled per spill (tonnes)**
Aircraft/airports	25	156	6.2
Coastal pipelines (refined products)	48	5,377	112.0
Industrial facilities	409	2,528	6.2
Marinas	26	63	2.4
Marine terminals	335	5,727	17.1
Military facilities	55	914	16.6
Municipal facilities	131	1,181	9.0
Reception facilities	4	11	2.1
Refineries	56	910	2.8
Shipyards	35	72	16.3
Storage tanks	44	109	2.1
Other	17	36	2.5
TOTAL	1,185	17,084	14.4

f. Response and cleanup. Oil spill response and cleanup is easier in ports than at sea. Ports are generally sheltered systems, connected to the open sea via narrow entrances, which are easy to close. Furthermore, booms and skimmers are often available in ports and intervention is definitely faster than at sea.

Port cleanup techniques can be different from those used in the open sea (Darbra *et al.*, 2002). The choice of one or another depends on the molecular weight and the viscosity of the product spilled.

In the case of light hydrocarbons (density > 27 ºAPI), one of the following options is usually chosen:

- Evaporation.
- Screws are used to stir water, so as to make dissolution and evaporation easier.
- Using dispersants (this can entail the environmental risk of contaminating bottom sediments and benthos).
- Using *absorbents*, in the shape of barriers (e.g. lipophilic polypropylene), wood shavings, peat, etc. In order to be effective, these have to be put in place hastily, since they are in good operational conditions only if the slick is thick enough.

Response to heavy hydrocarbon spills is usually accomplished using dispersants or skimmers. Booms are used in all cases, to hamper the expansion of the slick. Bioremediation and in-situ burning are not feasible in ports.

g. Economics of oil spills. As it has been mentioned (see section 2.1.1.j), Etkin (1999-1) devised a model for the estimation of cleanup costs of oil spills, which takes into account the specific location where the accident occurs. This can be either offshore, coastal, or a port.

The model proposed by Etkin is the following:

$$C_{\mathrm{u}} = C_{\mathrm{l}} \cdot t \cdot o \cdot m \cdot s \qquad [2.2]$$

$$C_{\mathrm{l}} = r \cdot l \cdot C_n \qquad [2.3]$$

$$C_{\mathrm{e}} = C_{\mathrm{u}} \cdot A \qquad [2.4]$$

where C_{u} is the response cost per unit, C_{l} the cost per unit spilled, C_{n} the general cost per unit spilled in the country n, and C_{e} the estimated total response cost. The values of some of the modifiers (t, o, m, s, r, l) that appear in equations [2.2], [2.3] and [2.4] are shown in Table 2.3 in order to give an idea of how important factors like oil type, spill size, etc. are in the definition of the cleanup cost. The author warns that the model is affected by high uncertainty. Nevertheless, it is one of the few that allows for a high number of variables. Moreover it is capable of describing both spills at sea and in ports. Observing Table 2.3, it is possible to notice how, according to this source, the unit cost of a port spill is, on average, slightly lower than a coastal spill, but it is almost three times as much as the cost of an offshore spill.

A lighter approach to the model can be found in Etkin (1998). French Mc Cay *et al.* (2002) and Etkin *et al.* (2003) use SIMAP (see section 2.1.1.c) to model several spill scenarios in San Francisco Bay and eventually estimate cleanup costs, as well as social and environmental costs.

Darbra *et al.* (2002) propose a simple method for port oil spill calculation, in which spill modelling is the step previous to the pricing of its cleanup. The scheme is summarised in Fig. 2.7 and Table 2.4.

Table 2.3. Values of the modifiers of equations [2.2], [2.3] and [2.4] (Etkin, 2000).

Cost factor	Modifier
Oil type (*t*)	
No. 2 fuel (diesel)	0.18
Light crude	0.32
No. 4 fuel	1.82
No. 5 fuel	1.82
Crude	0.55
Heavy crude	0.65
No. 6 fuel	0.71
Spill size (*s*)	
< 34 tonnes	2.00
34-340 tonnes	0.65
340-1700 tonnes	0.27
1,700-3400 tonnes	0.15
3400-34,000 tonnes	0.05
>34,000 tonnes	0.01
Location type (*l*)	
Near shore	1.46
In-port	1.28
Offshore	0.46
Primary cleanup method (*m*)	
Dispersants	0.46
In-situ burning	0.25
Mechanical	0.92
Manual	1.89
Natural cleansing	0.10
Shoreline oiling (*o*)	
0-1 km	0.47
2-5 km	0.54
8-15 km	0.54
20-90 km	0.61
100 km	1.06
500 km	1.53

Table 2.4. Estimated costs, itemised according to the operation (Darbra *et al.*, 2002).

Item	Estimated cost (€ 2002)
Cleanup/aeration:	
Preparing and transferring equipment	100 €/h
Labour (per person)	10 €/h
Depreciation/rent of boat, fuel	80 €/h
Transport (in casks)	20 €/m^3
Chemical analysis	500 €/spill
Treatment	40 €/m^3

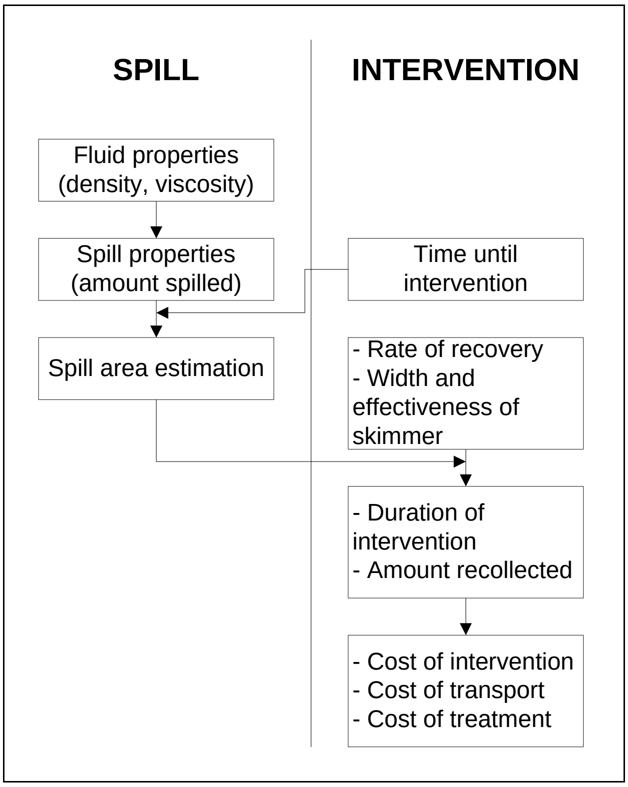

Fig. 2.7. Model for the estimation of port spill cleanup costs (Darbra *et al.*, 2002).

2.2 Risk assessment of general port accidents

This section deals with a number of aspects regarding risk assessment of port systems, not necessarily tied with the topic of oil spills. Risk assessment techniques are very numerous. It is not always possible to clearly differentiate among them. We tried to do it by dividing section 2.2 into four parts.

Subsection 2.2.1 is devoted to *historical analysis*, i.e. the study of past accidents as a means of describing the trends of HazMat accidents regarding various characteristics.

Subsection 2.2.2 focuses on the topic of *frequency and probability* of accidental events, as well as *event and fault trees*. These tools help define one of the two factors on which the definition of risk is based, i.e. the rate of occurrence of accidents.

Subsection 2.2.3, instead, addresses those risk assessment techniques, as *quantitative risk assessment* and IMO's *Formal Safety Assessment*, capable of combining both accidental frequencies and consequences in order to express the risk associated with a site or operation. The USCG's *Risk-based Decision-making Guidelines* (USCG Research & Development Center, 2001) are mentioned as well, because they are a comprehensive collection of risk assessment tools for ports and maritime settings.

Finally, subsection 2.2.4 deals with *risk indices and risk ranking*. The assessment methodologies reviewed here are consistent with the definition of risk as the product of frequency and magnitude of consequences; only, these methods are normally simpler than those reviewed in the previous subsection and require less effort in terms of time

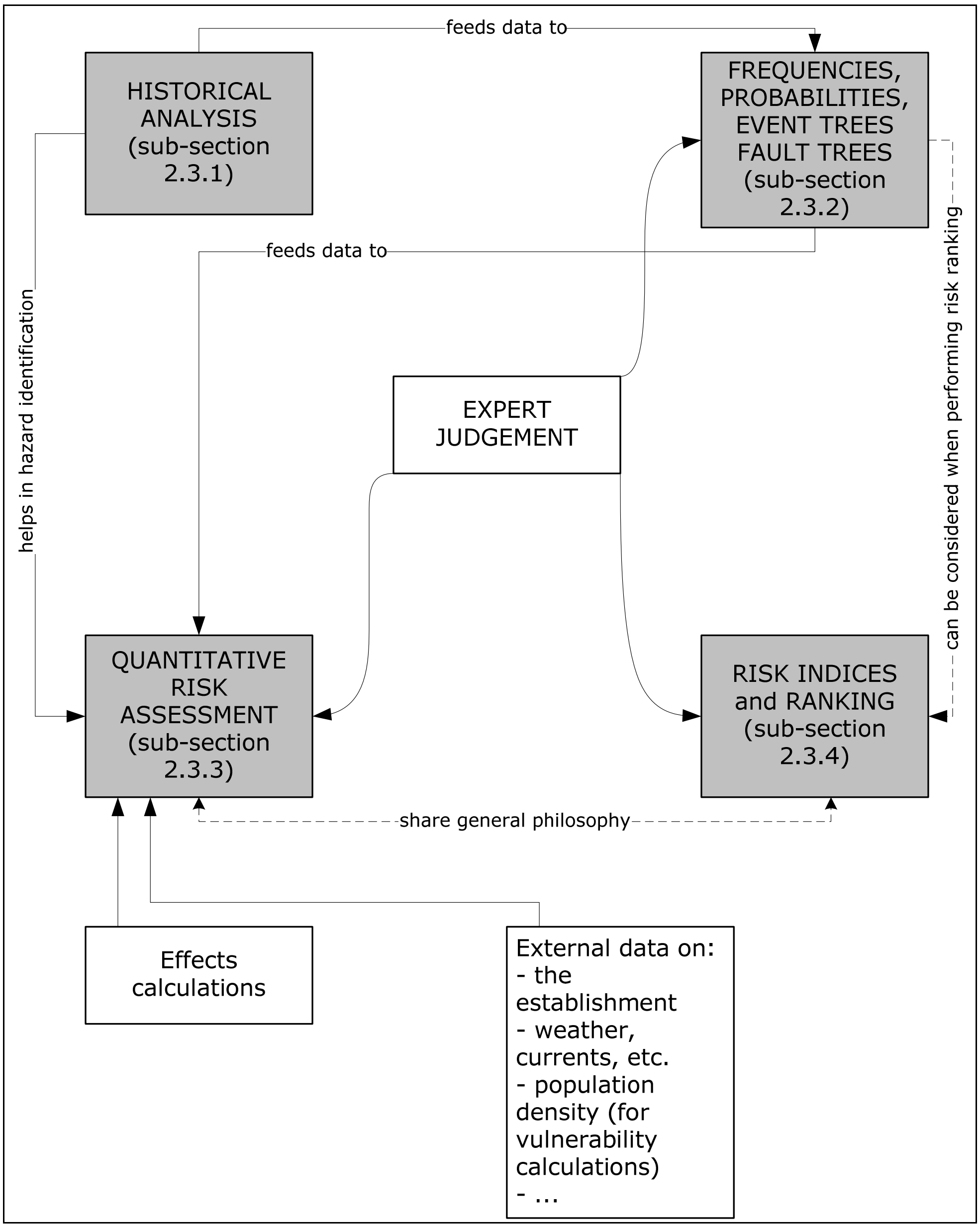

Fig. 2.8. Relationships among various risk assessment techniques.

and calculations. On the other hand, risk indices and ranking techniques are not designed to yield results expressed in standard risk units of measurements (e.g. expected casualties per year), which can make it difficult to compare risk levels of different facilities and to use the output for land use planning.

All the abovementioned techniques are intermingled and depend on one another. Fig. 2.8 roughly describes these relationships. Historical analysis is often used as a means to estimate the frequency and/or probability of accidents and thus design event or fault trees (for example, Paper 3 is focused on a survey of two accident databases, which was carried out in order to define the probability of ignition and explosion of flammable spills). Moreover, historical analysis is often used for hazard identification. In this sense, it is often used as a previous step to quantitative risk analysis for the identification of hazardous scenarios. Frequencies, probabilities, event trees and fault trees, in turn, are all subsidiary tools to quantitative risk assessment. Actually, an important part of the work of QRA analysts is accomplished by resorting to lists of frequency and probability data, which are then implemented into event and fault trees, as it will be explained later.

Apart from this, it must be stressed that QRA, Formal Safety Assessment and other comprehensive risk assessment methods depend also on other information needs. A lot of data about the system analysed, the weather (and/or sea) conditions, the population density around the site under examination, etc., must be known in order to assess risk through these tools. The effects of dangerous scenarios, i.e. toxic concentrations, blast overpressure levels and fire thermal radiation, must also be estimated.

More important than this, all of the above techniques and methods, possibly with the exception of historical analysis, are not independent from the use of expert judgement. Either they are designed based on expert judgement, as is the case with event trees and, above all, risk indices and ranking methods, or rely on the use of expert judgement when they are used in risk assessment. Quantitative risk assessment, for example, is a strictly formalised method, based on the mathematical integration of risk levels in or around the site analysed; nevertheless, a number of issues, such as the identification of proper hazardous scenarios and accident frequencies, directly involve the experience of the analyst.

Where pertinent, the contributions of the present thesis to the field of risk assessment of HazMat activities in port areas are highlighted in the subsections below and discussed in relation to other studies.

2.2.1 Historical analysis, databases, statistics

A peculiar form of identifying hazards is turning to the so-called *historical analysis* of accidents. Referring to past accidents is always a good way of forecasting possible undesired events in the future. This kind of analysis is essentially a qualitative one, but allows to draw quantitative conclusions if many accident records are available (Casal *et al.*, 1999). In several cases certain trends may be inferred from the data set, with respect to many variables and aspects involved in the accidents, such as:

- Causes of the accidents;
- Substances involved;
- Amount of HazMat spilled;
- Operation that was carried out when the accident occurred;
- Accident type (fire, explosion, gas cloud, or, on a deeper level, type of fire –pool fire, tank fire, jet fire...–, explosion –UVCE, confined explosion, dust explosion...–, etc.);
- Consequences of the accident (casualties, injuries, evacuees, economic loss, environmental damage).

Moreover, past accidents represent “experimental data”: no doubt, they are achieved at a high cost but, once the damage is done, the valuable lessons they teach must not be discarded. This is most true in a field where experimental activities are almost impossible. So, accident analysis, in the few cases for which enough information is provided, is an effective means of validating physical models for thermal radiation, blast propagation and gas dispersion.

For the above reasons, accident investigation is very important, and at present there are several public institutions aimed at analysing and recording HazMat accident information. These can be either national or international bodies. The Chemical Safety and Hazard Investigation Board (CSB), the National Transportation Safety Board (NTSB) and the National Response Center (NRC) must be cited as relevant institutions in the US. In the UK the Health and Safety Executive (HSE) must be mentioned. On a European level, the EU's Major-Accident Hazards Bureau (MAHB) is the institution responsible for collecting and publishing relevant accident information about fixed installations. MAHB is the body to which every EU member country has to report accidents occurred in its territory at Seveso sites.

If possible, not only *accidents*, but also *incidents* and *near-misses*[6] should be recorded, because they provide information and lessons as valuable as those deriving from actual accidents, which caused life loss or damage to property. Nevertheless, this does not always happen, because most of the near-misses are not reported. The same occurs with some accidents, above all those that have not caused significant loss. Badoux (1983) discusses this aspect.

Historical analysis is performed using *accident databases*. Several databases are available to the risk analyst, each having pros as well as cons. Some important databases listing HazMat accidents in general are reported in Table 2.5. An account of some of them has been given by Mannan (2004: vol. 3, Appendix 33) and Carol (2001). A number of databases are specifically devoted to marine accidents and spills. Table 2.6 names and briefly describes some of them. More details on the MHIDAS can be found in the first and second paper of this PhD thesis (Darbra *et al.*, 2005; Ronza *et al.*, 2003). See Paper 3 of this thesis (Ronza *et al.*, 2007-1) for a description and references of the MINMOD and the HMIRS. Another important source of information on the MINMOD is the study by Waters *et al.* (1999). Lin *et al.* (1998) used the MINMOD to draw quantitative conclusions about the factors affecting groundings of vessels on entering/exiting ports. Plenty of information about marine accident databases has been compiled by the US Coast Guard (USCG, n.d.) and the NTSB (2002). The databases listed in Table 2.6 do not necessarily focus on HazMat accidents. The most outstanding example is Lloyd's LMIS, which is about vessels in general, but has also data on marine and non-marine casualties (CBS Marine & BMT Reliability Consultants, Ltd., 2001). The inventory of Table 2.6 is not complete; among the databases not reported, DAMA (Norway; see for example Thevik *et al.*, 2001, and Rømer *et al.*, 1993), SAFIR (Norway), SYNERGI (Norway), MAIB-CHIRP (United Kingdom) must be mentioned. Some of them are briefly described by the USCG (1998). Most countries maintain a marine accident casualty database, be it in an electronic format or not. Caridis (1999) expresses the need for a unified reporting system, to be issued and maintained by a European institution and harmonised with IMO's recommendations.

