Assessing Safety Risks for the Sea Transport Link of a Multimodal Dangerous Goods Transport Chain

JOANNE ELLIS

Department of Technology Management and Economics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2011
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Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

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ABSTRACT

Transport of goods in containers and cargo transport units by sea as part of multimodal transport chains presents unique challenges from a safety perspective. The units can hold a broad mix of cargo types, including dangerous goods with hazardous properties. The purpose of this thesis was to assess the risk of carrying dangerous goods as packaged cargo by sea, with a main focus on transport safety. A better understanding of this risk can lead to fewer human, environmental, and economic losses.

Studies on the safety risks associated with sea transport of containerised goods were carried out, starting with an investigation into the overall risk of fires on container ships, continuing with analyses of the risk of dangerous goods carriage, and concluding with an investigation into the factors contributing to the release of dangerous goods on board. The sea transport link of the transport chain was of prime interest from a safety perspective, but earlier parts of the chain were also considered for the investigation of contributing factors. Analysis of accident, incident, and inspection reports and databases was a key part of the approach taken to carry out the work. Risk analysis techniques, primarily event tree and fault tree techniques, were used both quantitatively and qualitatively to estimate risk and develop explanatory models.

The container ship risk analysis modelling work determined that the fire/explosion accident category was the second largest contributor to overall human safety risk, and the analysis of historical data found it to be responsible for the most crew fatalities reported for the period 1993 – 2004. The cargo area was found to be the location of fire initiation for 32% of serious fire/explosion events on container ships for a later period investigated (1998 to 2008) and undeclared dangerous goods were found to be involved in 25% of these cargo area fires. Dangerous goods involvement was identified for 15% of crew fatalities resulting from container ship casualties during this 11-year period. The investigation of release of packaged dangerous goods during maritime transport found most contributing factors originated prior to the goods being loaded on to the ship. The findings are useful from a safety perspective as they identify where in the transport chain faults are occurring and also the importance of dangerous goods incidents and fires in relation to other accident types.

Key words: maritime safety, dangerous goods, cargo transport units, spills, container ships, accident, incidents, risk analysis
LIST OF PUBLICATIONS

The thesis is based on the work contained in the following publications:

**Paper I**

**Paper II**

Work published in:

**Paper III**

**Paper IV**

Distribution of work:

Paper I: All authors contributed towards study planning and scope definition. Each of the accident categories was investigated by one of the paper authors and all contributed to overall discussions of how the results could be integrated to produce a risk profile for container ships. J. Ellis developed the risk model for the fire/explosion accident category of the high-level study of container ship operations, which is described in more detail in Appendix I. She also contributed to the overall analysis and assessment of risk control options for fire/explosion.

Paper II: Planning of the work and initial discussion were carried out by J. Ellis, B. Forsman and K. Dausendschoen. J. Ellis carried out the data analysis, modelling and writing of the report.
Papers III and IV: J. Ellis was sole author and carried out the planning and analysis of the work and the writing of the papers.

All papers are provided in Appendix II.
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Göteborg, 2011
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**TERMINOLOGY**

*Accident* is an unintended event involving fatality, injury, ship loss or damage, other property loss or damage, or environmental damage (IMO, 2002).

*Cargo transport unit* is a road transport tank or freight vehicle, a railway transport tank or freight wagon, a multi-modal freight container or portable tank, or a multiple-element gas container (UNECE, 2009).

*Causal factor* “means actions, omissions, events or conditions, without which:
- the marine casualty or marine incident would not have occurred; or
- adverse consequences associated with the marine casualty or marine incident would probably not have occurred or have been as serious;
- another action, omission, event or condition, associated with an outcome in the above, would probably not have occurred.” (IMO, 2008b).

*Container* is a generic term for a box to carry freight, strong enough for repeated use, usually stackable and fitted with devices for transfer between modes (UN/ECE, 2001).

*Dangerous goods* mean the substances, materials and articles covered by the International Maritime Dangerous Goods (IMDG) Code (IMO, 2008a).

*Frequency* means “the number of occurrences per time interval” (Fullwood, 2000).

*Incident* is “an unintended event that can lead to an undesirable outcome such as an accident” (Ventikos and Psaraftis, 2004).

*Intermodal transport* is “the movement of goods in one and the same loading unit or road vehicle, which uses successively two or more modes of transport without handling the goods themselves in changing modes” (UN/ECE, 2001).

*Likelihood* is “a measure of the expected probability or frequency of occurrence of an event” (Center for Chemical Process Safety, 1995).

*Marine casualty* “is an event or sequence of events that has resulted in any of the following which has occurred directly in connection with the operations of a ship:
- the death of, or serious injury to, a person;
- the loss of a person from a ship;
- the loss, presumed loss or abandonment of a ship;
- material damage to a ship;
• the stranding or disabling of a ship, or the involvement of a ship in a collision;
• material damage to marine infrastructure external to a ship, that could seriously endanger the safety of the ship, another ship or an individual; or
• severe damage to the environment, or the potential for severe damage to the environment, brought about by the damage of a ship or ships.” (IMO, 2008b)

Marine incident “means an event, or sequence of events, other than a marine casualty, which has occurred directly in connection with the operations of a ship that endangered, or, if not corrected, would endanger the safety of the ship, its occupants or any other person or the environment.” (IMO, 2008b)

Multimodal transport is a carriage of goods by two or more modes of transport (UN/ECE, 2001).

Occurrence is an accident or incident (Australian Transport Safety Bureau, 2007).

Packaged dangerous goods means the substances, materials and articles covered by the IMDG Code carried in the form of containment as specified in the IMDG Code (IMO, 2008a). The term includes dangerous goods carried in containers and cargo transport units.

PLL (Potential Loss of Life) is “the predicted long-term average number of fatalities in a given time period” (DNV, 2002).

Probability is “a positive number between zero and one that measures the chance that an event will occur” (Frank and Todeschini, 1994).

Risk is “a measure of potential economic loss, human injury, or environmental damage in terms of both the incident likelihood and the magnitude of the loss, injury, or damage” (Center for Chemical Process Safety, 1995). The two elements of risk are the frequency of occurrence and the potential consequences.
1 INTRODUCTION

Transport of goods is essential for economic growth and the global community. Marine transport plays a key role in moving goods, with the UNCTAD reporting that about 80% of international trade is transported by sea (UNCTAD, 2010). There have always been accidents at sea, with many of the more notable maritime disasters involving foundering during storms, groundings, and collisions. Seafaring is noted to be one of the more dangerous occupations (Nielsen, 1999). The hazards involved with cargo being carried can also lead to accidents. Containerised cargo presents its own unique challenges, as up to 14,000 containers can be carried on the largest container ships. These containers can hold a broad mix of cargo types, including dangerous goods with hazardous properties such as toxicity, corrosivity, and flammability.

This thesis is a study into the safety risks of carrying containerised cargo by sea, with a focus on dangerous goods. With a better understanding of risks, comes the potential for improved safety and fewer human, environmental, and economic losses.

1.1 Background

Container trade has grown by about 10% per year from 1980 to 2008, with the only reduction in trade since the start of containerisation occurring during 2009 due to the global financial crisis (UNCTAD, 2010). Containerised trade accounted for 24.3% of the world’s total dry cargo in 2009. The same source reports that the container ship fleet has grown by 154% in the last decade. The number of vessels has increased from 1,954 in 1997 to 4,677 in 2010, and the average vessel size has increased from 1,581 to 2,742 twenty-foot equivalent unit (TEU) capacity during this same period (UNCTAD, 2010). The size of the largest container ships continues to increase as well, with the UNCTAD (2010) reporting that the largest container ship in operation in 2010 had a nominal capacity of 14,770 TEU.

The container trade has also seen an increase in the type of goods carried in containers. Rodrigue and Notteboom (2009) stated that initially containerised goods were dominated by finished goods and parts, but there has been a solid and growing market in the containerised transport of commodities over the last decade. Wang and Foinikis (2001) describe how with the evolution of container ships, goods carried have evolved from simple dry general cargo to refrigerated, corrosive, toxic, and explosive cargo, among other types. They state that the
carriage of new hazardous cargoes come with new hazards and calls for advanced safety measures. Kelman (2008) also points out that new products and carriage methods bring new and less understood hazards and that the growth in the size of container ships has meant that the potential loss from a single incident has reached new proportions.

Dangerous goods have hazardous properties that may result in harm or damage if the goods are released during transport. Carriage of these goods in packaged form by ship must be done according to provisions in the International Maritime Dangerous Goods Code (IMDG) (International Maritime Organization (IMO), 2008a). Dangerous goods are classified according to the hazard they represent into one of the following main classes:

- Class 1: Explosives
- Class 2: Gases
- Class 3: Flammable Liquids
- Class 4: Flammable solids; substances liable to spontaneous combustion; substances which, in contact with water, emit flammable gases
- Class 5: Oxidizing substances and organic peroxides
- Class 6: Toxic and infectious substances
- Class 7: Radioactive materials
- Class 8: Corrosives
- Class 9: Miscellaneous dangerous substances and articles and environmentally hazardous substances

In general, Class 3, flammable liquids, represents the largest percentage of dangerous goods transported by weight. The distribution of packaged dangerous cargoes handled at Hamburg Port by class during the period 2002-2006, as shown in Figure 1.1, is typical in that it has Class 3 as the largest handled (based on weight), with Class 8, corrosive liquids, also prominent. Hamburg was the second largest container port in Europe by TEU throughput over the period 2007-2009 (UNCTAD, 2010) and thus represents a large goods flow. Smaller ports may show different distributions based on type of local industries and goods handled.
On a per ship basis there is limited information on the amount and type of dangerous goods that are carried as packaged dangerous goods and quantities could vary considerably for specific ships and routes. The IMO (1996) estimated that 10 to 15% of cargoes transported in packaged form fall under the IMO criteria of substances, materials, and articles that are dangerous or hazardous from a safety or environmental perspective. Burgess (2006) states that on many shipping routes, dangerous goods are carried in about 10% of containers. A report by the Munich Re Group (2002) states that container vessels can sometimes carry as much as 10 to 40% hazardous cargo. Some examples for specific ships as reported in accident reports include: declared and undeclared dangerous goods together accounted for 5.4% of the Sea-Land Mariner container ship’s cargo at the time of a fire and explosion incident in 1998 (Maritime Administrator, the Republic of the Marshall Islands, 1999); dangerous goods were carried in approximately 7% of the 2318 containers onboard the MSC Napoli when it suffered a catastrophic hull failure and was beached in the UK in 2007 (Maritime and Coastguard Agency (MCA), 2008).

The transport of goods in standardised cargo transport units has greatly facilitated efficient handling of cargo but sometimes brings with it safety risks due to the properties and hazards of the cargo. Units may be moved and handled many times before arriving at a port for loading onto a ship and there may have been dangerous shifts of cargo or mis-communication along the transport chain regarding properties and hazards. Mawson (2003) stated that the safe transport of dangerous goods is one of the most serious challenges to container shipping, partly because the majority of goods arrive in closed and sealed containers and it is not possible to easily know the status of the contents. Kelman (2008) presents some case studies on dangerous goods events on container ships, a few of which
resulted in considerable ship damage and cargo losses. He states that the separation of crew from cargo that occurs on container ships can reduce the crew’s perception of the risks related to the cargo. Güner-Özbek (2008) puts forth that information is the most important factor in the carriage of dangerous goods, and that the master and crew need to be fully aware of the nature and properties of cargo for both cargo protection and safety of human lives and property.

Hengst and Molenaar’s paper (1995) on the safe transport of dangerous cargoes on container ships state that there are gaps in the statistics on ship safety, particularly concerning near-miss incidents, but more knowledge should be gained from operational experience because there are huge numbers of containers transported each year. The Center for Chemical Process Safety (1995) report that data for container accidents in transit are very limited. A literature review did not identify any studies reporting quantitative analysis or models on dangerous goods release risk from containers on board ships. This study had the goal of filling this gap.