A number of studies have been carried out using one of the aforementioned databases or, on occasions, some *ad hoc* accident list, in order to investigate trends of port and maritime accidents. Some of these studies are described below. Not all are

[6] The difference between *accident, incident* and *near-miss* are quite confused. It can be said that accidents are events that have important consequences on human health, property and/or the environment, incidents have only slight consequences while near-misses only prove to have the *potential* for some important aftermath. Anyway confusing accidents with incidents or incidents with near-misses is common.

focused on HazMat, and yet have to be mentioned either because of methodological issues or their interesting results.

Rømer *et al.* (1993) present the outcomes of a historical analysis of shipping accidents based on a Norwegian database (DNV’s DAMA) and a list built by the authors from data published in the “Incident Log” of the *Hazardous Cargo Bulletin*. 151 accidents are scrutinised. Small event trees are drawn, and accidental frequencies estimated for each branch of them. Accident types allowed for are fire/explosion, collision, grounding and structural damage. Overall, this study does not put forth interesting conclusions, mainly because the sample analysed is not significant. Nevertheless the proposal for a taxonomy of shipping accidents is novel and the scheme of accident analysis is interesting (accidents with spills < 100 tonnes *vs.* others, fraction of deadly accidents, etc.).

Later, the same research group (Rømer *et al.*, 1995-1) proposed a more extensive analysis based on an in-house database including information about 2781 HazMat transportation accidents occurred between 1945 and 1993, of which 1780 affected shipping transportation while the remaining 1001 happened during land transport. The main outcomes of the study, which uses probability *vs.* number of fatalities (*p*-*N*) curves to compare different classes of accidental events, are the following:

- 25% of shipping accidents occur in ports, 13% in inland waterways and 60% in a full marine environment (either open sea, coastal environment or restricted waters).
- The average number of victims as a consequence of a port accident is lower than the average number of victims of a full marine accident.
- Shipping accidents are categorised according to operation (or “transport phase”). Although most of the accidents occur during navigation, mishaps occurred during cargo transfer and tank maintenance generally cause a higher number of fatalities, as shown in Table 2.7.
- A comparison is carried out between shipping and land transportation accidents in terms of the distribution of fatalities, showing that vessel accidents easily involve higher mortality rates than land transportation accidents. This is probably due to a higher population density around the accident site. This population is often represented by the crew of the vessel(s) involved in the accident.

Marí & Martín (1998) present the conclusions of a historical survey of ship fires that provoked at least one fatality. One interesting outcome of the study is that HazMat vessels (oil, chemical and gas tankers) are safer than generic cargo ships.

Darbra & Casal (2004) is a historical analysis specifically focused on port HazMat accidents. The mishaps here considered are not necessarily shipping events; onshore events are taken into account as well, as long as they occurred in a port area. This is the first study to use the MHIDAS database, from which a sample of 471 accidents is extracted and investigated. The research behind this paper and, above all, the algorithm used to identify port accidents in the database were at the base of the efforts at the base of Darbra *et al.* (2005) and Ronza *et al.* (2003) –respectively Paper 1 and Paper 2–. The former study, in particular, has the same structure as Darbra & Casal (2004) and represents an improvement of this, since it is based on a sample of 1033 accidents. The main difference between Darbra & Casal (2004) and Darbra *et al.* (2005) is that the latter study makes use of a deeper categorisation of accidents, not dependent on

Table 2.5. Some valuable accident databases.

Database	Scope	Number of records	Observations
FACTS (managed by TNO, The Netherlands)	Worldwide scope. HazMat specific. Timespan covered: mainly events occurred in the last 75 years.	> 21,400	Available on CD-ROM. Fee required. Updated yearly. TNO maintains also a mini-database (FRIENDS) containing the same records, but with less information.
HMIRS (managed by the RSPA of the US Department of Transport)	Unintentional releases occurred during transportation of hazardous materials in the USA. HazMat specific. Timespan covered: 1993-present.	around 150,000 spills	Public, web-based.[7] Available in database format (not textual). Frequently updated. Huge amount of data. Very valuable for statistical purposes. Accident summaries not available.
IRIS (managed by NRC, US)	Telephonic reports of pollution incidents. Reporting to the NRC is required by the US *Hazardous Materials Transportation Act*. HazMat specific. Timespan covered: 1982-present.	> 500,000	Public, free, web-based.[8] Updated monthly. Accessible through queries or full downloadable spreadsheets. Accuracy and completeness depend on the entity submitting the report. Reports are often overstated and follow-up corrections may not be made.
MARS (managed by the MAHB, European Union)	Accidents occurred in the European Union establishments under the Seveso directive. Fixed installations only, marine accidents are not included (see Kirchsteiger, 1998). HazMat specific. Timespan covered: 1980- present.	603	Web based.[9] Accessible through queries. Almost completely public and free (only some details are not available, e.g. the name of the plant where the accident occurred). Information is complete and accurate, but records are comparatively few.
MHIDAS (managed by the HSE, UK)	Accidents occurred with HazMat in any country or activity. It includes maritime accidents as well. HazMat specific. Timespan covered: (practically) 1900-present.	15,790	Available on CD-ROM (Health and Safety Executive, 2006). A fee is required to subscribe to the service. Updated three times a year. Possibility of organising all the data in one table or spreadsheet. No clear criteria of inclusion for the accidents. Average quality information, plenty of records.

[7] <http://hazmat.dot.gov/pubs/inc/hmisframe.htm>, last consulted on September 21, 2006.

[8] <http://www.nrc.uscg.mil/foia.html>, last consulted on September 21, 2006.

[9] <http://mahbsrv4.jrc.it/mars/servlet/GenQuery?servletaction=ShortReports>, last consulted on September 20, 2006.

Table 2.6. Marine accident databases.

Database	Scope	Number of records	Observations
LMIS (managed by the Lloyd's Register, UK/international)	Vessels > 100 GT. The LMIS includes 5 sub-databases, one of which is about casualties aboard ships, but port accidents are not present. Not HazMat specific. Timespan covered: last decades.	> 85,000 vessels filed	Available in several electronic formats. A costly fee is required. Very frequent updates. Accurate data.
MARS (managed by The Nautical Institute, UK)	Marine accidents. The Nautical Institute established the MARS in 1992 in response to its members' needs. The MARS is a marine accident (and near miss) reporting scheme of a *voluntary* nature: anyone may report an accident to The Nautical Institute, on condition that the information is detailed. Nothing is published that may affect anonymity. Not HazMat specific. Timespan covered: 1992-present. See The Nautical Institute (n.d.).	767	Hardcopies (journal *Seaways*) and web-availability[10]. Monthly updates. Full text descriptions of the accidents (~ 1 page per accident). No information on location and ships involved in the accidents.
MINMOD/MISLE (managed by the US Coast Guard)	The MISLE has substituted previous USCG databases (PIRS, MSIS and MINMOD). It gathers information about vessel casualties in US waters. Not HazMat specific, but information on any hazardous cargo involved can be retrieved. Timespan covered: 1992-2001.	> 170,000 (MINMOD)	Public. Web-based (textual). Valuable information.

Table 2.7. Shipping accidents (Rømer *et al.*, 1995-1).

Transport phase	% accidents	% accidents with more than one death
Sailing (i.e. navigation)	67	20
Cargo transfer	15	32
Empty tanks	7	74
Other	11	21
TOTAL	100	26

10 <http://www.nautinst.org/mars/index.htm>, last consulted on September 21, 2006.

MHIDAS classification, as all the records were checked prior to investigation in order to establish which operation, among seven possible (vessel approaching port, vessel manoeuvring in port, (un)loading vessel, vessel maintenance, storage of goods on land, process, and land transport), was being carried out when the accident occurred. This allowed for the examination of new issues not immediately retrievable from the database.

One noteworthy study about HazMat accidents in onshore port-areas is Christou (1999). The author collects 617 HazMat accidents happened in marshalling yards and port areas from several databases (including MHIDAS, FACTS, and MAHB's MARS). A series of *p-N* curves are estimated and proposed. The fact is stressed that EU Seveso directive does not affect these areas.

Some authors have instead focused on port/marine accidents unrelated to the handling or transportation of hazardous materials. See Kite-Powell *et al.* (1997, 1998, 1999), –which include a review of USCG vessel casualty data–, Nielsen (1999) and Hansen (1999) –who analyses data retrieved from USCG and Lloyd's databases–.

A comprehensive historical analysis of LNG accidents is found in CH·IV International (2004), where the good safety record of the LNG production and transportation chain is demonstrated. A review is presented of the quasi-totality of the accidents happened occurred in LNG export and regasification plants and to LNG carriers. Most of the accidents happened on land did not involve LNG directly, but are rather to be attributed to the formation of explosive atmospheres in enclosed spaces as a results of bad maintenance or to problems unrelated to the dangerous properties of LNG/natural gas (which is the case of the Staten Island, NY disaster of 1973, where 40 workers lost their lives when the roof of an empty, under-maintenance LNG tank collapsed).

As mentioned above, Paper 1 of this thesis (Darbra *et al.*, 2005) is an account of a historical analysis of HazMat accidents in port areas.[11] The analysis was carried out using the MHIDAS database. The principal contributions of this paper are the following (see Chapters 3 and 4 for more information):

- It describes the distribution of port accidents according to the accident types (loss of containment, fire, explosion, gas cloud), according to the operation that was carried out when the accident occurred and the substance involved.
- It also describes how lethal port accidents are, by showing a cumulative *p-N* curve (probability that an accident causes more than *N* deaths as a function of *N*).

2.2.2 Frequencies, probabilities, event trees

In the frame of probabilistic risk assessment and quantitative risk assessment, it is often necessary to assign:

- A *probability* that a certain event happens instead of others. For example: the probability of a gas cloud being ignited, instead of being dispersed in the atmosphere. Probability is a dimensionless number between 0 and 1.

[11] This study was originally published in the proceedings of the 11th International Symposium on Loss Prevention and Safety Promotion in the Process Industries (Darbra *et al.*, 2004).

- The *frequency* of a certain event happening over time. For example: the frequency of a tank failure. Frequency is expressed by way of events/duration units, normally yr^{-1}. Thus, the frequency of a tank failure can be 1×10^{-7} yr^{-1} (once in ten million years). Alternatively, frequency can be expressed on a per-operation basis, especially if the failure is expected to occur only when a certain device, vehicle or machine is operating but not when it is not used. Example: a ship-ship collision in a port may be expected to happen, on average, once every ten thousand port calls. In this situation the unit of measurement is tailored according to the event considered. In the case mentioned, the unit of measurement is $(\text{port call})^{-1}$.

Probability and frequency data are used above all in the frame of QRA analysis. In QRA, it is necessary to assign a frequency to every accident scenario identified. The frequency of the scenario is then multiplied by its consequences (e.g. the number of expected fatalities), to obtain the levels of individual or societal risk (see section 2.2.3). Frequencies are the expected rates of occurrence of an event, while a probability is the likelihood that an event, once it has happened, gives rise to a certain outcome. For example, once the frequency of tanker groundings in a port is defined (for example: 3×10^{-1} yr^{-1}), the risk analyst normally wants to know what is the probability that the oil or chemical substance transported is spilled. Supposing this is 0.1, a further question can arise, whether the spill can be ignited. If a probability of 0.4 is assigned to this outcome, then the analyst's estimate of the frequency of a fire as a consequence of a tanker grounding in a port will be $f = 3 \times 10^{-1}\ yr^{-1} \times 0.1 \times 0.4 = 1.2 \times 10^{-2}\ yr^{-1}$, i.e. a little more than once in 100 years.

The above scheme of calculation entails a series of probability data, often arising from sheer expert judgement, but sometimes estimated on the basis of historical analysis. Furthermore, it involves a structured form of forecasting how an event evolves, called an *event tree*. Event trees are discussed in Paper 2 and 3 of this thesis. See the Fig. 1 of the latter paper for an example of event tree referred to an LPG spill.

The way the above example frequency was obtained involves also the necessity to define the frequency of the *initiating event* (the grounding). In general, this is found by way of one of three methods: historical analysis, expert judgment or fault tree analysis (FTA). The first two methods are common when the event is strongly dependent on the human factor and/or conditions hard to describe in a "non-fuzzy" way. For example, a tanker grounding likely depends on visibility and weather/sea conditions, as well as on the pilot's experience, but supposing that, when a tanker enters a port, there is bad weather and sea, little visibility and an inexperienced pilot onboard, it cannot be positively predicted that an accident will take place; similarly, it is possible that an accident happens even in the best possible conditions of sea, weather, etc. If, instead, the system under observation is rigidly depending on a series of devices that either work or do not work at all, then the fault tree technique can be applied. Fault trees work based on Boolean logic, obtained by combining the frequency of failure of a limited number of items (like valves, electrical devices, etc.) that make up the system under observation. The frequencies of failure of these items are the very basic elements of FTA. They are available in specialised databases for a wide range of items and devices (several types of flow valves, relief valves, engines, pumps, seals). They are always calculated after the observation of a large number of such devices during very long working times. The FTA approach is often used with chemical process risk analysis. Some authors have tried to use fault trees to describe events not determined by a rigid set of conditions, as, for example, vessel groundings and collisions as well as all types of transportation accidents, but in our opinion this technique is inadequate in these cases. More on event trees and fault trees can be found in Mannan (2004) and Casal *et al.* (1999).

The standard source for probability and frequency data in the frame of probabilistic risk assessment (including quantitative risk assessment) of hazardous materials activities –transport, storage, process– at a European level is Dutch CPR's *Purple Book* (CPR, 1999; now available in a new edition: VROM, 2005). The *Purple Book* consists of two parts (Uijt de Haag & Ale, 1999; Tiemessen *et al.*, 1999) devoted to the risk assessment of fixed establishment and transport of hazardous materials, respectively. The *Purple Book* provides a complete framework for QRA. It was designed to standardise QRA in the Netherlands, in the frame of the Seveso directive, but was then adopted as a reference tool by several countries, including Spain (see section 1.3.2). Beerens *et al.* (2006) summarise the history of the frequency data included in these guidelines. The bulk of the figures proposed proceed from statistical studies –like IPO (1994)– performed on Dutch premises. Some of these studies, including the *Rijnmond Report* (Rijnmond Public Authority, 1982) are already more than two decades old. The new edition of the *Purple Book*, simply titled *Guidelines for Quantitative Risk Assessment*, does not entail relevant changes with respect to the former edition (1999), even if the CPR (Dutch Commission for the Prevention of Disasters) is now abolished and substituted by another organisation (Advisory Council on Dangerous Substances, AGS) that will soon deal with a re-edition of the document, with substantial changes. In fact, many claim that some data are outdated, as stressed by Beerens *et al.* (2006).

The *Purple Book* is a Dutch study. Therefore, it is easy to understand why ports and waterways play an important role in it. The *Purple Book*, also known as *CPR 18E*, includes frequency data of several loss of containment scenarios for ports and maritime terminals. The frequency data corresponding to loading arm failures and vessel impact are used in Paper 4 of this thesis (Ronza *et al.*, 2006-1). The ignition probability data for loading/unloading and waterway transport loss of containment events are listed and commented on in Paper 3 of this thesis (Ronza *et al.*, 2007-1).

In 1983, TNO published *LPG, a Study*, a “comparative analysis of the risks inherent in the storage, transshipment, transport and use of LPG and motor spirit” (TNO, 1983-1; TNO, 1983-2). This project is an early example of QRA, as applied to the entire LPG transport chain, as compared with other automotive fuels (see section 2.2.3). In this frame, the research group in charge of the project designed a series of frequency and probability data for LPG accidents, which cover many port/maritime events, from ship groundings and collisions to pipeline and loading arm failures.

Four Elements Ltd (n.d.) is another interesting source of frequency data for oil and LPG carrier groundings.

Roeleven *et al.* (1995) describe a method to calculate the probability of an accident in the frame of a model that calculates the integral impacts of safety measures for the entire waterway system in the Netherlands, including the risks of transporting dangerous goods. The probability of an accident is modelled per elementary traffic situation (a combination of several ships carrying out a ship motion produces a traffic situation) as a function of the attributes of the waterway and the specific circumstances. The primary governing variables appear to be visibility, wind speed, the ratio of the navigable width and the necessary width for an elementary traffic situation, and the bend radius of the waterway. The circumstances (visibility and wind speed) are more explanatory with respect to the probability of accidents than the waterway characteristics are.

Rømer *et al.* (1995-2) describe the results of a review of marine accident frequencies reported in 20 different sources. There seems to be consistency within the sources in the use of the terms total loss, casualty and accident/incident. The rates were observed to decrease by an order of magnitude going from accident/incident to casualty and likewise from casualty to total loss. The overall frequencies were found to be in the range of 0.009 to 0.07 total losses per 10^{-6} ship miles, 0.03 to 1 casualties per 10^{-6} ship miles, and 0.5 to 13 accidents/incidents per 10^{-6} ship miles. It was found that the frequency depends on visibility, brightness, geographical environment, age of vessel and size of vessel. Collision and grounding frequencies were found to increase with decreasing visibility, brightness and more restricted waters. Collision frequencies were found to increase with increasing size of vessel. Fire/explosion and structural damage frequencies were found to increase with increasing age, and collisions to decrease with increasing age. No firm trend was found from the effect of flag state or type of vessel.

Amrozowicz *et al.* (1997) put forth fault trees describing the accidental powered grounding and drift grounding of oil vessels. The proposal is original but questionable, because it is an attempt at formalising, in a quantitative way, the development of a series of human actions. As mentioned above, fault trees are a good tool for describing systems mainly controlled by automatic devices, but are often defective when it comes to analyse human error.

The frequency of vessel groundings and collisions in US waters was studied by a team leaded by Hauke Kite-Powell (Kite-Powell *et al.*, 1997, 1998, 1999) in the frame of risk factor prioritisation (see section 0).

Correa Ruiz *et al.* (1999) use statistical traffic data in order to estimate the frequency of collision of vessels in the Algeciras-Gibraltar bay.

Det Norske Veritas (2001) estimate the frequency of oil leaks around floating production, storage and offloading installations, using several base probabilities proceeding from different studies like McMahon Anderson & LaBelle (1994).

A collection of frequencies for maritime accidents in the context of the transportation of oil and other hydrocarbons can be found in Álvarez & Larrull (2003).

Ligthart (1980) opened up the way to the study of the frequencies of accidents in LNG transportation. Accident and traffic data for the period 1963-1974 and the port of Rotterdam were used to identify the frequency of collision and grounding of LNG carriers entering or leaving the port. This area was selected because of its high traffic density and the variety of vessels calling there. Only 70 accidents had occurred in the period analysed so the possibilities for extensive investigation were limited. Anyway the author proposes frequency data ranging from 3 to 25 collisions per 100,000 vessel movements, while no figure is proposed as regards groundings.

This thesis includes two contributions on the topic of probability data. In Paper 2 of this thesis (Ronza *et al.*, 2003) a description is found of how event trees for port accidents were obtained based on historical analysis. The research was carried out using a sample of 828 port accident records, retrieved by way of a specific methodology from the MHIDAS database (see section 2.2.1). Due to the limitations imposed by the MHIDAS data, the event trees considered are of a basic type. They take into account sequences of the following events: loss of containment, fire, explosion, gas cloud. An interesting element of this study is that all port operations involving HazMat handling or storage are accounted for. Nevertheless, some operations –process, land transport, maintenance– are so scantily represented that no positive statistical conclusion can be drawn as to the level of risk they entail. The results of this study were further refined –although without substantial changes– following the introduction of some 200 more accident records into the data sample (Ronza *et al.*, 2004-1; Ronza *et al.*, 2004-2).

The second study on probability data is Ronza *et al.* (2007-1) (Paper 3 of this PhD thesis), which is focused on the probability of ignition and explosion of flammable spills happened during the transportation of hazardous materials. This analysis is based on two US federal databases: the Department of Transportation's HMIRS and the US Coast Guard's MINMOD. The former was used to infer a model to predict the ignition and explosion probability of road/rail transportation spills, while the results obtained from the latter are relevant to maritime spills. Among other things, this article can be considered as a source of ignition/explosion probability data for their use in quantitative risk analysis of port environments, as opposed to land transportation. Moreover, the paper –by expanding a previous, briefer report (Ronza *et al.*, 2005)– reviews several probability data found in specialised literature.

2.2.3 Comprehensive risk assessment techniques

The present section is devoted to risk assessment methods accounting for hazard identification, frequency and probability of hazardous events, and the consequences of accident scenarios. In other words, these methods deal with risk as defined in section 1.1, i.e. the arithmetic product of the *consequences* by the *frequency* of accidents over time. Three sets of techniques will be analysed separately:

- Quantitative risk assessment (QRA), a method that rigorously follows the definition of risk.
- Formal safety assessment (FSA), a sort of adaptation of the QRA techniques to ships and maritime settings in general, as promoted by the IMO.
- USCG's *Risk-based Decision Making Guidelines*, a set of methodologies in use at the Marine Safety Offices of the US Coast Guard.

a. Quantitative risk assessment. A classic description of quantitative risk assessment is found in Pietersen & van het Veld (1992). QRA aims at estimating the risk entailed by a system, in terms of human loss or, on some occasions, economic loss. QRA results are presented in two forms:

f-N curves. After completing a QRA process, the frequency (*f*) of and the number of victims (*N*) caused by a number of accident scenarios are known. It is therefore possible to draw a plot representing the frequency of the events against their importance in terms of victims caused. Such curves, normally plotted in a log-log space, represent the frequency of accidents with more than N casualties. Therefore, f-N curves are always decreasing. They are often used to test the system analysed in terms of acceptable risk against some criteria defined in regulations and guidelines. Acceptability criteria are sometimes represented by way of straight, decreasing lines, and mathematically expressed by the following equation:

$$fN^{\alpha} = \text{constant} \qquad [2.5]$$

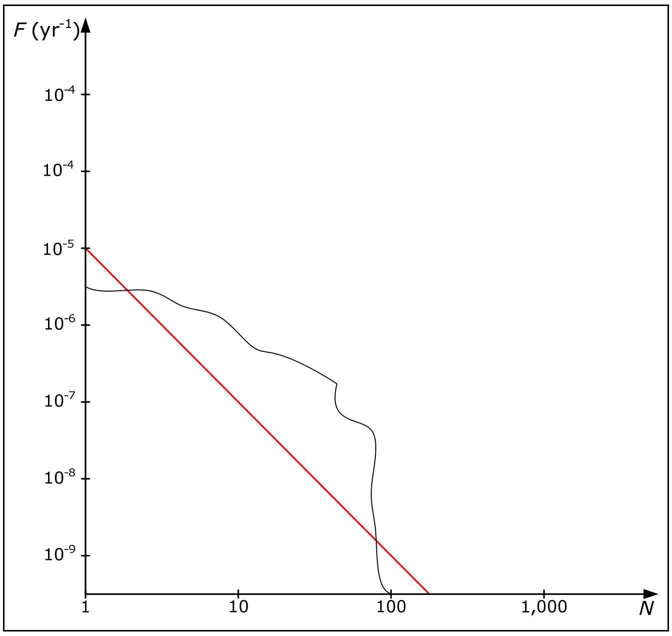

Fig. 2.9. Example *f-N* curve (——), partially exceeding the acceptable level of risk (——).

Risk must be considered acceptable if the *f-N* curve lies entirely below the acceptability line (see Fig. 2.9).

- *Risk contours* or *iso-risk curves*. These curves represent the levels of individual risk[12] around the installations analysed. They are used above all for land use planning, i.e. to ensure that residential areas, schools, hospitals, etc., fall outside specific risk contours. A common risk acceptability level is 10^{-6} yr^{-1}. An example of iso-risk map is Fig. 4 of Paper 4 of this thesis (Ronza *et al.*, 2006-1).

As mentioned before, QRA builds on a number of other methods, including historical analysis as a tool for hazard identification, as well as fault and event trees. Moreover, quantitative risk analysis makes use of accident consequence calculation and vulnerability theory in order to fully define individual risk. The combination of all these tools into a single methodology makes QRA a very comprehensive instrument. For the same reason, QRA is more demanding than other risk assessment techniques, in terms of time and training required to the risk analyst. Nowadays, a series of computer programmes are available on the market, which help accomplish the cumbersome QRA tasks. These include DNV's SAFETI and TNO's RISKCURVES. The latter was used in the frame of Paper 4 of this thesis (Ronza *et al.*, 2006-1). Fig. 2.10 summarises the various steps involved in a QRA. 1.3.1. See Casal *et al.* (1999), Mannan (2004) and Pietersen & van het Veld (1992) for more insights on QRA.

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[12] If risk is expressed in terms of fatal victims, *individual risk* is a function of the spatial coordinates representing the probability that an individual, placed during one year in a fixed point, die as a consequence of the accidents considered for the system analysed, whereas *societal risk* is the expected number of casualties per year. The unit of measure of individual risk is yr^{-1}, that of societal risk is casualties · yr^{-1}. Societal risk is calculated as follows:

$$\text{Societal risk} = \int (\text{Individual risk}) \cdot [\text{population density}(x, y)] \, \mathrm{d}x \, \mathrm{d}y$$

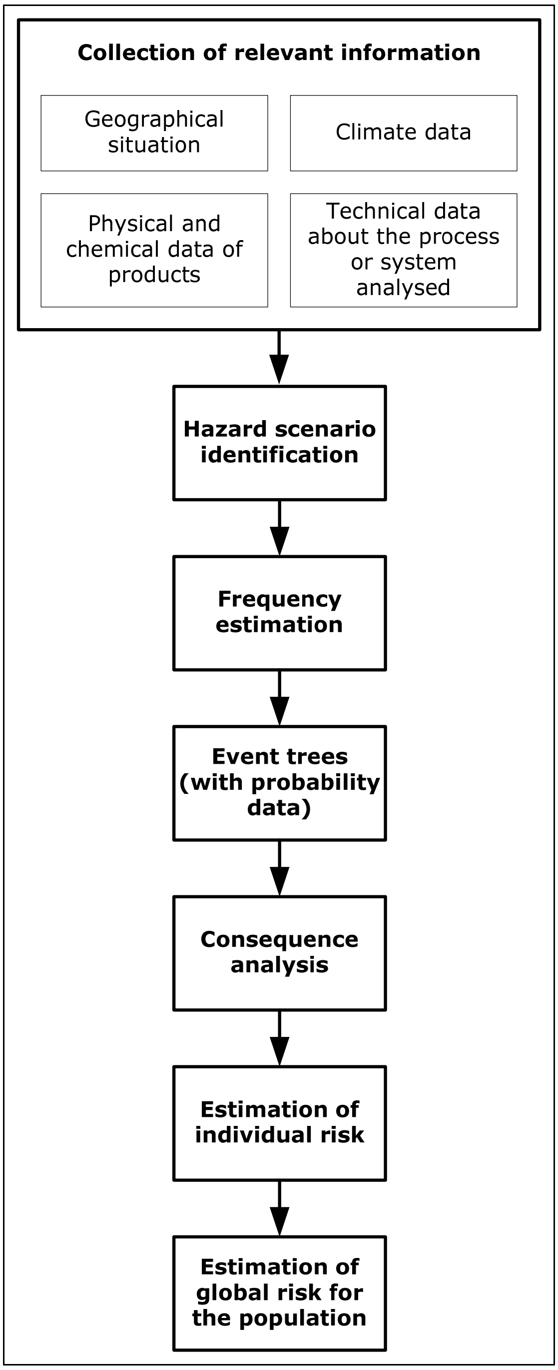

Fig. 2.10. Steps required to perform QRA.

The first milestones of quantitative risk assessment of large HazMat handling/storage/processing areas are the two *Canvey Reports*, by the UK Health and Safety Executive (Health and Safety Executive, 1978; Health and Safety Executive, 1981), and the *Rijnmond Report*, issued by the Rijnmond Public Authority (1982). These studies, which were later used in the implementation of QRA reference guides such as the Dutch *Purple Book* (CPR, 1999; VROM, 2005), are comprehensive hazard assessment of specific industrial areas located at the mouth of, respectively, the Thames, in the UK, and the Rhine, in the Netherlands.[13] They were commissioned by public authorities (the Health and Safety Commission in the case of the *Canvey Reports* and the Dutch Ministry of Social Affairs for the *Rijnmond Report*) in response to the requirements of the industry and the population, both concerned about the risks entailed by such large concentrations of HazMat handling and storing facilities. These studies are so important that they are treated by Frank P. Lees in separate, extensive Appendices to his monumental *Loss Prevention in the Process Industries* (Lees, 1996-1; Lees, 1996-2). It is interesting to note that both Canvey Island and the Rijnmond district are complex *industrial port* areas. The former falls under the jurisdiction of the Port of London Authority and the latter belongs to the Port of Rotterdam.

At the time of the risk assessment behind the reports, Canvey Island facilities included an LNG storage/regasification plant, two LPG terminals, an oil products storage terminal, two oil refineries, an ammonium nitrate plant, while the construction of two new oil refineries was under way. The Canvey Reports, the first one in particular, represent an important effort in the investigation of accident frequencies. These were obtained by way of several methods entailing different levels of uncertainty. Where possible, they were assessed statistically from historical data; otherwise they were estimated on the basis of expert judgement or simplified fault trees. Failure data include the possibility of ship collision, groundings, etc.14 The first Report was not well received by some of the parties involved, because the estimated levels of societal risk were deemed too high. It is generally recognised that risk was in fact overestimated, mostly due to an exaggeratedly conservative approach. Nevertheless, in the wake of the publication of the results, several improvements were put in place in some of the plants affected. These changes and the criticisms received drove the HSE to carry out a new study, whose results were published in 1981 in the second *Canvey Report*. An important improvement of the second *Report* was the introduction of a full set of ignition probability data for flammable clouds, which are reviewed and commented in Paper 3 of this thesis.

One year after the issuing of the second *Canvey Report* the Rijnmond Public Authority published the *Rijnmond Report*, in five parts, including a review by an external party (the Battelle Institute), to ensure the neutrality and reliability of the study. The scope of the report, as its full title indicates, are “six potentially hazardous industrial objects in the Rijnmond area”, which include five storage facilities (acrylonitrile, ammonia, chlorine, LNG and propylene) and a hydrodesulphuriser. The major achievement of this project is the reorganisation of a great deal of failure

[13] “Rijnmond” is Dutch for “mouth of the Rhine”. Rijnmond is in fact the greater Rotterdam metropolitan area.

[14] These latter data are used in the fourth publication of this Ph.D. thesis (Ronza *et al.*, 2006-1).

frequency data collected from several sources. The failure events considered allow for a large inventory of pieces of equipment such as tanks and vessels, pumps and pipework –including hoses and loading arms–, valves, instrumentation and electrical equipment. Another important aspect of the study is the high effectiveness of the representation of the results, achieved by way of *f-N* curves and risk contours. The *Rijnmond* project was focused on land installations; so, although these belong to a port area, no specific port accident events, such as vessel (un)loading spills and ship groundings/collisions, were included in the scope of the study. As Beerens *et al.* (2006) demonstrate, the *Rijnmond Report* is the main source of data for the *Purple Book*.

The CPR 18E, or *Purple Book* (CPR, 1999; VROM, 2005; Uijt de Haag & Ale, 1999; Tiemessen *et al.*, 1999; see section 2.2.2) not only defines the frequencies of several maritime transportation accidents, but also describes an approach to quantify the amounts spilled from punctured vessels (see Table 2.8). Though this is not justified in any way and is likely the result of expert judgement, it is probably a good approach for spills likely to happen in a port, which are generally smaller than those in open sea. The *Purple Book* does not include any other specific guideline on maritime and port accidents.

The *Guidelines for Chemical Transportation Risk Analysis* by the Center for Chemical Process Safety of the AIChE (CCPS, 1995) is the US reference guide to performing HazMat transportation QRA. Together with the CCPS' *Guidelines* for fixed installations (CCPS, 1989), it represents a sort of American counterpart to the *Purple Book*. The Dutch and American guidelines do not contradict each other, but can be used together to complement possible missing data in one of the two sources. CCPS' *Guidelines* are a solid source of information on quantitative risk analysis, more mature and general than the scattered, project-specific data provided by the *Canvey* and *Rijnmond Reports*.

Table 2.8. Risk analysis approach to maritime spills, as suggested by the *Purple Book*.