1.2 Purpose

As described in the background section, there has been increased transport of all goods types in containers and cargo transport units as part of multimodal transport chains. This transport has been important to economic growth and world trade. Dangerous goods are part of this flow and represent a risk to safe ship operations. This has been identified in the literature but there have been few studies assessing or modelling the risk and a gap has been identified. The overall purpose of this work is as follows:

- to assess the risk of packaged dangerous goods transport by sea and to identify contributing factors to dangerous goods release on board, with the view to improve transport safety.

To achieve this overall goal, four research topics were successively investigated. The starting point of the work was an investigation of fires in cargo areas of container vessels, as all major dangerous goods accidents on this ship type identified from the literature involved fires and explosions. This was followed by an analysis of the risk of dangerous goods releases on container vessels and an assessment of the contribution to overall risk of container ship operation. Additional work following from this included an investigation into contributing factors to dangerous goods releases and a study into the problem of undeclared dangerous goods. The research topics and links between them are shown in Figure 1.2. Specific research questions (RQs) were formulated for each of the topics, and are discussed as follows.
Fires on container ships have been identified in previous studies as an accident type that results in relatively greater severity of cargo damage (Talley, 1996) and are responsible for more than a third of fatalities and injuries due to container ship accidents (DNV, 2003). A quantification of the risk and development of a consequence model for container ship fires was considered important to improve the understanding of the problem and contribute to identifying risk control measures for fires. Determining the contribution of accidental fires to the overall risk profile for container ship operations was also considered valuable within the context of managing overall risk. It is important to know which accident types are most critical in terms of human safety, and whether overall risk is within an acceptable range.

In the course of answering the research question and modelling consequences of fires to estimate the risk of cargo area fires, it was considered that dangerous goods and in particular undeclared dangerous goods could lead to higher-consequence fire events. Available information on this was found to be limited and thus the need for more study in this area was identified, which lead to the next two research questions.

**RQ2**: How much does the carriage of dangerous goods contribute to the risk of container ship operations?

Although dangerous goods cargo had been identified as a contributing factor in some serious container ship accidents (Burgess, 2006; Compton, 2006), and a
formal safety assessment of container ships indicated that they could result in higher consequence fire events, the risk of dangerous goods carriage to crew safety had not been quantified. International ship casualty databases do not include sufficient information on casualty causes to permit quantification for specific contributing factors such as dangerous goods so additional information on accidents is required.

Estimation of the risk associated with carriage of dangerous goods on container ships was approached through analysis of information on dangerous goods releases for occurrences of all consequence levels. Event tree modelling was carried out for various dangerous goods classes and sub-classes, and this was used to develop risk estimates. For high consequence occurrences resulting in crew fatalities, ship casualty data from international sources together with information from literature searches and accident investigation reports were used to estimate the contribution of dangerous goods releases to total fatality rates resulting from container ship accidents.

The qualitative review of accident and incident report narratives for dangerous goods releases carried out during the process of estimating risk for carriage of dangerous goods release indicated that contributing factors to the releases in many cases originated on the “land” side of the transport chain. These included faults occurring during packing and filling containers and preparing transport documentation, declarations, and marking. Research Questions 3 and 4 were developed to guide further investigation of contributing factors to dangerous goods release incidents on ships. These included undeclared dangerous goods and activities occurring prior to the goods being loaded on the ship.

**RQ3:** What are the contributing factors to and potential consequences of undeclared dangerous goods carriage by sea?

The carriage of dangerous goods that have not been correctly declared for transport have contributed to some serious fires on container ships. Undeclared dangerous goods have been noted to be a concern for maritime transport (TT Club, 2007), but little information could be found on the extent of the problem. Levinson (2006) suggests that containers can be an efficient way of smuggling undeclared merchandise, given the large volumes of containers transported and the time required to inspect a fully loaded container. Knowledge of factors contributing to the carriage of undeclared dangerous goods by sea and the potential consequences and impacts resulting from the carriage are an important step towards reducing the risk. Research Question 3 was formulated to contribute towards this knowledge, and to develop a qualitative model to illustrate factors contributing to carriage of undeclared dangerous goods and potential consequences.

**RQ4:** What are the main categories of contributing factors to packaged dangerous goods release on ships and where do they originate in the transport chain?
As dangerous goods releases were identified to be a problem in the research on overall risk of container ship operations and were found to contribute to the fire accident scenario, further information was sought on factors contributing to the release. Previous work also showed that activities occurring prior to the goods being loaded on the ship, and which the ship operator had little chance of controlling or verifying, contributed to many of the releases. Improper declaration of dangerous goods were noted to be a contributing factor to some releases, and this was investigated through Research Question 3, but there were also other types of factors that needed further investigation.

RQ4 was focussed on categorising all factors contributing to packaged dangerous goods release on board ships. These included faults that occurred during activities such as preparation of the goods for transport, packaging, stuffing containers, and loading the ship. Records of dangerous goods release occurrences from two databases were analysed to identify and categorise contributing factors and develop a distribution showing which types of faults most commonly contributed to releases on board ships. It was of interest to know the approximate point along the transport chain where the faults were introduced, to determine whether the majority could be addressed on board the ship or whether a focus further up the transport chain was more appropriate.

Each of the four research questions is addressed in the appended papers (PI – PIV). The research topics, associated research questions, and the primary papers addressing these questions are shown in Figure 1.3.
### Risk of container vessel fires

**RQ1:** What is the risk of accidental fires on container ships and specifically what is the risk of cargo area fires?

**PI:** A Risk Model for the Operation of Container Vessels

### Influence of carriage of dangerous goods cargo on container vessel risk

**RQ2:** How much does the carriage of dangerous goods contribute to the risk of container ship operations?

**PII:** Dangerous Goods Transport with Open-Top Container Vessels – Risk Analysis

### Risk implications of undeclared dangerous goods

**RQ3:** What are the contributing factors to and potential consequences of the carriage of undeclared dangerous goods by sea?

**PIII:** Undeclared Dangerous Goods – Risk Implications for Maritime Transport

### Factors contributing to dangerous goods releases during maritime transport

**RQ4:** What are the main categories of contributing factors to packaged dangerous goods release on ships and where do they originate in the transport chain?

**PIV:** Analysis of accidents and incidents occurring during transport of packaged dangerous goods by sea

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**Figure 1.3** Research topics, research questions, and papers/studies addressing the questions

### 1.3 Scope

The risk assessment part of the work was limited to the sea transport link of a multi-modal transport chain, as shown in Figure 1.4. Cargo area fires and dangerous goods occurrences involving the release of dangerous goods on board a vessel were the primary events of interest. All release events were of interest, including small releases of less dangerous substances where consequences were expected to be small, to large releases resulting in serious consequences. This facilitated a more complete view of the risk. The dangerous goods risk studies were limited to packaged dangerous goods carried in cargo transport units (CTUs), which are defined as containers and trailers, carried on board a commercial ship. Bulk transport of dangerous goods was not included.
Risk of fire and onboard occurrences involving release of dangerous goods cargo

Goods origin → Land Transport → Departure Port → Ship → Destination Port

Investigations of factors contributing to onboard dangerous goods occurrences include the transport chain to the destination port

**Figure 1.4** Transport chain segments covered by the research

While the study of risk of dangerous goods releases was focussed on the ship transport segment of the transport chain, as shown in Figure 1.4, the investigation of contributing factors included activities from the origin of the transport chain. The parts of the transport chain prior to ship transport, including preparation of the goods for transport, were considered from the perspective of identification of potential factors contributing to dangerous goods release incidents on board. All studies were limited to safety risks of the sea transport link, and did not consider the safety risks during land transport and intermediate storage.

**1.4 Overview**

The thesis consists of this summary report of the work and four appended papers. This introductory chapter has provided some background and introduction to the research, and described the purpose, research questions, and scope. Chapter 2, “Frame of Reference”, provides a summary of the current state of research in the field and more in-depth background. Chapter 3 describes the research approach and methods used in the studies. Chapter 4 is a summary of the appended papers, describing purpose, scope, and findings for each paper. The links between the papers are also presented and described. Chapter 5 presents an analysis and discussion of the main findings of the papers as they pertain to the research questions and summarises the main contributions of the work. Chapter 6 presents overall conclusions, contributions, and possible directions for further research.
Dangerous goods are transported within an established transport system, and are transported according to international regulations designed to prevent harm to people, property, and the environment. Risk assessment and analysis within maritime transport is becoming more established although there are limited studies on the risks associated with transport of packaged dangerous goods. The following sections provide more information on the maritime container transport chain, dangerous goods regulations, and risk assessment for the transport of dangerous goods.

2.1 Maritime container transport chain

Freight is moved along a transport network of links and nodes, from a point of origin to a final destination. The nodes in the transport network include the origin and destination points, and places where the goods come to rest temporarily to be handled or transferred. The nodes may be a warehouse, a consolidation point, or a terminal where goods are transferred to another carrier or mode. The links in the transport network are characterised by a transport mode (e.g. ship, road, rail) and the supporting infrastructure (e.g. fairway, roadway, railway track) (European Conference of Ministers of Transport (ECMT), 2005).

At the goods origin node, such as a factory, there may be sufficient cargo to fill a whole container. In this case, goods may be transported directly by road or rail to a port, if they will be transported in an intermodal transport chain that includes a sea transport link. They may also require transshipping at a terminal, as portrayed in Figure 2.1. If the quantity of goods is insufficient to fill a whole container, they may be transported to a consolidation centre where they are packed with goods from other shippers into a container. The container could then be transported to a port or potentially another transport node. After sea transport, the container may be transshipped to another vessel for another sea transport journey, or it may continue its journey by land. At the origin of the transport chain, there are many shippers feeding into a smaller group of intermediaries such as consolidation centres, which in turn feeds to one ship, as shown in Figure 2.1. The flow of goods and containers becomes more concentrated as it reaches the ship, which carries goods for a large number of cargo interests. Once the ship
reaches the port, the goods flow then becomes more diffuse as the goods are transported to final destinations.

**Figure 2.1** Simplified transport chain for containerised goods with sea transport link, illustrating types of links and nodes

The OECD Maritime Transport Committee (2003) estimated that a typical door-to-door journey for a shipping container can involve the interaction of 25 different participants, generate 30 to 40 documents, and involve two to three modes of transport. The container may be handled at 12 to 15 locations (OECD, 2003).

Even with the handling required for each container as described above, transport has become much more efficient than was the case prior to its widespread adoption in the 1960s. Levinson (2006) states that the container both reduced transport costs and saved time as handling times were much quicker than the older method of piece by piece freight handling. With goods packed in sealed containers, however, there is little opportunity to verify contents. The ECMT (2005) publication on container security states that “the shipper is the only actor in the chain with detailed first-hand knowledge of the goods placed into a container”. Although this statement was made to highlight issues with security, it is also important from a safety perspective, regarding knowledge of the condition of the contents and securing of the goods inside the container. Rao and Raghavan (1995) state that from a safety perspective regarding containerised hazardous chemical cargo, there are difficulties because port authorities have to rely on shipper’s documentation regarding the identity and hazards of the cargo, and may not know if cargo is properly secured and braced. Deficiencies in this regard may result in serious incidents.

### 2.2 Dangerous goods regulations and compliance

#### 2.2.1 Regulations

Regulations are in place to attempt to ensure the safe transport of dangerous goods and these are harmonised across modes. Lowe (2005) states that transporting dangerous goods poses a range of safety and environmental risks
irrespective of the transport mode used. Regulations for all transport modes are based on the *Recommendations on the Transport of Dangerous Goods, Model Regulations*, which were first published by the United Nations Committee of Experts in 1956. The model regulations are updated every two years, with the most recent version published in 2009 (UNECE, 2009). The aim of these regulations is “to make transport feasible and safe by reducing risks to a minimum” (UNECE, 2008). A common base for regulations also facilitates ease of transport between modes.

For sea transport of dangerous goods, the applicable regulation is the International Maritime Dangerous Goods Code (IMDG) (IMO, 2008a), which was made mandatory under the International Convention for the Safety of Life at Sea (SOLAS) Chapter VII (Carriage of Dangerous Goods) amendments adopted in 2002. The development of the IMDG code dates back to the Safety of Life at Sea Conference in 1960, and an IMO working group began preparing the code in 1961 (IMO, 2010). This was done in close co-operation with the UN Committee of Experts on the Transport of Dangerous Goods. The code describes the provisions that govern the carriage of dangerous goods in packaged form by sea. Goods that are listed within the code must be transported according to the provisions which specify requirements for packing, consignment, and transport operations, including packaging to be used, marking, labelling, placarding, stowing, segregation, and transport documentation.