Modes of loss of containment for ships in an establishment	
L.1	Full bore rupture of the loading/unloading arm: - Outflow from both sides of the full bore rupture.
L.2	Leak of the loading/unloading arm: - Outflow from a leak with an effective diameter equal to 10% of the nominal diameter, with a maximum of 50 mm.
E.1	External impact, large spill: - Gas tanker continuous release of 180 m^3 in 1800 s - Semi-gas tanker (refrigerated) continuous release of 126 m^3 in 1800 s - Single-walled liquid tanker continuous release of 75 m^3 in 1800 s - Double-walled liquid tanker continuous release of 75 m^3 in 1800 s
E.2	External impact, small spill: - Gas tanker continuous release of 90 m^3 in 1800 s - Semi-gas tanker (refrigerated) continuous release of 32 m^3 in 1800 s - Single-walled liquid tanker continuous release of 30 m^3 in 1800 s - Double-walled liquid tanker continuous release of 20 m^3 in 1800 s

Table 2.9. Sea-going vessel casualties per 10,000 port calls, collected in CCPS (1995; original source: Sandwell, Inc., 1991).

Casualty type	All tankers	Chemical tankers	Tanker barges
Collisions	1.0	1.25	1.5
Groundings	4.0	4.80	1.0
Strikings (rammings)	7.0	8.75	7.5
Fires/explosions	2.0	2.20	0.5
Structural failures	0.5	0.53	1.5
TOTAL	14.5	17.5	12.0

The *Guidelines for Chemical Transportation Risk Analysis* are strictly focused on HazMat transportation. They are designed to assess the individual and societal risk of transportation routes and account for pipelines, rail tankers, road tankers, barges, ocean going vessels and intermodal containers. In the context of ports and maritime transport, the major point of interest of this document is the collection of ship accident frequencies and spill probabilities, some of which are reported in Table 2.9. Other interesting chapters of the *Guidelines* are devoted to examine a series of ignition probability data and algorithms, which are reviewed in Paper 3 of this thesis (Ronza *et al.*, 2007-1) and to list and assess an extensive collection of information on transportation accidents, including the HMIRS and MINMOD databases, also used in that publication.

A more recent QRA approach to port areas is the ARIPAR method, which was first adopted for a pilot study of the Ravenna industrial/port area (Adriatic Sea, Italy), featuring both chemical and petrochemical establishments (Amendola & Contini, 1998). Egidi *et al.* (1995), in describing the methodology, recognise the debt they owe to the *Canvey Reports*, recognised as the first effort to draw a consistent QRA methodology for large industrial districts, including marine terminals. The pilot study allowed for fixed installations and HazMat transportation, i.e. road and rail transportation, marshalling yards, pipelines, and ship transportation. The near absence (at that time) of historical data to predict carrier accident frequencies is stressed (see section 2.2.2).

An example application of the ARIPAR methodology is given in Lisi *et al.* (2003) for the industrial area of Gela (Sicily, Italy), including its port. An interesting result of this project was that the expected mortality rate specifically due to the maritime transport of dangerous goods is lower than that due to road and rail transport and fixed plants, which is the same result obtained for the Ravenna area in 1993 (Egidi *et al.*, 1995).

Overall, the ARIPAR methodology is not really innovative as compared with the classic QRA method summarised by Pietersen & van het Veld (1992), although it is one of the first QRA methods to incorporate GIS tools (see e.g. Maschio *et al.*, 2001).

It is noteworthy that the ARIPAR methodology, like the *Canvey* and the *Rijnmond Reports* –all important efforts to improve HazMat QRA techniques– were focused on port industrial areas. All of those projects were made possible by substantial public funding. This demonstrates that the sheer magnitude of port industrial districts, as well as their proximity to urban areas, greatly concern the general public and the authorities.

Liquefied gas handling, loading and unloading entail very specific safety features (see section 1.2.1). Overall, the LPG and LNG industries' have a cleaner safety record than other HazMat-related ones. Nevertheless, they have always been a major concern because of their potential for being sources of large scale accidents. Although the interest in the safety assessment of LPG storage and LNG regasification plants is as old as general HazMat risk analysis (see Keeney *et al.*, 1979; Konkel, 1987), the institutions involved in gas trade are still making efforts to demonstrate that the gas industry is willing to further reduce the risk of accidents (SIGTTO, 1999). These endeavours are particularly intense in the case of LNG, which is getting more and more important in the global energy market. This forces the LNG industry, as well as the public authorities that back it, to influence the public opinion with regard to the great opportunities offered by regasification plants as compared to their low environmental cost and high safety standards.

Additionally, regasification plants have recently been indicated as potential major targets of terrorist attacks (Fay, 2003-2). However, the technology employed in these terminals is generally very advanced –and inherently safe–, especially if compared to most oil terminals.

An early but complete example of QRA of a marine LNG terminal is found in Keeney *et al.* (1979), who, however, fail to justify adequately the frequency/probability data used.

The already mentioned *LPG, a Study* (TNO, 1983-1; TNO, 1983-2) is a sort of QRA analysis applied to the entire LPG and motor spirit (petrol) transport chain, including maritime/waterway transport, vessels unloading at berth and storage at port terminals. A full range of accident scenarios are considered for each of the typical settings where LPG is handled and/or stored. Finally, *f-N* curves are estimated, in order to compare the societal risk entailed by the LPG and the motor spirit transport chains. The analysis showed that, in terms of societal risk, motor spirit, i.e. petrol, is safer than automotive LP gas (TNO, 1983-2). The *LPG Study* was performed in the wake of the *Rijnmond Report*, thus making extensive use of the experience gathered in that previous study.

The study by Boult (2000) is an example QRA for the LPG logistic chain into and out of a port area, much in the style of the *LPG Study*.

Quantitative risk analysis techniques, as well as other forms of risk assessment, have seldom been used with container terminals, warehouses and other temporal storage areas. Rigas & Sklavounos (2002) give an example of risk analysis for port marshalling yards and warehouses. However, they overlook the topic of accident frequencies. The authors consider four different accident scenarios: ethylene oxide BLEVE, toxic dispersion and UVCE and toxic dispersion from a pesticide fire. Royal Haskoning (2003) carried out a complete QRA for a projected container terminal. This study, however, is not satisfactory, because it only covers few hazards among several possible accident scenarios expected in such a complex setting as a container terminal. Temporal storage poses an important challenge to risk analysis. The inventory and placement of dangerous goods in these areas are not fixed. They are instead subject to continual change. This makes it difficult to describe them by way of classic QRA and other methods based on the identification of relevant accident scenarios. Moreover, to our knowledge, there is a generalised legislative gap regarding these settings, which, however, are gaining more and more importance as a result of the exponential growth of container transportation. In our opinion, it is possible to satisfactorily deal with temporal HazMat storage sites by using other risk assessment methodologies, like risk indexing/ranking.[15]

The present thesis contains two contributions focused on QRA, i.e. Papers 4 and 5. The former, titled “A Quantitative Risk Analysis Approach to Port Hydrocarbon Logistics” (Ronza *et al.*, 2006-1) summarises the main findings of the major-accident section of a project called FLEXRIS,[16] which was carried out in 2003-2004. The principal aim of this project was to develop a method to valuate, from the economic point of view, the consequences of HazMat handling in port premises. In order to devise and demonstrate the method, a pilot study was carried out on the facilities of the Port of Barcelona. The scope of the study was restricted to hydrocarbon logistics, that is to say the transportation of oil products –including LPG– plus liquefied natural gas to/from berths and jetties, as well as the (un)loading operations of those products to/from tankers. While a research team focused on long-run ecological risk (Centre Tecnològic de Manresa, 2004), another (Arnaldos *et al.*, 2004) concentrated on accidental risk. A third team (González *et al.*, 2004) collected the results of the two former and translated them into monetary units. The major-accident study (Arnaldos *et al.*, 2004) generated the above mentioned *Journal of Hazardous Materials* article and its results were also reported at an international congress (de Pablo *et al.*, 2005). This study is an attempt at defining, in a standardised way, a consistent methodology to perform the quantitative risk assessment of port milieus, as regards maritime energetic hydrocarbon transportation and (un)loading operations. One of the major contributions of the paper is a structured scheme to predict the frequencies of tanker accidents, which is based on the possibility of a tanker being struck while at berth/during navigation, striking another vessel or grounding. The study puts forth two different methodologies for punctual accident events (accidents that occur while the vessel is at berth and (un)loading spills) and “linear” accident events (accidents that occur while the vessel is in route to/from the berth).

Paper 4 also contains a shortcut to predict the number of injured people based on the number of fatal victims. This shortcut, specifically devised for port quantitative risk assessment, helps estimate the number of injured victims without further calculations than those needed for determining the number of fatalities. QRA sometimes poses the problem of finding the number of non-fatal victims. The standard way to solve the problem is to apply vulnerability analysis. Vulnerability equations are empirical relations that link the effects of accidents (thermal radiation, overpressure, toxic concentration) with the probability that a certain receptor suffers a certain consequence, via a probit function. The receptor can be a human individual or an object, like a structure or some piece of equipment. In the case the receptor is a person, the consequence examined can be either death or some kind of injury. For example, given an explosion whose overpressure is 1200 mbar at a certain location, it is possible to estimate that the probability that an individual dies because of pulmonary haemorrhage

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[15] However, we have not found in the literature any such method specifically designed for container terminals. This could be an interesting line of research for the future.

[16] Acronym for “Nueva metodología Flexible para la valoración económica de los Riesgos ambientales – Aplicación a la logística de hidrocarburos en el Port de Barcelona” (New Flexible methodology for the economic valuation of Environmental risks – A case study: the logistics of energetic hydrocarbons at the Port of Barcelona).

is 10% and the probability that he or she suffers ear drum damage is 59% (Casal *et al.*, 1999). The probit calculation of the number of injured people can be tedious. The analyst can deem excessive the effort required, especially if only a rough approximation is needed, as it often happens. The goal of the quick method presented by Ronza *et al.* (2006-1) is precisely a way to help estimate the number of injured people bypassing the cumbersome probit calculations. The shortcut scheme is based on the historical analysis of the port accidents considered in previous research (Darbra *et al.*, 2005).

The topic of the relationship between the number of fatal and non-fatal casualties of major accidents is further developed in Paper 5 of this thesis (Ronza *et al.*, 2006-2). This paper is not focused on port/maritime milieus alone, but on accidents at large. The article reports the results of statistical research carried out on a large accident sample retrieved from the MHIDAS databases by way of techniques such as principal component analysis and data clustering, among others. A simple correlation was found that estimates the mean number of injured people as a function of the number of fatal victims.

b. Formal Safety Assessment. In 1997 the IMO introduced a new scheme that is gaining importance year after year: the Formal Safety Assessment. FSA represents an important attempt to spread risk assessment practice in the maritime area. IMO (n.d.) defines FSA as a “way of ensuring that action is taken before a disaster occurs”. In IMO’s words, FSA is “a systematic process for assessing the risks associated with shipping activity and for evaluating the costs and benefits of IMO’s options for reducing these risks”.

FSA can be used as a tool to help evaluate new regulations or to compare proposed changes with existing standards. It enables to draw a balance between various technical and operational issues, including the human element and between safety and costs. FSA, which was originally developed as a response to the Piper Alpha disaster of 1988,[17] is now being applied to the IMO rule making process. Interim guidelines were adopted in 1997 and IMO Member States have been invited to carry out trials and report back to IMO.

FSA consists of five steps:

1) Identification of hazards, i.e. preparing a list of all relevant accident scenarios with their respective causes and outcomes;
2) Assessment of risks, i.e. evaluation of risk factors;
3) Risk control options, i.e. devising regulatory measures to control and reduce the identified risks;
4) Cost benefit assessment, i.e. determining cost effectiveness of each risk control option; and
5) Recommendations for decision-making, i.e. defining a decision strategy based on the results obtained in the previous steps.

Application of FSA can be relevant in the case of proposals for regulatory measures that have broad implications in terms of costs or imply administrative and

[17] When an offshore platform exploded in the North Sea causing 167 fatal victims.

legislative burdens. The basic goal of FSA is to facilitate a transparent decision-making process. In addition, FSA provides a means of being proactive, enabling the interested parties to consider potential hazards before a serious accident occurs. In IMO's intentions, FSA represents a fundamental change from what was previously a largely piecemeal and reactive regulatory approach to one that is proactive, integrated, and above all based on risk evaluation and management in a transparent and justifiable manner, thereby encouraging greater compliance with the maritime regulatory framework. Overall, FSA is an attempt at standardise, formalise, and regulate worldwide the practice of risk assessment of marine facilities, especially sea-going vessels and offshore platforms. FSA shares with QRA the overall goal of defining the levels of risk for a given system thus providing a means for decision making. However, QRA is not the same thing as QRA. In fact, it normally makes use of simplified risk matrices (see section 2.2.4) instead of a full risk estimation algorithm based on consequence calculation. FSA is relatively recent and IMO has not yet provided definite guidelines for its application.

One area where FSA is already being applied is bulk carrier safety. The SEALOC project (SEALOC Consortium, 1998) represents and early attempt of implementing an FSA at large scale. The case studies included in this EC-funded project cover maritime transport of crude oil, LPG and containerised dangerous cargo to and from European ports.

Trbojevic & Carr (2000) (see also Trbojevic & Carr, 2001) advance a further proposal for a hazard identification method in ports in the framework of the FSA. This scheme and the SEALOC are based on risk matrices. The authors demonstrate a way to design a port safety management system based on FSA.

Skjong (2003) discusses IMO's viewpoint on FSA. Wang (2001 and 2002) demonstrates some procedures used to apply FSA on ships and offshore installations in the UK. An interesting approach to FSA in ports is the safety report commissioned by the Port of London Authority (Leedham & Riding, 2001). The project was made necessary to comply with the UK's Port Marine Safety Code, but the analysts chose to follow almost entirely the FSA method (only cost benefit analysis was discarded).

c. The *Risk-based Decision-making Guidelines*. The United States Coast Guard has recently shown a great interest in risk analysis techniques and accidental risk prevention and has developed several solutions and tools for risk analysis and management. The scope of such tools is maritime accidents in general, with occasional focus on port accidents. The USCG allows for HazMat transportation in several of the methodologies presented, but dangerous goods are not necessarily the specific target of USCG's methods.

The milestone summing up USCG's work in this field are the *Risk-based Decision-making Guidelines*, a sort of comprehensive handbook collecting the information generated by the diverse Marine Safety Offices around the US since 1997 (USCG Research & Development Center, 2001). As Garrick (1999) stresses, this work involved a great effort to adapt the standard techniques of risk analysis to port areas (or, in general, maritime and coastal environments), only comparable to the program of Formal Safety Assessment introduced by the IMO (see below) and the risk assessment for Prince William Sound (where the stranding of the "Exxon Valdez" took place; see section 2.1.1.f). The *Guidelines* are made up of 3 volumes:

- Vol. 1 (Risk-based Decision-making Navigator) is an index of the following two, and includes a didactic and methodological introduction to the text.
- Vol. 2 (Introduction to Risk-based Decision Making) describes the principles of risk-based decision making and of risk evaluation, management and communication.
- Vol. 3 (Procedures for Assessing Risks) describes the following risk assessment tools, which are mainly derived from the standard techniques used in the process industry:
    a) Pareto analysis;
    b) Checklists;
    c) Relative ranking and risk indexing;
    d) Preliminary risk analysis (PrRA);
    e) Change analysis;
    f) What-if analysis;
    g) FMEA;
    h) HazOp;
    i) Fault trees (FTA);
    j) Event trees (ETA);
    k) Event and causal factor charting;
    l) Preliminary hazard analysis (PrHA).

According to the USCG, the approach of the *RBDM Guidelines* is one that offers to the Marine Safety Offices (MSOs) a complete, reliable and easy to use toolbox, so that they can carry out their own projects in the field of risk assessment, management and evaluation. As said above, the notion of risk on which the *Guidelines* are based is relatively wide and involves not only hazardous cargo, but also unexpected events causing harm to people, installations and the environment.

Several of the techniques presented in the *RBDM Guidelines*, because of their high logical formalisation and intrinsic need to be implemented on well defined systems (as the ones of process industry), cannot be adapted to such complex (and fuzzy) environments as ports considered in their entirety. Such is the case of HazOp, FMEA and fault tree analyses; the examples presented in the text and the practical applications by the USCG (Walker, 2000-1; Walker, 2000-2; ABS Group, Inc., 1999; Guthrie, 2000) are focused on small systems found in port environments. The report by Walker (2000-1), for instance, includes an attempt to apply HazOp to small (un)loading hydrocarbon terminals for barges.

Macesker *et al.* (n.d.) give a complete account of the implementation of the *Guidelines* by the Marine Safety Offices. More papers regarding the *Guidelines* can be found on the journal-newsletter *Proceedings of the Marine Safety and Security Council* (n.d.).

The PrRa (Preliminary Hazard Analysis) is a semi-quantitative technique incorporating some features of a standard risk index. It is based on the HazOp process. In the framework of this methodology, three levels are defined for accidental consequences (minor, moderate, major). Accident severity is measured by economic impact. Three frequencies are assigned to accidental scenarios, one for each level of

Table 2.10. Pattern suggested for frequency scoring in the PrRA technique (USCG Research & Development Center, 2001).