### 2.2.2 Compliance

Although codes and guidelines for transport of dangerous goods by sea have been in place since the 1960s, non-compliance is common. The IMO urges member countries to carry out inspections of cargo transport units (CTUs) carrying dangerous goods to determine compliance with applicable IMO standards (IMO MSC 1998), but this is not mandatory. Results of inspection programs carried out in 2008 showed that on average 34% of inspected cargo transport units (primarily containers and trailers) were noted to have deficiencies, for the 11 countries reporting (IMO Sub-Committee on Dangerous Goods, Solid Cargoes, and Containers (DSC), 2009a). To get a longer term view of non-compliance, inspection data submitted to the IMO’s DSC from 2000 to 2008 was reviewed. Data from five countries where inspections had been carried out for at least the last four years was reviewed and plotted, as shown in Figure 2.2. For all countries except Sweden, the data is from the program results submitted by the member countries to the IMO’s DSC. For Sweden, the information was summarised from Swedish Coast Guard inspection data after a review of the inspection forms and spreadsheets.
The percentage of cargo transport units with deficiencies with respect to dangerous goods regulations is relatively high and varies by country, as shown in Figure 2.2. In Belgium, an average of 52% of the units inspected over a nine-year period had deficiencies. In the US, an average of 18% of containers inspected over the last 4 years by the US Coast Guard had deficiencies. Because inspections are carried out in different ways in different countries, it is not appropriate to draw conclusions about the differences in deficiency rates among countries. For example in Belgium, inspections are carried out on a daily basis on outgoing Cargo Transport Units by a specialised group of inspectors (IMO DSC, 2005a). In Sweden, inspections may be carried out by specially trained inspectors on either outgoing or incoming cargo transport units, and the goal is to carry out inspections on at least a quarterly basis in each harbour where dangerous goods are transported. A random selection of units containing dangerous goods may be selected for inspection in some cases, as is done in Sweden, while in other countries a more targeted approach may be taken. The US Coast Guard uses a targeting matrix to select containers for inspection (IMO DSC, 2005b).

A least-squares regression analysis was carried out on the annual inspection results from each country to determine whether there is any significant rate of change over time. A regression slope t-test was used to determine whether estimated rates of change were significant. Only the data from Canada showed that there had been a significant improvement over the years, with a modelled decrease of 3.6% per year. The percentage of units with deficiencies was estimated to be decreasing, on average, by 0.4 to 6.7% per year during the period.
The container transport industry in Canada has been carrying out some “self-inspection” in recent years (Transport Canada, e-mail communication, 2010) and this could be one possible explanation for the decrease.

### 2.2.3 Undeclared Dangerous Goods

Undeclared dangerous goods is a specific type of non-compliance for which there is limited information. Inspection results reported to the IMO are from inspections carried out on cargo transport units that are already known to be carrying dangerous goods. They are not targeted towards discovering goods for which all documentation and marking is completely absent. The carriage of undeclared dangerous goods is acknowledged to be a problem, as is the lack of information on the frequency of the occurrence and the extent of the problem. Wang and Foinikis (2001) state that cases of undeclared dangerous goods have been identified but are rarely reported to authorities. Mullai (2007) states that case histories have shown that in many instances dangerous goods are not declared and are carried illegally onboard ships. Kelman (2008) states that mis-declaration of cargo increases the risk to crew and cargo on board. He notes the lack of information on the extent of mis-declared cargo in container shipping. Recent random inspections of general cargo containers in the US found that 9% (1235 out of 13,398 containers) contained undeclared dangerous goods (IMO DSC, 2009b). The percentage of undeclared dangerous goods transported worldwide is not known.

The review of compliance monitoring data and information on undeclared dangerous goods shows that even with regulations in place to control risks, these are not always being followed and there is still a possibility of dangerous goods accidents due to both non-compliance and other factors.

### 2.3 Risk assessment in maritime transport

Risk is generally considered to have two main elements - likelihood and consequences. Kaplan and Garrick (1981) state that risk should be defined as a “set of triplets” where the three elements are the scenario (or unwanted event), the probability of the scenario occurring, and the consequences of the scenario. Risk can be presented by a set of curves that represent a range of scenarios that could develop from an activity. Within the IMO’s Guidelines for Formal Safety Assessment (IMO Maritime Safety Committee, 2007a), risk is defined as “the combination of the frequency and the severity of the consequence”. To consider the risk of maritime transport, it would thus be important to consider a range of possible scenarios that result in negative consequences, including both frequent events with minor damage, and rarer, larger consequence events.
2.3.1 Formal Safety Assessment

The Formal Safety Assessment (FSA) methodology is a structured approach to risk analysis and cost benefit assessment that has been approved for use within the IMO’s rule-making process. Guidelines for FSA were first approved by the IMO’s Maritime Safety Committee in 2001 and were updated in 2007. Wang reported in 2001 that formal safety assessment was a new approach to maritime safety that used risk and cost-benefit assessment techniques to assist with decision-making. Previous to this, new regulations were often initiated as a reactionary approach to serious accidents and lessons learned from them.

There are five main steps in the FSA process, as shown in Figure 2.3: identification of hazards; risk analysis; risk control options; cost benefit assessment; and recommendations for decision-making (IMO Maritime Safety Committee (MSC), 2007a). These steps are quite typical for risk analysis methodologies applied to other industries and problems (Guedes Soares and Teixeira, 2001). The FSA process is used to assess “the risks relating to maritime safety and the protection of the marine environment” (IMO, 2002). Thus the approach prioritises consequences with respect to human safety and the marine environment. Wang (2001) states that a formal safety assessment approach is “designed to be applied to safety issues common to a ship type (such as high-speed passenger vessel) or to a particular hazard (such as fire)”.