Frequency description	Frequency value (yr^{-1})	Score
Continuous	$> 10^2$	8
Very frequent	$10^1 < f < 10^2$	7
Frequent	$10^0 < f < 10^1$	6
Occasional	$10^{-1} < f < 10^0$	5
Probable	$10^{-2} < f < 10^{-1}$	4
Improbable	$10^{-3} < f < 10^{-2}$	3
Rare	$10^{-4} < f < 10^{-3}$	2
Remote	$10^{-5} < f < 10^{-4}$	1
Incredible	$< 10^{-5}$	0

Table 2.11. Pattern suggested for defining and scoring consequences in the PrRA technique (USCG Research & Development Center, 2001).

Severity	Safety impact	Environmental impact	Economic impact
Major	One or more deaths or permanent disability	Releases that result in long-term disruption of the ecosystem or long-term exposure to chronic health risks	≥ US$ 3×10^6
Moderate	Injury that requires hospitalisation or lost work days	Releases that result in short-term disruption of the ecosystem	< US$ 3×10^6 ≥ US$ 10×10^3
Minor	Injury that requires first aid	Pollution with minimal acute environmental or public health impact	< US$ 10×10^3 ≥ US$ 100

severity; the frequencies are then given a score between 0 and 8. The recommended patterns for frequency scoring and the definition of the levels of severity are shown in Table 2.10 and Table 2.11. A short account of some practical applications of the PrRA is given by Macesker (1999). He describes in particular a PrRA based on several risk indices characterising harbour operations. Even though the paper does not provide a satisfactory account of the tool, it is evident that the indices are based on an economic measure of the risk.

2.2.4 Risk indices and ranking

Risk indexing expresses the level of risk associated with a plant or an installation. Nevertheless, the scope of an index can be other than establishments, facilities, building and machinery. For instance, there are indices describing the inherent hazards of substances, reacting systems, etc.

Risk indexing first appeared as a risk assessment technique in the chemical industry. The first important index to be proposed and used was the Dow Chemical Company's Fire and Explosion Index, which was originally published in 1964 and has since gone through seven editions. The most recent one was published in 1994 (Dow Chemical Company, 1994). The Dow Index was introduced into safety audits for the purpose of insurance premium rating (see Velasco, 2005, for an original application of this index to the loading/unloading of liquefied gas tankers). The Mond index was likewise developed for the insurance industry at the end of the 1970s. Another important ranking technique has recently been proposed in the frame of the European project ARAMIS (Planas *et al.*, 2004-1; Planas *et al.*, 2004-2).

Rosenblum & Lapp (1987) give an enthusiastic account of risk indexing practice in the chemical industry. As early as 20 years ago, this technique had already gained a

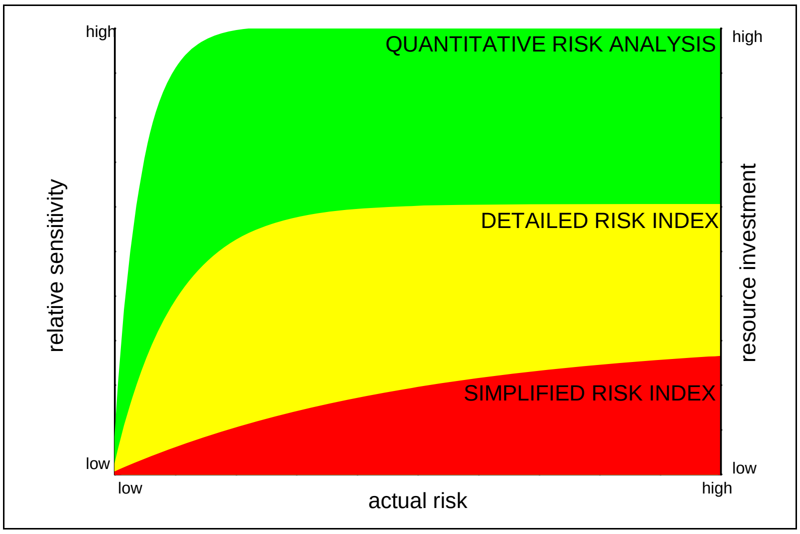

Fig. 2.11. Relative sensitivity (responsiveness to actual risk variations) of risk indexing vs. QRA methods (Rosenblum & Lapp, 1987).

widespread acceptance as a cost-effective prioritisation and screening tool for risk assessment programmes. From a simplistic point of view, it can be said that risk indexing is the same as quantitative risk assessment, in that both approaches are intended to describe the level of risk of a certain object/system (be it a plant, a process unit or a chemical). Whereas QRA expresses risk in proper units of measurement (e.g. expected number of casualties per year) and is a deterministic methodology, risk index provides only a ranking (that is a value to be compared with those previously calculated for other plants/units) and is essentially based on expert judgement. The ranking is generally expressed by way of a dimensionless number, which is normally provided a verbal translation by way of verbal assessments such as “unacceptable”, “tolerable”, “negligible”, etc. Risk indexing is not a substitute for a detailed risk analysis, but it is probably the best assessment tool at the stage of planning, screening and ranking priorities.

A risk index may be more or less complex. Generally, the more complex the index, the more aspects related to a plant or installation are taken into account, and the “better” the device. An index demonstrates good performance when it has a good sensitivity to the presence of safety systems. While using a risk index may be very cost-effective in comparison with turning to a QRA, a risk indexing algorithm has to be sufficiently well structured and representative of the system for which it has been devised: using a very simplified method could lead to significant errors in the decision making (see Fig. 2.11).

As it has been briefly stated above, there is another difference between risk indexing and QRA. Although risk indexing was first introduced as a means of evaluating *plant and unit* hazards (like QRA), it was soon understood that it was a much more adaptable tool. So, in the course of the last decades, a number of indices have been published, describing the inherent risk/hazard of chemical substances, runaway reacting systems, environmental hazards, etc.

A section of the *RBDM Guidelines* (USCG Research & Development Center, 2001, vol. 3, chapter 5; see section 2.2.3) describes risk indexing and ranking techniques. USCG’s intention is to provide MSOs with practical, not necessarily very original and/or elaborate tools. Thus, risk indexing is presented above all as a form of prioritisation. Assigning a risk index is describing numerically the risk inherent to an installation, vessel. Risk indices, above all, must make decision making easier. The essential features of this risk indexing are the following:

- Risk indices are conceived based on expert judgement.
- An index is normally devised by a group of experts instead of a single individual.
- The process of designing an index can involve interviews, brainstorming, lists of past accidents, bibliography and on-site inspections.

The basic steps to take when using a risk index, as described by the *RBDM Guidelines*, are:

a) Define the scope of the study;

b) Select a prioritisation (ranking) method;

c) Gather the data needed to run the tool;

d) Calculate the indices;

e) Use the results in the decision making process.

The crucial step is obviously the selection of the ranking method, which defines the structure of the index and its practical effectiveness. According to the USCG, the risk analyst can resort to a USCG-designed method,[18] or to other existing methodologies, such as Dow's Fire and Explosion Index, or devise a custom risk index.

Of all, the latter is the most daring option. However, in certain situations, it may be the only viable one, because the existing methodologies cannot be adapted to the scope of the study. The *Guidelines* describe the process of defining an effective risk index in the following fashion:

1) Define what the index is supposed to represent: its scope may be limited to the frequencies of certain accidental events, or to their consequences, or rather to their risk (frequency × consequences).
2) Identify a list of factors that affect the value of the index, through historical analysis, expert judgement and/or by the study of technical literature.
3) Identify specific situations that require special actions, i.e. those situations in which the index shall represent the maximum risk.
4) Characterise the sensitivity and selectivity for each factor; this, together with step 2), is the most critical in designing the index; expert judgement, comparison with reference points and statistical assessments must be used carefully in order to optimise this step.
5) Select a ranking algorithm (multiplicative, additive, etc.).
6) Develop ranking scales for each factor, based on the sensitivity and selectivity of the factors.
7) Select action thresholds for the index.

[18] Examples: the Foreign Vessel Targeting Matrix (Fig. 2.15), the Ports and Waterways Safety Assessment (The George Washington University – Institute for Crisis and Disaster Management, 1996), the Waterway Evaluation Tool (Volpe National Transportation Systems Center – Economic Analysis Division (1997).

8) Organise the scoring scales, index calculations and action thresholds into a job aid (spreadsheets, checklists, etc.).
9) Validate the methodology and the job aid through test applications, obtain views from experts and test the method through historical data.

Several risk ranking techniques will be described below. Such schemes can be regarded as both PrRAs and ranking methods. Studies are presented in chronological order.

Marí (1991) introduces a risk prioritisation method for fires onboard vessels, based on historical analysis. He carries out a correspondence analysis to rank several risk factors like number of crew, classification society, etc.

Rao & Raghavan (1996) introduce the issue of the identification and quantification of risk in port environments referring to some tools used by the USCG. The authors report analytical formulae to calculate diverse indices. They do not quote their source, which is actually a paper by Luckritz & Schneider (1980), who in turn makes a reference to Danahy & Gathy (1973), who were the first to introduce the Equivalent Safety Concept (ESC; see below). The equations are fairly simple and immediate. The aim of the method is estimating the dangerousness of a certain cargo entering a port by way of a Transportation Index (TI). TI is a function of the inherent hazard of the substance transported and the vessel that transports it:

$$\mathrm{TI} = \frac{\mathrm{CI}}{\mathrm{VI}} \quad [2.6]$$

where CI is a Cargo Index and VI is a Vessel Index. The higher CI the more dangerous the substance transported; the higher VI, the safer the vessel. Therefore, a high TI means serious hazard.

The equation defining CI depends on whether the hazard of a substance is toxicity or flammability. CI depends only on the properties of the transported materials:

$$\mathrm{CI} = \begin{cases} 10K_1\sqrt{\rho_\mathrm{v}\cdot\dfrac{T_\mathrm{amb}}{T_\mathrm{BP}}\cdot\dfrac{1}{\mathrm{TLV}}} & \text{(toxic cargo)} \\ \dfrac{K_1K_2}{2}\sqrt{\dfrac{\mathrm{UFL-LFL}}{\mathrm{LFL}}\quad\rho_\mathrm{v}\quad\dfrac{T_\mathrm{amb}}{T_\mathrm{BP}}} & \text{(flammable cargo)} \end{cases} \quad [2.7]$$

where:

- K_1 is defined by the following equation

$$K_1 = 3\left(1 - e^{-\frac{P_\mathrm{v}}{20}}\right) \quad [2.8]$$

- P_v = Reid vapour pressure (Pa).
- ρ_v = vapour density (non dimensional; air =1).
- T_amb = ambient temperature (K).
- T_BP = boiling point (K).

- TLV = Threshold Limit Value (ppmv), as established for each by the American Conference of Governmental and Hygienists.
- UFL = upper flammability limit ($\%_{vol}$).
- LFL = lower flammability limit ($\%_{vol}$).
- K_2 is defined by the following equation

$$K_2 = 0.1\left(10 - e^{-\frac{500}{T_{AI}}}\right) \quad [2.9]$$

- T_{AI} = auto-ignition temperature (ºC).

VI measures ship safety. It is a calculation of the relative ability of a vessel to contain the cargo and minimize or avoid damage:

$$\text{VI} = K\,\frac{F_1}{F_2 F_3} \quad [2.10]$$

where:

- K is a scale function.
- F_1 measures the safety of the ship structure (double bottom, ship stability, etc.).
- F_2 is a capacity factor.
- F_3 depends on the vessel's size , turning factor, etc.

A fourth index (PSI, Port Safety Index) is finally introduced. PSI describes the safety conditions of a port and the vulnerability of its surroundings. Contrary to its name, the higher the PSI, the greater risk. Three multiplicative factors define PSI. They are related to the physical and topological features of the port (width of waterways, corners to be covered, etc.) and the population and logistic/industrial activity density in the port and its context:

$$\text{PSI} = 10^{-5}\,T S_1 S_2 \quad [2.11]$$

$$S_1 = 3\sqrt{\frac{1}{V} + \frac{100}{W} + \frac{500}{R} + \frac{10}{d} + \frac{n^3}{3} + \frac{V_k^2\theta}{5}} \quad [2.12]$$

$$S_2 = \frac{4P_1 + P_2 + P_3 + P_4}{5000} + A + C \quad [2.13]$$

where:

- T = traffic density (tonnes/month).
- V = unobstructed line of sight (m).
- W = channel width (m).
- R = channel radius of turn (m).
- d = distance from side of channel to solid obstruction (m).

- n = number of channel junctions and river crossings.
- V_k = maximum water current (km/h).
- θ = angle of current measured from channel axis (rad).
- P_1, P_2, P_3 = fixed population densities (people/km^2) at different distances from the waterway.
- P_4 = mobile population density (vehicles/km^2).
- A = public/commercial activities within 3 km (people/km^2).
- C = industrial activities within 3 km (people/km^2).

In order to evaluate whether a ship transporting certain products needs specific control measures, TI has to be compared with PSI: if the latter is higher than the former, a ship call is considered safe, otherwise special safety measures have to be taken.

The indices described by Luckritz and Schneider (1980) are related to navigational aspects alone. Moreover, the scope is not the port in itself, but the relation between vessels transporting hazardous materials and port of calling. The aspects allowed for are the properties of the cargo, the vessel characteristics, traffic density, geometric features of the waterways, current speed and population density in areas close to the harbour.

In a report by the Institute for Crisis and Disaster Management (The George Washington University – Institute for Crisis and Disaster Management, 1996), prepared for the USCG, an interesting list of variables is proposed, on which to base vessel and port risk assessment, in the frame of the so-called Ports and Waterways Safety Assessment. This list can be used also for risk indexing. A first list, focused on vessels, is displayed in Table 2.12. The variables are the same as in the Foreign Vessel Targeting Matrix (USCG, 1982), which will be referred to later on. The second list (Table 2.13) is about port features.

In diverse works by Hauke Kite-Powell (Kite-Powell *et al.*, 1997; Kite-Powell *et al.*, 1998; Kite-Powell *et al.*, 1999) a Bayesian model is formulated to estimate the physical risk of grounding during transits into and out of port as a function of potential risk factors. Information on groundings in three US ports between 1981 and 1995 is assembled and analysed. Although the data are far from perfect, associations are established between grounding risk and changes in factors such as vessel type and size, wind speed, and visibility. Authors affirm that groundings of commercial ships account for about one third of all commercial maritime accidents. Their intention is to calculate, through the cited Bayesian model, the probability of an accident as a function of several factors, the relative importance of which must be determined based on historical analysis. It is interesting to have a look at the variables that the model uses:

- Vessel characteristics (draft, beam, manoeuvrability);
- Topography of the waterway (water depth, channel width, channel length, complexity of turns, traffic density);
- Environmental conditions (wind, visibility, currents, waves);
- Operators (experience with the vessel, training, local knowledge);
- Information available to operators (quality of charts, quality of information about tide levels and currents, VTS guidance, navigation aids).

Table 2.12. List of variables influencing vessel accident risk (The George Washington University – Institute for Crisis and Disaster Management, 1996).

Variable	Typical values
Vessel type	Deep draft calling fleet Passenger vessels Tank vessels Container vessels Bulk cargo vessels Special purpose vessels Other Shallow draft transit fleet Tugs with tows Line haul tows Fishing vessels River/inland passenger vessels Other Shallow draft local fleet Ferries Excursion boats Gambling boats Other
Vessel age	0 ÷ 15 years 15 ÷ 25 years > 25 years
Classification society	IACS member IACS associate member Not classed by recognised classification society
Pilot	Pilot on board More than one pilot on board No pilot on board
Flag	US/Canadian/traditional maritime Flag of convenience Targeted flag
Management changes	No changes in owner, flag or class society within 3 years Change in either owner, flag or class society within 3 years Frequent changes or targeted owner/operator
Vessel violation/incident history	No violation or casualties within 3 years Minor violation or incidents within 3 years Repeated minor or recent major incident or violation

In order to produce the model, a historical analysis was carried out on five US port areas (San Francisco, Houston/Galveston, Tampa, New York, and Boston). Grounding data were retrieved from USCG's databases (MSIS above all). Vessels are roughly divided into two groups: "large" (draft > 30 ft) and "small" ones (draft < 30 ft). Barge trains are considered apart. The data were used to draw a distribution of explanatory factors, but this was not satisfactory. Quantitative weights were not assigned to the risk factors while several qualitative remarks arose from historical analysis:

- On vessel type and size: barge trains are more likely to ground than ships; large ships are more likely to ground than small ones.
- Wind speed has apparently no significant effect on grounding probability; however historical analysis may be perturbed by port closures (during high winds port are closed and no accident is recorded in those periods).
- Lack of visibility increases grounding risk in a clearer way than high winds.