![Flowchart showing the steps in the Formal Safety Assessment process (adapted from IMO MSC 2007a)](image)

**Figure 2.3** Flowchart showing the steps in the Formal Safety Assessment process (adapted from IMO MSC 2007a)
Since its introduction at the IMO, FSA has been applied to a range of ship-related safety questions. In some cases, the FSA has been quite high-level, addressing a whole ship type, such as container ships (IMO MSC, 2007b), LNG carriers (IMO MSC, 2007c), or passenger vessels (IMO Sub-committee on Safety of Navigation, 2005). In other cases it has been used to look at very specific types of risk control options, such as Electronic Chart Display and Information Systems (ECDIS) (IMO MSC, 2006). Kontovas and Psaraftis (2009) state that FSA is “currently the state-of-the-art method to assess maritime risk and formulate safety policy”, but identify some areas of improvement for application of the methodology, including improved transparency in the studies.

### 2.3.2 Risk analysis techniques

The risk analysis step of the FSA, shown as step 2 in Figure 2.3, is an investigation of the causes, frequencies, and consequences of the important scenarios identified during the hazard identification phase (IMO MSC, 2007a). Fault trees and event trees are mentioned as standard risk assessment techniques that can be used to build a risk model. The FSA document is not prescriptive with regards to methods and mentions that other suitable techniques such as Bayesian network analysis may be used. It is important to be flexible with regard to techniques because not all problems may be suited to the same methods, and the amount of information available may also be limited in some cases. Event trees and fault trees are, however, the most common methods used to date for risk analysis as part of recent formal safety assessments submitted to the IMO. For example the risk analysis of LNG carrier operations conducted by Vanem, et al. (2008) based the frequency assessment on historical data, and consequences were assessed using event tree techniques. The bulk carrier FSA submitted by Japan to the IMO in 2002 (IMO MSC, 2002) used qualitative and quantitative fault trees and event trees. Mullai’s (2007) risk analysis framework for maritime transport of packaged dangerous goods recommended fault tree and event tree analysis. Bayesian networks, however, are also gaining prominence for particular types of maritime risk analysis, for example collision and grounding analysis (IMO Sub-committee on Safety of Navigation, 2005) or to incorporate the human element into risk models (Eleye-Datubo, et al., 2008).

#### 2.3.2.1 Event tree analysis

An event tree is a risk modelling tool that “looks forward from a starting point and considers the possible future outcomes” Vose (2008). It is a branching technique that starts with an initiating event, and is developed through several branches to possible outcomes or consequences. It shows alternative chains of events from an initiating event to final consequences. It can be used qualitatively, without probabilities on the branches, or quantitatively with an initiating event frequency and probabilities estimated for branches. DNV (2002) states that for qualitative use, it is valuable for understanding how event outcomes escalate and how safeguards may be put in place to mitigate outcomes.
Ronza, et al. (2007) describe the main advantages of event trees as being “their immediateness of representation and their potential for being described in a probabilistic way”.

Initiating Event:

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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>YES</td>
<td>p_4</td>
<td></td>
<td></td>
<td>Some cargo and ship damage</td>
</tr>
<tr>
<td></td>
<td>NO</td>
<td>1 - p_4</td>
<td></td>
<td></td>
<td>More serious cargo and ship damage</td>
</tr>
<tr>
<td></td>
<td>YES</td>
<td>p_5</td>
<td></td>
<td></td>
<td>Extensive damage possible fatalities</td>
</tr>
<tr>
<td></td>
<td>NO</td>
<td>1 - p_5</td>
<td></td>
<td></td>
<td>Spill requiring clean-up</td>
</tr>
<tr>
<td></td>
<td>YES</td>
<td>p_4</td>
<td></td>
<td></td>
<td>Some cargo and ship damage</td>
</tr>
<tr>
<td></td>
<td>NO</td>
<td>1 - p_4</td>
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<td>More serious cargo and ship damage</td>
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<tr>
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<td>Extensive damage possible fatalities</td>
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<tr>
<td></td>
<td>NO</td>
<td>1 - p_5</td>
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<td>Spill requiring clean-up</td>
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</table>

Figure 2.4. Simplified event tree for release of flammable liquid from an on board container

The simplified event tree shown in Figure 2.4 is an example of how frequencies can be estimated for various outcomes resulting from release of a flammable liquid from a container. The frequency of the initiating event is represented by “f” and “p” represents probabilities for each of the branches. Ronza, et al. (2007) state that for the process industry a typical initiating event is the spill of a hazardous material. Full quantification of an event tree requires a frequency for the initiating event, perhaps estimated from historical data from an incident database. Branch probabilities could also be estimated from historical data, if available, or by using expert judgement or modelling, or a combination. Ronza, et al. (2007) state that fires and explosions are a type of event where probabilities are normally assigned using historical and statistical analysis of past accidents. If initiating event probabilities are not available, conditional probabilities for
outcomes can be derived if branch probabilities can be estimated, and this may be useful for ranking of consequences.

2.3.2.2 Fault tree analysis

Fault trees take a reverse approach to an event tree in that they start with a “top event” or outcome and work back from this to identify contributing factors. Beresh, et al. (2008) state that fault tree analysis (FTA) is used in numerous applications, from accident investigation to design prototyping. They describe how FTA is deductive in nature, beginning from generalisations and moving to specifics. Fault trees are developed from a “top event” down through intermediate events to basic events. Fault trees are binary in nature and the events are connected with logic gates, usually ‘AND’ and ‘OR’. The ‘AND is the equivalent of a Boolean ‘•’ operator and the ‘OR’ gate is the equivalent of ‘+’. Fault tree analysis may be qualitative or quantitative. Qualitative fault trees provide information about which combinations of failures can result in the “top event” (Aven, 2008).

2.3.3 Risk Measures

Risk measures are used to present the results of the risk analysis of the activity of interest. They combine the likelihood and consequence estimates to produce an estimate of risk. The Center for Chemical Process Safety (1995) states that there are three basic types of risk measures used for transportation risk analysis: risk indices, individual risk measures, and societal risk measures. These are measures that describe risk from a safety perspective. Risk indices are single numbers which are correlated to the magnitude of the risk (Center for Chemical Process Safety, 2000). Individual risk is a measure that is person and location specific (IMO, 2007a). It considers risk to an individual who may be in the effect zone of an incident (Center for Chemical Process Safety, 2000). Societal risk measures present the overall risk to a particular group of people located in the effect zone of an incident or set of incidents (Center for Chemical Process Safety, 2000).