Table 2.13. List of port- and waterway-dependent variables influencing accidental risk (The George Washington University – Institute for Crisis and Disaster Management, 1996).

Variable	Typical values
Waterway configuration	Open (fairway with good water on both sides) Restricted (shallow water or hazard near the marked channel) Converging (multiple channels that meet or cross)
Visibility	Good Adequate Restricted/rapidly changing
Wind	Light Bothersome Difficult (rapidly changing or high)
Current	None Low Difficult (rapidly changing or high)
Traffic situation	Single vessel Simple situation (meeting, overtaking) Complex situation (multiple vessels crossing/passing)
Traffic density	No vessel within 0.5 miles One vessel within 0.5 miles Multiple vessels within 0.5 miles

The authors express criticism about of the databases used (see also Paper 3 of this thesis).

Another study on waterway risk prioritisation is presented by Nally (1998), who ranked 33 waterways of southeast Alaska according to their commercial importance, environmental value and navigational difficulties. The ranking is based on a questionnaire handed out to 368 experts and/or waterway users, the results of which are arithmetically averaged for each of the 33 waterways considered. The methodology does not entail mathematical complications. The questionnaire was a concise checklist, made up of 26 questions, whose answer was to be chosen among four score levels. The waterway ranking is derived from the checklist through a simple additive process. The scope of this study, although not focused on open sea navigation, is not strictly centred on port settings, but rather on vast and particularly problematic navigable areas, characterised by straits, small islands and a broken coastline.

A common use of the prioritising technique described in the *RBDM Guidelines* is the classification of foreign (i.e. non-US flagged) vessels, for the prioritisation of the operations of boarding and inspection. A report focused on vessel inspection prioritisation was produced by EQE International, Inc. (2000). This study introduces a new form of ranking, slightly different from a previous one, used since the beginning of the 1980s (USCG, 1982). The method is consistent with the *RBDM Guidelines* recommendations.

Thomas (1999) presents diverse risk assessment tools in use at Jacksonville harbour (Florida), which are based on the strategies outlined in the *Guidelines*:

- Three indices are used to measure the inherent risk of vessels: the Inherent Risk Factor (IRF), the Discrepancy Risk Factor (DRF) and the Crew Drill Score (CDS). The IRF represents intrinsic vessel features, the DRF is calculated based on the regulatory discrepancies established after checking the safety conditions of the vessel, while the CDS describes the level of risk prevention training and awareness in the crew.
- The three indices are combined to give the Vessel Risk Factor (VRF):

$$\mathrm{VRF} = 0.25\,\mathrm{IRF} + 0.5\,\mathrm{DRF} + 0.25\mathrm{CDS} \qquad [2.14]$$

- In the same way, for each port installation (loading arm, crane, jetty, etc.) a specific risk index is defined, as linear combination of three sub-indices depending on the characteristics of the installation, based on the results of the yearly installation audit and on the responsible personnel.
- Also, a Port Activity Risk Index is introduced (although in a descriptive way), which is a function of the activities carried out in a harbour during a certain week.

The paper by Thomas does not contain detailed insights into the mathematical definition of the indices. However, it is interesting to observe what groups of variables are considered, and the fact that, at least in the case of the VRF, compliance with the safety checklist is weighted twice as much as inherent vessel features and crew training/awareness.

A better description of the Port Activity Risk Index (PARI) is found in Hartley (1999). This tool is in fact an adaptation of the one proposed by Thomas (1999), and was used in the port of Los Angeles/Long Beach in order to define the level of risk associated with the daily activity of the port. The index is based on 16 risk factors that were decided in a brainstorming session. Among them, one can find the number of vessel movements, weather conditions and the status of navigational aids (buoys, lighthouses, etc.). A complete account of the 16 factors is actually missing, but it is evident that they are not related to the intrinsic features of the port, since the PARI is not intended to be a tool for comparing of ports among them, but for a quick risk assessment of the activity of one port during a certain day. A partial list of the risk factors is displayed in Table 2.14.

The author states that the expert board also agreed on a scoring scheme for the index; in fact, the PARI is nothing but the sum of all the values assigned to each risk factor, according to semi-quantitative relations (some of which are shown in Table 2.14). Its value can vary between 0 and 160.

Schoolcraft (2000), in a report prepared for the USCG, describes a ranking of navigable areas around the Florida Panhandle (northwest Florida), aimed at planning actions in the field of hydrocarbon spill prevention. As found in Nally (1998), the scope of the study is neither ports, nor open sea, but coastal waters. The approach is simple and based on opinions from a 10-member expert panel. After deciding on a suitable division of the area analysed into 12 “districts” for prioritising purposes, six risk factors were proposed during a brainstorming session, to each of which a score was assigned between 0 and 100. Then, by turning to a software for expert opinion analysis (the DECIDE), a weight was established for each factor. Again, the ranking index is obtained by summation (= Σ(factor value) $\times$ (factor weight)). The list of prioritising factors, as well as their relative weight, are shown in Table 2.15.

A prioritisation of risk factors for ports is presented in several studies by the George Washington University for the USCG (Harrald & Merrick, 2000; The George Washington University – Institute for Crisis and Disaster Management, 1998-1; The George Washington University – Institute for Crisis and Disaster Management, 1998-2). In this case the ranking is a step prior to a decision making process about the choice of vessel traffic systems (VTS) for US ports. The authors introduce six factors influencing accidental risk in ports and waterways. Four of them (composition of calling fleet,

Table 2.14. Structure of the Port Activity Risk Index: list of some risk factors with their scoring scale (Hartley, 1999).

Risk factor	Possible values	Weight
Number of vessels due to arrive	0 ÷ 5	1
	6 ÷ 12	2
	13 ÷ 20	3
	> 20	5
Number of vessels due to depart	0 ÷ 5	1
	6 ÷ 12	2
	13 ÷ 20	3
	> 20	5
Number of vessels due to arrive under deviation	1	1
	2	2
	3	3
	> 3	4
Cruise ship activity (day of week)	Other	0
	Sunday	1
	Monday and Friday	3
	Monday and Friday, with additional traffic	5
Forecasted wind (knots)	5 ÷ 10	2
	11 ÷ 25	6
	26 ÷ 40	4
	> 40	8
Forecasted visibility (nautical miles)	2 ÷ 5	2
	1 ÷ 2	4
	0.5 ÷ 1	6
	< 0.5	8
Special operations	No impact on channel/traffic	1
	Minor impact	3
	Medium impact	5
	Significant impact	8
Forecasted sea state	1 ÷ 3	1
	3 ÷ 5	2
	5 ÷ 10	3
	> 10	4
Vessel radar/tracking equipment status	...	
Conditions of navigational aids (buoys, etc.)	...	

Table 2.15. List of risk factors and their respective weight (Schoolcraft, 2000).

Risk factor	Possible values	Weight
Exposition	Level of hazardous material/petroleum spill exposure based on the combination of the volume of HazMat transiting the area, as well as the number of HazMat/petroleum transfer operations conducted in the given subdivision	10
Natural resource sensitivity	Credible damage potential to natural resources based on the hazards associated with the expected spill profile and the actual presence of sensitive natural resource receptors	10
Socio-economic sensitivity	Credible industry impact potential (tourism, fishing, etc.) based on the wide range of consequences associated with the expected spill profile	10
Known risk factors	Presence of factors significantly increasing risk (such as navigation difficulties, emergency response inhibitors, unfavourable river/sea state conditions, etc.)	20
History	Frequency of accidents that (could) have caused medium or large spills	30
Health/safety sensitivity	Annual frequency of reported incidents that caused (or could have caused) major or moderate spills	20

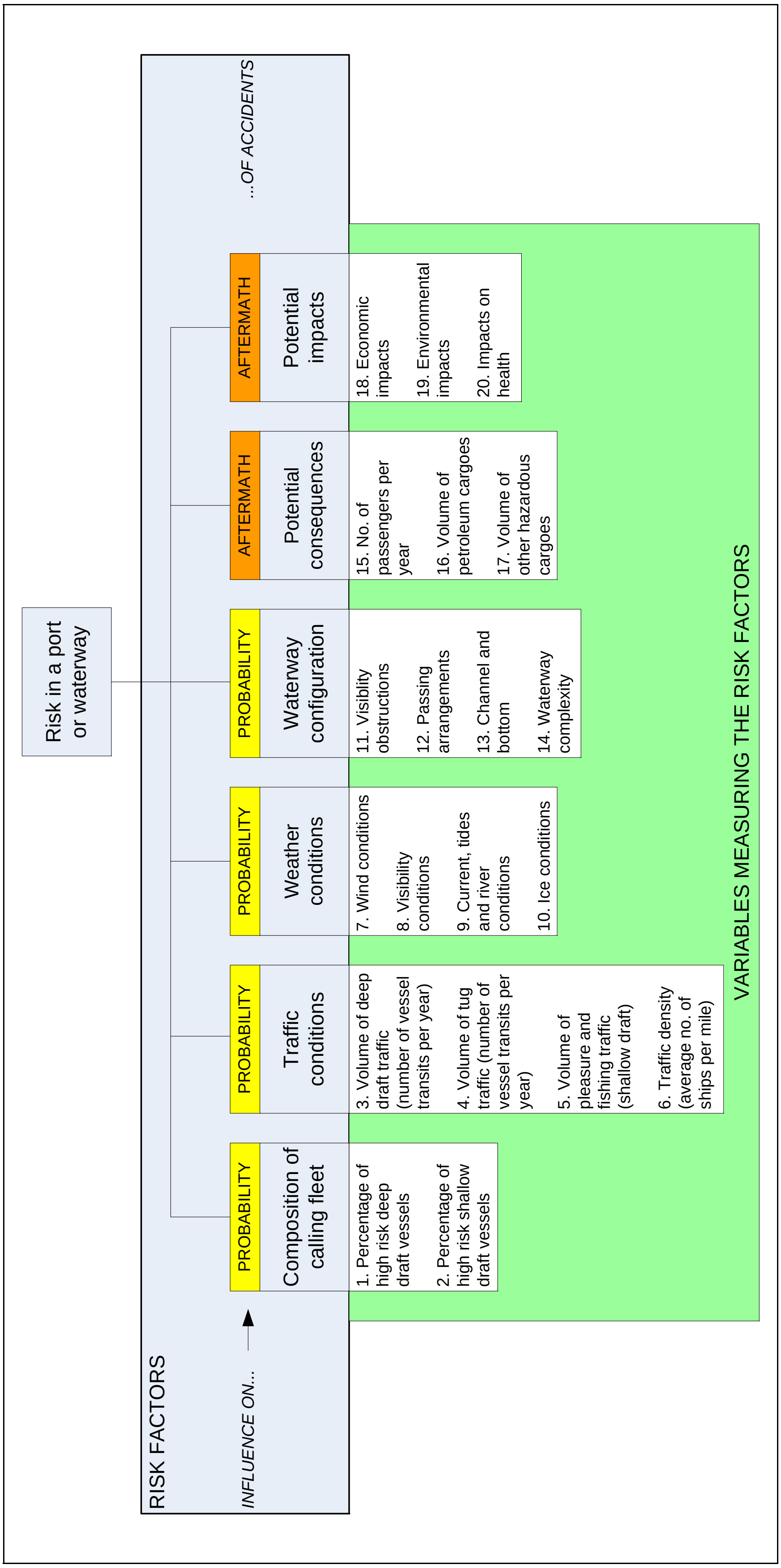

Fig. 2.12. Risk factors prioritised by Harrald & Merrick (2000).

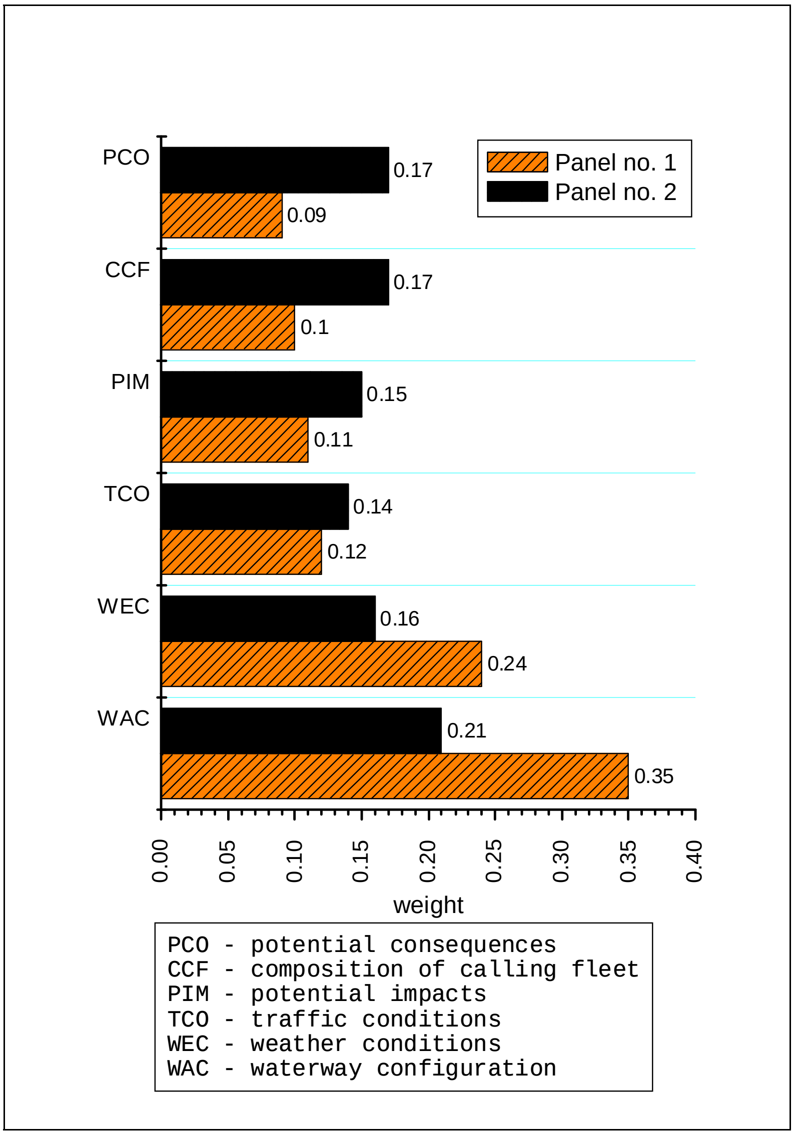

Fig. 2.13. Results of the inquiry on risk factors (Harrald & Merrick, 2000; The George Washington University – Institute for Crisis and Disaster Management, 1998-2).

traffic conditions, weather conditions, waterway configuration) influence the probability of accidental events, the other two (potential consequences, potential impacts)[19] affect their aftermath. There is no evidence as to how such variables were chosen or the respective sub-factors were selected. The set of risk factors, and of the sub-factors that "measure" them, is shown in Fig. 2.12.[20]

The approach used to establish the weights for each factor is based on the use of expert panels. Its essential steps are the following:

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[19] The authors refer to the physical effects of the accidents as *consequences*, and to the economic and environmental repercussions as *impacts*.

[20] A seventh factor, the historical frequency of accidents, which is present in the original version of Fig. 2.12, is subsequently abandoned by the authors (Harrald and Merrick, 2000).

- The best and the worst level were established for each risk factor, according to the actual situation in US ports.
- All possible pairs of risk factors were compared, through the elicitation technique and the application of software for expert opinion analysis, thus obtaining relative weights for each factor.
- In the same fashion, the weight attributed to each factor was then subdivided into additive sub-weights (one for each measuring variable of Fig. 2.12).

This procedure was accomplished with two different expert panels; both panels were made up of experienced personnel, but one (15 officers, some of whom from the USCG) proceeded from various ports, while the other (12 port employees) was entirely from Hampton Roads harbour (Virginia). The results of the analysis are shown in Fig. 2.13 and Fig. 2.14.