Different risk measures convey different types of information, and the choice of risk measure can depend on the purpose of the risk analysis, the available information and resources, and whether there is an established risk standard to which the results will be compared. The IMO FSA Guidelines recommend that risk should be judged from at least two perspectives, from that of the individual and from that of society (IMO, 2007a). Individual risk is estimated for a particular person at a given location (IMO, 2007a), for example a crew member or a passenger aboard a ship. It is the average risk for a person in the designated location of interest. Societal risk is defined by the IMO as “average risk, in terms of fatalities, experienced by a whole group of people (e.g. crew, port employees, or society at large) exposed to an accident scenario” (IMO, 2007a). Societal risk measures described in the IMO FSA guidelines are Potential Loss of Life (PLL) and F-N diagram (a graph showing frequency (F) of N or more fatalities per year on the y-axis against number of fatalities (N) on the x-axis).
PLL is described as the expected number of fatalities over a year (Aven, 2008), and is a relatively simple measure of societal risk. For describing risk in shipping, PLL is usually presented as fatality per ship year (IMO 2007a). The PLL per ship year is thus the number of expected fatalities that would occur during one year of a ship’s operation. This measure is an average and does not distinguish between high fatality and low fatality accidents. The F-N diagram presents risk in a more comprehensive way that provides information on both low and high fatality accidents. F-N curves are typically log-log plots because the range of values for F and N can span orders of magnitude, as shown in the example in Figure 2.5.

![Figure 2.5](image)

Figure 2.5. F-N curves for different tanker types, showing risk acceptance curves (IMO MSC 2000)

The F-N curve shown in Figure 2.5 was plotted using historical accident data for the period 1978-1998 (IMO MSC 2000). The dotted lines plotted on the diagonal show societal risk acceptance criteria estimated for tanker ships. The ALARP designation means that risks should be reduced to a level “as low as reasonably practical” (IMO MSC 2000). Aven (2008) states that the ALARP principle “means that the benefits of a measure should be assessed in relation to the disadvantages or costs of the measure.”
2.4 Accident and incident databases

The majority of the marine transport dangerous goods risk studies make some use of historical accident and incident data, and some are based only on this type of data. Starling (2006) states that “risk analysis should start with a quantification of the current level of risk based on historical data on accidents, incidents, and near misses.” Guedes-Soares and Teixeira (2001) state that casualty statistics provide an overall view of the level of safety and allow quantification of real safety levels for different ship types as well as main modes of failure. Wang and Foinikis (2001), referring to container ship accident statistics, state that a certain amount of data is considered necessary to enable the determination of probability and consequences of a hazardous event.

There are three main databases containing information on worldwide ship casualties for all flag states and geographic areas. Two of these, IHS Fairplay (previously Lloyd’s Register - Fairplay) and Lloyd’s Maritime Information Unit (LMIU) database, are proprietary databases and fees must be paid for access to data. The International Maritime Organisation’s Global Integrated Shipping Information System (GISIS) Marine Casualties and Incidents Module is a public database but is relatively new and does not contain as many records as the proprietary databases. In general, it can be said that all three worldwide databases contain only the more serious accidents and incidents involving ships.

National casualty databases, such as the Swedish Sea Accident (SOS) database or the UK’s Marine Accident Investigation Branch’s (MAIB) Marine Accident database, generally contain accidents and incidents on the nation’s own-flagged vessels in all waters, and vessels of all flags in national territorial waters. Requirements for reporting vary according to national regulations, but usually accidents and incidents with lower consequences than would be reported in the worldwide databases are included. For example, the MAIB considers a reportable accident to be “an undesired event that results in personal injury, damage or loss” (MAIB, 2009a). In addition, occurrences where there has been “an escape of any harmful substance or agent” if the occurrence “might have caused serious injury or damage to the health of any person” is included in the definition of a reportable accident (MAIB, 2009b). Thus these national databases can be a good source of information on incidents with lower consequences.

For release of dangerous goods during transport, there a few countries that maintain national databases. The US Department of Transportation’s Pipeline and Hazardous Materials Safety Administration’s (PHMSA) Hazardous Materials Incident Reporting System (HMIRS) database and Canada’s Dangerous Goods Accident Information System (DGAIS) are examples. No other similar national databases could be found. These databases provide information for all cases where there has been a spill of dangerous goods during transport.
2.5 Container ship risk studies

Wang and Foinikis (2001) evaluated the potential application of the IMO’s FSA framework to container ships. At the time of their study, the use of FSA was quite new within shipping and studies had only been carried out for a few ship types. As a test case, they investigated only the “fire” accident category for container ships. They considered a full-scale FSA including all accident categories to be too large a scope for their paper. They provide some quantitative estimates on fire frequency for container ships but do not show the significance of this accident type within the larger context of all major accident categories. They used fault tree and event tree structures to show a risk contribution tree for fires on container ships. A breakdown of fires by ship compartment is provided, estimating that 6% of fire incidents are expected to occur in cargo spaces (Wang and Foinikis, 2001). Engine room fires are estimated to account for 75% of all fires. The source for these estimates is not explicitly stated but reference is made to the use of expert judgment, and the authors state that there is insufficient historical data. Talley (1999), in a statistical study of tanker, container, and bulk ship accidents investigated by the US Coast Guard, stated that their results suggest fire/explosion ship accidents result in a greater number of fatal crew injuries than collision, material/equipment failure, or grounding accidents. This was not quantified for each of the ship types. Fowler and Sørgård (2000) included the fire/explosion accident category in their ship transportation risk model, but included container ships together with general cargo ships and ro-ro ships in a broad “general cargo” ship type category. The focus of their model was on the collision and grounding accident categories and the fire/explosion risk was estimated based only on historical frequencies for the world fleet and number of ship-hours in the case study area.