It is clear that the results provided have a strong dependence on the panel that helped infer them. This is a partial proof that the method used to identify the weights is not completely reliable, even though the authors state that much better outcomes would arise from an inquiry based on a larger and more homogeneous panel. The discrepancy between the boards is likely to be attributable to the difference in their inherent composition: while panel no. 1 proceeded from several ports and organisations, panel no. 2 belonged in its entirety to the personnel of one port only. Therefore, it is probable that the latter answered the questionnaire referring to the features of that harbour. While

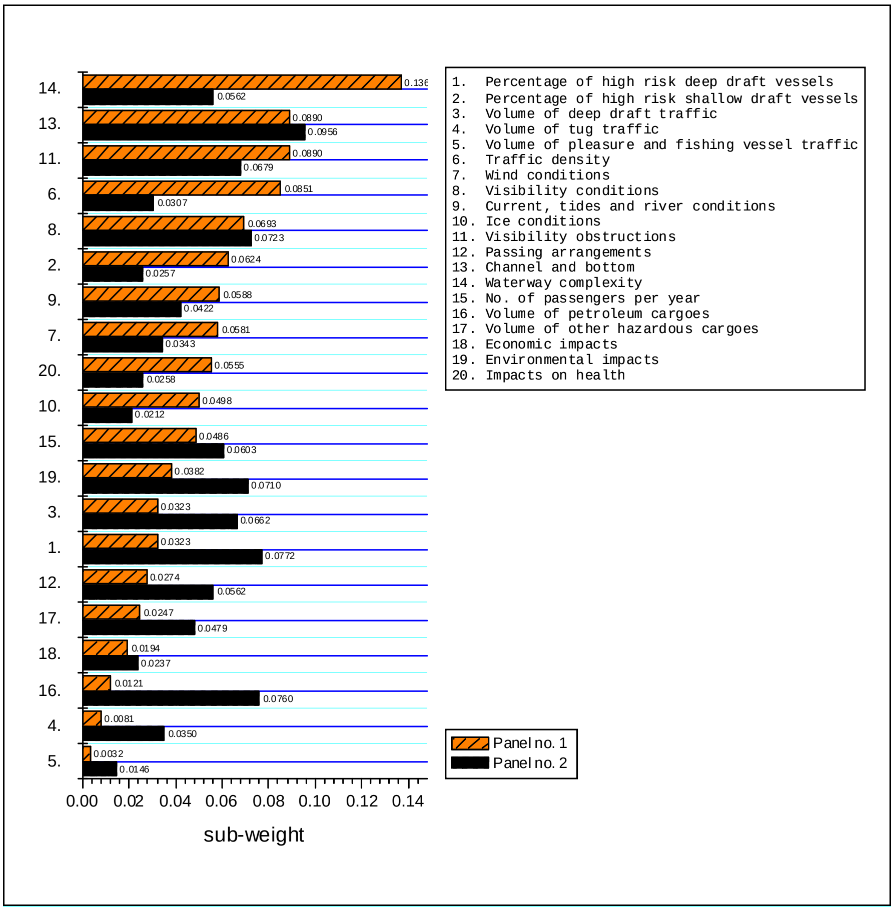

Fig. 2.14. Results of the inquiry on the weights to attribute to the variables gauging the risk factors (Harrald & Merrick, 2000; The George Washington University – Institute for Crisis and Disaster Management, 1998-2). In the case of panel no. 2 (Hampton Roads harbour) the results have been normalised so as to sum up 1 and thus be comparable with the ones from panel no. 1.

probably we can assert that the result from panel no. 1 is more reliable, the following issues have to be stressed:

- Both panels referred to the composition of the calling fleet as the most critical risk factor. Weather conditions are the second most important item.
- On the deeper level of the variables measuring the risk factors (which are a kind of "sub-factors"), disagreement between the two boards was very strong. Waterway complexity was the most outstanding issue according to panel no. 1 while panel no. 2's choice was conditions of channels and waterway bottoms (dredging, etc.), that was in turn indicated as the second most important by panel no. 1. Both boards ascribe the least relative weight to the traffic of pleasure and fishing boats.
- If one averages the results from the two panels (using member numbers as weights), the five most significant sub-factors appear to be respectively waterway configuration, channel and bottom, presence of visibility obstructions, visibility conditions, and traffic density.
- The amount of hazardous materials transported (both hydrocarbons and chemicals: sub-factors 16 and 17) was not considered as a decisive factor. This depended –at least partially– on the approach followed, which is generic and not specifically focused on HazMat transport.

An example of foreign vessel prioritisation is reported in Fig. 2.15. This scheme identifies five groups of factors that affect the inherent level of risk of a vessel: ship owner, flag, classification society, boarding history (with respect to accidents and violations), and vessel type.[21] To each of these classes, one or more scoring factors are assigned. The total sum of the scores expresses a risk level that, in comparison with other vessels, makes it possible to prioritise USCG's ship inspections.

Cunningham (2001) provides an overview of a risk methodology for marine terminals based on risk matrices as a way to rank accident scenarios.

2.3 Conclusions

The first remark about the present bibliographic review is that, in general, stronger research efforts have been made on maritime oil spills than on any other risk issue affecting the maritime environment and port systems. As a result, many more studies were found on oil spills than were on other types of accident, even though only the most significant among the former have been referenced in this chapter.

[21] The variables highlighted by this method are very similar to those proposed by The George Washington University – Institute for Crisis and Disaster Management (1996).

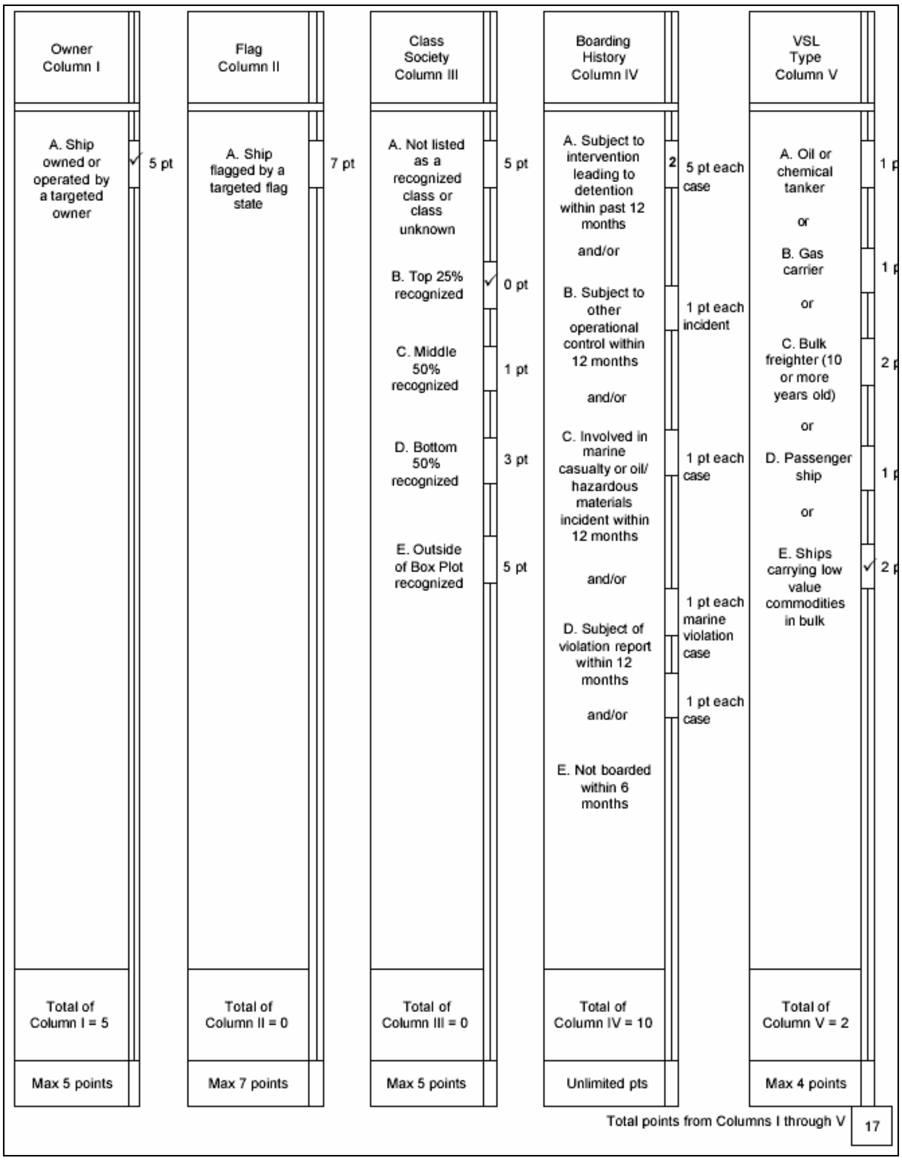

Fig. 2.15. Example of risk index (Foreign Vessel Targeting Matrix) for the prioritisation of inspections to foreign flagged vessels (USCG Research & Development Center, 2001; for a complete account see USCG, 1982).

A reason why specialised literature is more abundant on oil spills than other accidents is that the former are distinctively maritime events, while most other accidents are not specific to the maritime transport, which results in a relatively scarce amount of references devoted to the topic of non-oil-spill accidents in ports. In other words, ports are “less popular” with risk analysts than open-sea transportation, land transportation and the process industries. In this sense, one of the aims of the present thesis is to develop a series of risk assessment tools specifically designed for ports and particularly for port-specific operations –such as navigation in port waters and vessel loading and unloading–, hitherto somehow overlooked and put on an equal with general transportation and process accidents.

It was not possible to find interesting studies on the economic valuation of the consequences of general port accidents. On the other hand, it was possible to scrutinise and review a certain amount of references focusing on the costs of maritime oil spills in open sea and ports. As the FLEXRIS project demonstrated, port authorities and terminal management are interested in forecasting the environmental cost of their activities, in terms of both continued pollution and accidental events. Hopefully the sixth –and last– paper included in this thesis (titled “Economic Valuation of Damages Originated by Major Accidents in Port Areas”; Ronza *et al.*, 2007-2) is a first step towards the definition of a comprehensive method to forecast the costs of HazMat-related accidental events in ports, including oil spills. As to oil discharges into water, the scheme proposed incorporates the approaches of Etkin and Cohen (Etkin, 2001-2; Cohen, 1986), whereas a series of original criteria are discussed that address the valuation of potential damage to the environment, equipment and buildings as well as. the loss of profits due to activity breakdown and indirect costs. One drawback of this part of the thesis is that the method described presently needs a programme of validation, due to the strict confidentiality of the data related to the costs of accidents, that no firm or port authority is really willing to share… If this validation is carried out, the method of economic valuation could receive substantial improvements and –together with the necessary complement of quantitative risk analysis– be effectively used to predict the expected environmental costs of port terminals for budgeting purposes.

Overall the bibliographic research carried out has shed light on a wide variety of port and maritime risk-related topics. It was therefore of great importance for this thesis. A number of papers and studies proved of some relevance to the research, and are cited and commented accordingly in the corresponding article enclosed in this document.

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3 Objectives, methodology and main results

As it is evident from the *Introduction* and the *Bibliographic Survey*, ports are a relatively propitious setting for major accidents to occur.

Ports are generally large industrial districts including several standard manufacturing and transport activities, among which it is worth mentioning:

- Chemical plants;
- Other process plants;
- Oil and chemical depots;
- Road transport;
- Rail transport;
- Oil and gas pipelines.

Nevertheless, port areas have peculiar characteristics that make them different from other industrial facilities. Among these attributes, the following are the most important:

- Ports are invariably located on the edge of a large body of water. They often entertain a difficult relation with it, be this the ocean, an inner sea, a river or a lake.
- As a corollary of the previous point, ports are characterised by the presence of ships, boats, carriers, liners, tankers, in other words *vessels*. Almost all of these are propelled by fuel oil or diesel oil and thus represent a potential source of HazMat spills. Moreover, a number of vessels visiting ports are carriers specifically designed for the transport of huge quantities of hazardous materials. Sea going vessels are the world's largest carriers of goods, infinitely more sizeable than lorries and even freight trains, and the only periods they spend in the vicinities of populated areas are port calls.

- Ports are quintessential intermodal clusters. Practically any possible means of transport can have (or should have) access to a port, from railcars to lorries, from pipeline transport to –obviously– vessels. Even airports are sometimes enclosed in ports (as in Genoa, Italy). Goods are handled in every possible form, including liquid, liquefied gas and solid bulk, containers (which are gaining an increasingly important role in the global transport of goods) and several others.
- Ports are not only located on the edge of a body of water, but also on the edge of, or even *inside*, urban areas. This entails additional problems related to land use planning, pollution, rail/road traffic. Standard industrial districts may not be affected by these problems, if they are of recent construction and thus located away from cities as a consequence of careful planning. Ports, however, are normally ancient sites, so cities grew around them rather than the contrary.
- From an administrative point of view, ports can be managed by a variety of organisations. A Port Authority normally has jurisdiction on the landward side of the shoreline, while navigation affairs are under the competence of a Harbourmaster's Office, but things depend on local laws and customs. Port authorities and harbourmaster's offices are under control of local authorities or national governments.

In spite of all this, the risk assessment of port operations is currently carried out as if ports were standard industrial districts. It is true that the bulk of such approaches may be correct, but it is urgent to review the problem of ports –as related to the risk assessment of major accidents– under a different light, to add some specific information that would be unavailable or overlooked if generic risk assessment tools were used.

The main objectives of this thesis are therefore:

1. To analyse the specific features of port areas from the point of view of the risk entailed by port operations;
2. To identify and characterise a series of tools to be used in risk assessment of port areas, based on existing risk analysis tools but, at the same time, allowing for specific port features.

We will spend here some words on the methodology followed in order to attain such objectives, although this is described more extensively in the papers constituting this thesis.

It is important to stress that the order in which the papers are presented is not strictly chronological. On the one hand, the editorial process was sometimes shorter for papers written well after other ones, which caused the former to be published before the latter. However, the order of presentation does not even respect closely the actual sequence of preparation of the papers. They are instead presented in a logical sequence more suitable to demonstrate the commitment of each paper to fulfil the above mentioned objectives.[1]

[1] Thus, for example, Paper 1 was written after Paper 2 (and in fact the latter is based on an accident sample a little smaller than the one of Paper 1), but in this thesis is made to precede Paper 2. In fact Paper 1 is essentially analytical –a historical analysis of accidents– while Paper 2 is more oriented to tool-building –simplified event trees–. Paper 3, also because of editorial reasons, was the last to be completed, but it is presented before Paper 4 because: a) Paper 4 is more tool-oriented, being focused on adapting

An important part of the research developed is based on *historical analysis* of past accidents. Various accident samples have been identified and analysed. Historical analysis and/or accident database analysis play a fundamental part in Papers 1, 2, 3 and 5.

Paper 1 ("A Survey of Accidents in Ports") is in itself a historical analysis of port HazMat accidents, based on an accident sample of 1000+ events, retrieved from the accident database MHIDAS (Major Hazard Incident Data Service, see Table 2.5). The algorithm used to retrieve the relevant accidents, i.e. port accidents, and thus discard non-port accidents, is based on that shown in Fig. 1 of Paper 2. The objective of this paper is to analyse the fundamental trends of port accidents, allowing for their specific characteristics.

The main findings of Paper 1 are the following:

- The research shed light on the operations most commonly generating accidental situations (Figure 2 of Paper 1). Typical port operations as ship (un)loading, ship manoeuvre and ship approach to berths are the most important in this sense.
- The hazardous substances most commonly involved in port accidents are crude oil, fuel oil and petrol, i.e. hydrocarbons (Table 1 of Paper 1).
- A general probability-number of casualties curve was obtained, and three specific *p-N* graphs found as a function of the state of development of the country where the accident happened (Figures 3 and 4).

Paper 2 is based on the historical analysis of an accident sample similar to that of Paper 1, but the objective of the research is here to study the occurrence of accidental sequences in port areas and to statistically describe them by way of simplified event trees. "Simplified" means that such trees allow for events such as spill, fire, explosion and gas cloud, without entering into further detail as event trees in risk analysis normally do. The accidents analysed were examined to scrutinise their accidental sequences, i.e. in which order the above mentioned events (fire, explosion, gas cloud) occurred. The methodology followed is similar to that of Paper 1, i.e. use of a port accident sample extracted from the MHIDAS and analysed in worksheets.

The main result of Paper 2 is the ranking of accidental sequences, classed according to the operations (approach + manoeuvre, loading/unloading, land operations) that were being carried out when the accident occurred. Among the several quantitative conclusions drawn and listed in Section 4 of the article, it is worth mentioning that the percentage of release cases without further consequences is always the highest and one out of every 13.0 releases gives way to a fire. Overall the simplified event trees of Table 8 and Figure 2 can be used in QRA studies. To do this, it is necessary to know the frequency of the initiating event of the accident scenario examined. Table 9 is a list of expected frequencies for a number of common port accident scenarios.

QRA to port milieus, while at least the first part of Paper 3 is analytical (research of ignition/explosion probability data in literature and database analysis); b) The very subject of Paper 3 –ignition/explosion probability– is preparatory to the next Paper, being probability data an essential component of QRA.

Paper 3 is maybe the most extensive of this thesis. It is focussed on the topic of ignition and explosion probabilities of flammable spills. This issue has a special interest in the frame of quantitative risk assessment, which is treated in a more general form in Paper 4. The specific objectives of the paper are: to review the data available in the literature, to determine if two accident databases can be used to estimate the probability of ignition and/or explosion of flammable releases, and, if this is the case, to propose such probability data based on the database analysis. It is evident that, in order to accomplish the second objective, the databases used must be such that *minor accidents are not underrepresented*. If non-ignited spills and non-exploded clouds go unrecorded in the process of database compiling, then it is not possible to draw statistical conclusions on the relative possibility that a spill, in general, is ignited or a cloud generates a blast. So the initial idea of using MHIDAS, as in Paper 1 and 2, was discarded. Two databases were identified that, instead, allow for minor spills: the HMIRS and the MINMOD. Both are managed by US Federal institutions (the Department of Transportation and the US Coast Guard, respectively) and are, or were, part of comprehensive and compulsory schemes to inventory all the spills of hazardous materials, for land transportation (road, rail) in the case of HMIRS and for maritime transportation in the case of MINMOD.

The findings of Paper 3 are the following:

- In Tables 1 and 2 two comprehensive and detailed lists of literature data are presented of, respectively, ignition and explosion probabilities for use in QRA. Collecting the data helped define the major variables that influence those probabilities. Some of these regard the accident setting (weather, density of ignition sources), other the type of accident and others the material properties and the amount of substance spilled. The data collected are much more numerous for ignition than explosion. Data are discussed showing that, for example, authors tended to overlook the possibility of a blast of flammable vapour clouds originated from liquid spills.
- A general analysis of the databases (Section 4) showed that these are fit to be used for the purpose of obtaining ignition and explosion probabilities. Two variables were allowed for: material properties (basically the flash temperature of the hydrocarbon mixture spilled) and the amount spilled. Average ignition rate proved to consistently increase with the amount spilled and decrease with the flash point. Explosion rate increases with the amount spilled whereas shows a maximum when it is plotted against the flash temperature. In any case ignition probability of maritime accidents is one order of magnitude lower than for land transportation, due to the scarcity of ignition sources around maritime vessels.
- The use of the two databases allows for considering the two fundamental activities of port areas related to the use of hazardous materials and, in particular, energetic hydrocarbons/oil products, i.e. land and sea transportations. Actually, however, the scope of the article is more comprehensive than port areas alone and the results can be applied outside port boundaries as well.
- Figure 10 and Eq. (5) are a quantitative scheme for predicting ignition probability for land transportation spills, whereas Figure 11 and Eq. (6) refer to maritime spills. The equations were obtained by interpolation and allow for both the amount and the type of substance spilled.

- As for explosion probabilities, interpolation was not an option, and figures are proposed in a different way (Table 5), but always taking into consideration both the substance and amount spilled.
- The methods proposed are summarised in Table 6, which allows for fixed plants as well.
- The schemes put forward are finally contrasted against some literature data.

Paper 4 is the major outcome of a project called FLEXRIS (Nueva metodología Flexible para la valoración económica de los Riesgos ambientales) financed by the Spanish Ministry of Science and Technology and carried out on the premises of the Port of Barcelona. The objective of our segment of the project was, in short, to propose a QRA-based methodology for HazMat risk assessment of port areas. The scope of the project was maritime and (un)loading accidents. Together with Paper 6 this is the least "analytical" part of this thesis, being in fact focused on the adaptation of QRA tools to port settings.

The major outcome of the project is a general scheme for performing QRA of port operations involving the transit and (un)loading of HazMat tankers.[2] The following results deserve special highlighting:

- It is proposed that $4n + 2m$ scenarios be considered in the QRA, being *n* the number of substances transported and (un)loaded and *m* the number of substances bunkered (fuel oil and/or diesel oil). As to the *n* substances transported/loaded/unloaded, 4 scenarios are allowed for: major and minor spill for loading arm failure, major and minor spill for vessel hull failure. The two former scenarios are merely punctual, while the two latter are both punctual (if the accident happens while the vessel is at berth) and linear (if instead a collision or grounding happen while the vessel navigates through port waters). Bunkering scenarios are tackled in much the same way, but no major spill is allowed for in this case, due to the relatively small amount of fuel involved. A definition of "minor" and "major" spill is proposed, based on previous results found in the specialised literature.
- A novel scheme is proposed to estimate the spill frequency of those scenarios. This must be employed for all the substances handled in the ports and for all the berths used by HazMat vessels. The scheme is summarised in Tables 4 and 5 of the paper.
- Other important issues are defined for port QRAs, as the spilled amounts to be expected in case of hull or loading arm failure and the most proper software to calculate accident effects as a function of the type of scenario.
- The method was tested in the Port of Barcelona, Spain, where $n = 5$ (LNG, LPG, petrol, kerosene/diesel oil and fuel oil) and $m = 2$ (fuel oil and diesel oil). The case study yielded coherent results, which are shown in individual risk plot of Figure 4 and the *p*-*N* curve of Figure 5.

[2] Although the paper is focussed on oil product and gas tankers, the method can easily be extended to other chemical products, including toxic products.

Paper 5 develops a proposal briefly introduced in Paper 4. Risk analysts generally seek to estimate the overall number of people affected by a set of accident scenarios, i.e. their aim is evaluating the expected number of fatalities, injuries and possibly evacuees arising from accidents. Standard QRA focuses mainly on calculating the number of fatal victims as well as calculating the distances that define the areas to be evacuated. The number of injured people is seldom evaluated, as it would involve significant additional effort. These estimations are all based on calculating the effects of an accident, and they are independent from each other, being each estimation referred to a specific *vulnerability* criterion and thus requiring a certain amount of calculation. The objective of the research behind this paper was to find a shortcut allowing estimating the number of injured people based on the number of fatalities of an accident. The shortcut would permit to obtain complete vulnerability results in the frame of a QRA without recurring to complicate vulnerability calculations for injured people. Moreover, it can be used in the aftermath of HazMat accidents to get an idea of how many people need to be hospitalised based on the known or expected number of deaths.[3]

The methodology followed to find such shortcut was, once again, the analysis of past accidents and the database chosen the MHIDAS. Note that this database is suitable for this task, while it was definitely not for seeking ignition/explosion probabilities. In fact, the accidents considered in the statistical sample were only those that caused one or more fatality and are assigned a certain number of injured people in the database (sometimes this field is left blank). This means that data bias is minimised, as fatal accidents are normally reported and included in the database, forming a homogeneous and reliable accident sample. In this case the sample, of 975 events, was analysed by way of statistical tools more refined than in the previous works:

- PCA (principal component analysis) was used to establish which variables have the greatest influence on N_K/N_I, ratio between the number of fatalities and the number of injured people.
- Another technique, i.e. data clustering, was used with the same aim.
- The outcome of the above mentioned analyses was that the only aspect worth allowing for among a set of accident variables, including location, accident origin –process, warehouse, etc.– and accident type, was the accident type (explosion, fire or toxic gas cloud).
- Overall, however, the first conclusion drawn from the multivariate analyses was that there is no reason to correlate the data with a generalised linear model or other regressions, since N_K/N_I correlates very poorly with other variables other than the accident type. Attempts to define a linear model based on 10-12 variables gave discouraging results.
- On the basis of these considerations, it was decided to analyse the percentiles of the data distribution. By observing the 97.5% percentile, it was possible to assert that in an industrial accident with less than 25 deaths, it is highly unlikely that the number of injured people exceeds 150. The major result of the research is Eqs. (2-5), obtained by interpolating the average number of injured people for a series of intervals of the variable N_K,

[3] The scope of this paper is not only port accidents but HazMat accidents at large. the research was undertaken in the wake of the FLEXRIS project, when the need of calculating the expected number of injured people for a high number of scenarios made it apparent that some kind of reasonable shortcut would have been very useful.

separately for the three above mentioned accident types. The equations represent a shortcut to evaluate rapidly the number of injured people once the accident type and the number of fatal victims is known. On average, the ratio N_I/N_K is highest for gas clouds and lowest for fires, although in the case of gas clouds N_I shows a low increase with N_K if compared to fires and explosions.

Finally, the objective of **Paper 6** was to come up with a scheme to evaluate, from an economic point of view, the damage caused by HazMat accidents in port areas. The scheme can be applied after an accident has happened or *a priori*. In this second case, the scheme can be used for example as a tool to complete the results of a QRA by adding an economic estimation of the damage expected on certain premises on top of the classic evaluation of the expected individual and societal risk.

The methodology followed to design the scheme was to "dissect" the various components of the economic damage of accidents and subsequently analyse each of them establishing a shortcut method of evaluation based on previous work and literature.

The major outcomes of the paper are the following:

- A classification of damages caused by accidents is proposed, as follows:
    - Damage to human life and health;
    - Environmental damage;
    - Material damage;
    - Indirect costs (loss of profits).
- The damage to human life and health is estimated by way of a summation of the costs due to, respectively, fatal victims, injured and evacuees. The number of injured people can be estimated based on the number of fatal victims thanks to the equations put forth in Paper 4. The cost of an individual fatal victim is estimated on the basis of Spanish legislation on compensation for traffic accidents. The cost of an injured person has been estimated with a weighted average of the expected costs of, respectively, light, serious and very serious injuries. The cost of the evacuees is calculated on the basis of the cost of the number of people and the number of days of evacuation.
- Environmental damage is split up in: valuable animals (productive animals and endangered wildlife) lost due to the accident; cost of water cleaning after spills, which is made to depend basically on the amount of substance spilled; and the cost of soil remediation.
- Material damage is estimated by way of unitary costs of the equipment and structures lost in the accident, which in turn can be obtained from simplified equations found in literature. However, as to ships, it is proposed that an *ad hoc* treatment be followed for each accident since it is almost impossible to evaluate the economic damage to ships due to the many factors that affect it (ship age, type, flag, damage received, etc.).
- Indirect costs/loss of profits are divided into breakdown costs, due to the necessity to stop activities and/or shut down the terminal, the cost of lost

wages (i.e. wages paid to workers unable to work due to the shut-down), other indirect costs (like loss of image, administrative costs, reduced productivity of workers on light duty, etc.). Breakdown cost are determined on the base of the length of mooring line affected by shut-down to be multiplied by the average daily income of the terminal per meter of mooring line. Other indirect costs are instead evaluated based on direct costs. Among these losses, there are morale effects on coworkers, personnel allocated to investigating the accident, recruitment and training costs for replacement workers, reduced quality of recruitment pool, reduced productivity of injured workers on light duty, overhead cost of spare capacity maintained in order to absorb the cost of accidents, rise in insurance premiums, communication costs, administrative costs, prevention initiatives, etc. A ratio of 1:1 between direct and indirect cost is proposed based on previous literature.

- A case study is presented in an Appendix, in which it is shown that a diesel pool fire due to a loading arm failure should cause a damage of about 1×10^6 € (2005).

All in all, while Papers 1 and 2 are quite descriptive, Papers 3, 4, 5 and 6 may well represent, as a whole, a complete, QRA-based risk assessment methodology for port settings: the risk analyst could follow the QRA scheme, described in Paper 4, using the ignition and explosion probability data proposed in Paper 3; in order to shorten vulnerability calculations, he or she could use the shortcut described in Paper 5; finally, he or she can obtain an economic estimation of the damage expected.

4 Conclusions

Detailed conclusions for the individual segments of the thesis can be found in the published papers, a copy of which is attached to this document. However, in this chapter, we relate the major outcomes of the whole of the research. The reader should refer to the individual papers for more details.

1. Historical analysis demonstrated the distribution of accidents in ports as a function of several parameters such as the type of accident (70% involve a loss of containment, 30% involve fire, 24% involve explosion, 5% involve gas clouds) and the operation carried out when the accident occurred (the most important being loading/unloading, ship manoeuvre and approach, in this order). The substances most commonly involved in the accidents were, not surprisingly, crude oil and its derivatives, ammonia being the first chemical in the list. Specific *p-N* curves for port accidents are another result of the historical analysis.

2. Historical analysis of a large sample of port accidents led to the definition of a series of simplified event trees for port accidents. On one hand this allowed to describe the most common accident sequences in port settings, as a function of the activity/operation carried out when the accident occurred (namely ship approach/manoeuvre, ship (un)loading, land operations). Moreover, the event trees proposed can be used in quantitative risk assessment of port accidents.

3. Given that the majority of port HazMat spills involve flammable hydrocarbons and/or oil derivatives and have, as a possible ultimate consequence, a fire and/or explosion, the probability of ignition and blast wave formation of hydrocarbon spills was further researched, by way of two US federal spill databases. Extensive bibliographical analysis of probability data used in HazMat QRA showed that figures put forth by a variety of authors during the last decades are seldom in agreement and depend on an array of variables such as material properties, amount spilled, and accident

type. The probabilities collected were put in their original context, which made it possible to weigh them against each other. It was specified whether ignition probabilities were referred to immediate rather than delayed ignition. The spill databases HMIRS and MINMOD were investigated in order to propose alternative probability data for hazardous materials spills that occur during land and sea transport, respectively. A selection of significant commercial hydrocarbons were taken into account, which brought to examine more than 12,000 spills for HMIRS and more than 34,000 for MINMOD. Database analysis enabled to explain how ignition and explosion probability vary as a function of the amount and the substance spilled. The analysis was surprisingly consistent and yielded coherent results due to the great amount of accident records provided by the two databases analysed. Ignition probability was found to increase with the amount spilled and to decrease with the flash temperature of the mixture spilled. Explosion probability grows with the amount spilled as well, whereas its trend as a function of flash temperature presents a peak corresponding to crude oil and kerosene. Significant differences were found between land and sea transport. Accordingly, a quantitative scheme, which includes the possibility of extending the findings of the analysis to fixed plants, was proposed to predict ignition and explosion probability of hydrocarbon spills. The fact that specific ignition/explosion probabilities are put forth for sea transportation spills is particularly important, due to the near absence of such data for these scenarios in the literature. The study proved that the data systems analysed, apart from being broad, appear to be particularly reliable and unbiased.

4. The pilot study carried out for the Port of Barcelona, allowed to refine some aspects of the application of quantitative risk assessment of bulk hydrocarbon logistics in ports. Initiating events were identified for four types of scenario (major/minor loading arm failure and major/minor tanker hull failure). Frequencies were estimated for all the initiating events through an extensive bibliographical survey. A set of equations was consequently proposed to estimate the global frequency for every scenario type. It was found that 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 of the method was identified to be frequency estimation. The case study provided results that are consistent with classic quantitative risk analyses as applied to chemical plants and storage areas. An aspect that was addressed is how to take into account the presence of both single- and double-hulled liquid tankers in port waters.

5. Paper 5 (“Consequences of Major Accidents: Assessing the Number of Injured People”) is not specifically based on port settings, but is of general interest. It develops some aspects previously introduced in Paper 4. A criterion to evaluate N_I (number of injured people in an accident) as a function of N_K (number of fatal victims) was identified based on historical analysis. The sample used in this survey followed a trend of N_I increasing with N_K. However, due to the degree of data dispersion, a conventional statistical correlation approach proved to be unreliable. Two multivariate analyses were consequently used to study the data: principal component

analysis and clustering. These procedures showed that the variables describing the accident type have the most influence on the ratio of injured people to fatalities. Both principal component analysis and clustering revealed a pattern according to which the highest values of N_I/N_K pertain to gas cloud accidents, followed by fires and then explosions. This was confirmed by plotting the mean N_I data against proper ranges of N_K for the three different accident types. Finally, a set of correlations were proposed that estimate the mean number of injured people as a function of N_I. These equations can be helpful in the case of fatal accidents involving hazardous materials, since they give an idea of the number of people that are expected to be hospitalised after an accident with fatalities occurs. On the other hand, using these criteria a priori is a way of saving time in estimating the number of injured people without resorting to effects calculations and *probit* techniques.

6. The last paper of the thesis ("Economic valuation of damages originated by major accidents in port areas") is focused on the assessment of the cost of the diverse losses originated by a major accident in a port. The difficult and controversial issue of attributing a value to human life was addressed. A set of values was proposed for compensations due to death, injuries or evacuation of people. As for the damages to the environment, three aspects were essentially considered: water, soil and fauna. Economic values were proposed for the decontamination of water, as a function of the amount of spilled material, soil remediation and losses in fauna. Damage to equipment was estimated by applying standard values per unit surface area or per lineal metre. Finally, a set of equations was described that can be applied to assess the loss of profits due to the ceasing of activities. By applying the method devised, it is possible to allow for all of the expectable costs of a port accident.

Overall, the thesis has attained its objectives –described in Chapter 3 – Objectives and Methodology–. First, thanks to historical analysis, an original overview was provided of several specific risk aspects of ports. Secondly, the outcomes of such overview and the statistical analysis of past accidents are used for the proposal of methodologies specific to port areas and/or maritime transport (Papers 2 and 3) or even general methodologies (Paper 5). Lastly, the knowledge gathered through the reading of specialised literature and the collaboration with the Port of Barcelona led to formulating two original tools, i.e. a general methodology for bulk hydrocarbon liquid transport in ports (Paper 4) and a scheme for the economic valuation of damage caused by major accidents in ports (Paper 6).