2.6 Risk analysis of dangerous goods transport

The Center for Chemical Process Safety wrote in 1995 that risk analysis “has been used as a management tool to understand and control the risks of selected transportation movements for over twenty years”, but that compared to the analysis of fixed facilities, the use of transportation risk analysis is quite limited. They stated that methodologies for transportation risk analysis are less widely used and understood than methodologies for fixed facilities. Rosness (1998) describes transportation systems such as for marine transportation as distributed large-scale systems that have a decentralised structure for their normal operating functionality. Thus they can be more difficult to analyse and manage from a risk perspective than a fixed facility that has better defined system boundaries.

Centrone, et al. (2008) conducted a literature review for the topic of hazardous materials transportation and the majority of articles addressing risk assessment were for the land transportation modes. There were 55 identified for road, 12 for rail, and 3 for marine transport. Additional references were identified during the literature review for this thesis and the most relevant are discussed in the following paragraphs.
An investigation of marine transport dangerous goods accidents from the years 1986 to 1991 was carried out by Rømer, et al. (1993). The accidents included in the investigation were serious accidents, with the threshold for inclusion being that there was at least one fatality or more than 100 tons of cargo was spilled. All accidents where dangerous goods were involved, either as a cause or as a consequence, were included in the analysis. Their work was based on sea-going tankers and gas carriers, so only considered bulk transport of dangerous goods. Historical data was used in a statistical manner – using a linear regression model to correlate ship size with oil spill size for four main accident types: collision, grounding, structural damage, and fire and explosion. Quite good correlation between spill size and tanker size was found for all accident types.

Talley’s (1996) study of container ship accidents in US waters (both US and foreign flag) used accident data from the period 1981-1989 to generate descriptive statistics from the data and used statistical analysis to determine which of available variables were significant with respect to cargo damage given an accident. Of four vessel accident types, fire/explosion and collision were found to have a higher propensity for incurring cargo damage. Licensed operators were found to have less damage than unlicensed operators, and damage was less for larger-sized versus smaller-sized ships. Consequences to crew were not considered in the study. Causes for the fire/explosion accidents were not part of the investigation, and an estimate of frequency was not generated as part of the study.

Ronza, et al. (2003) developed event trees from historical data for events involving hazardous substances in port areas. The accidents in port areas identified in the historical database, Major Hazard Incident Data Service (MHIDAS) included accidents that occurred during ship approach and manoeuvring, loading and unloading, and land operations (process, storage, and transport) at ports. A general event tree model was developed to show probabilities of events following release, fire, or explosion. Limitations of the database did not allow more specific breakdown by type of ship or activity. It was proposed that these probabilities could be combined with frequencies of root events (initiating events) to estimate outcome frequencies in more specific cases.

Ronza, et al. (2007) used historical data from two spill databases to propose probability data for spills of hazardous materials that occur during land and sea transport. A selection of commercial hydrocarbon products were considered. Probabilities for ignitions and explosions given a spill during transport were proposed.

Yip (2008) used regression analysis of port accident statistics (from a marine accident database) in the Port of Hong Kong for the period 1992 – 2004 to illustrate key characteristics of port risk profile. Factors investigated for influence on port injuries and fatalities included: vessel’s port of registry, type of vessel, type of accident, type of waterway, and whether the vessel was idle or underway.
In summary, the studies found in the literature on risk of dangerous goods or hazardous materials transport accidents were carried out using analysis of historical data and/or risk analysis techniques such as fault tree and event tree analysis. None of the studies found provide an estimate of probabilities for packaged dangerous goods release on board or investigated the distribution of contributing factors for on board releases.
3 METHODOLOGY

The methodology used to carry out the studies and address the research questions is described in the following sections on research strategy and methods. Data sources and analysis techniques are described, and validity and reliability are also discussed.

3.1 Research strategy and justification

The research strategy selected should be appropriate to the research questions and the problem being studied. Yin (1994) states that there are three conditions that should be considered when selecting a research strategy:

- the type of research question posed
- the extent of control an investigator has over actual behavioural events
- the degree of focus on contemporary as opposed to historical events.

The main research strategies identified by Yin (1994) are experiments, surveys, archival analysis, histories, and case studies. Strategies such as surveys and analysis of archival records are considered to have advantages when the research goal is “to describe the incidence or prevalence of a phenomenon”. They are appropriate in situations where the investigator does not have control over events, which was the case for the studies of maritime transport risk.

The archival analysis research strategy is suited to research questions such as “how many” or “how much” (Yin, 1994). It also suits the “who”, “what”, and “where” research questions. The research questions posed for this thesis, as shown in Table 3.1 (and described in Section 1.2), fit firmly into these categories of research questions. One is a “how much?” question for the risk associated with the carriage of dangerous goods on container ships while another is “what is the risk of accidental fires on container ships?”. The other two are “what” questions for determining the contributing factors to undeclared dangerous goods carriage risk and to dangerous goods release respectively. The research strategy of archival analysis, specifically of accident, incident, and inspection reports and databases from selected sources, was thus considered very appropriate to answering the questions. Previous studies carried out by others in the field of maritime transport risk analysis (e.g. Rømer, et al. (1993); Talley, 1996; Wang and Foinikis, 2001) also make use of this type of archival analysis, demonstrating that it is an accepted research strategy for the field of study.
Table 3.1 Research strategy and type of analysis to address research questions

<table>
<thead>
<tr>
<th>Research Questions</th>
<th>Paper/Study</th>
<th>Research Strategy / Analysis method</th>
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<tbody>
<tr>
<td>RQ1: What is the risk of accidental fires on container ships and specifically what is the risk of cargo area fires?</td>
<td>PI: A Risk Model for the Operation of Container Vessels</td>
<td>Quantitative analysis of accident data, modelling of consequences using quantitative event tree analysis</td>
</tr>
<tr>
<td>RQ2: How much does the carriage of dangerous goods contribute to the risk of container ship operations?</td>
<td>PII: Dangerous Goods Transport with Open-Top Container Vessels – Risk Analysis (also partly addressed in PIV)</td>
<td>Quantitative analysis of archival data paired with quantitative event tree analysis techniques</td>
</tr>
<tr>
<td>RQ3: What are the contributing factors to and potential consequences of undeclared dangerous goods carriage by sea?</td>
<td>PIII: Undeclared Dangerous Goods – Risk Implications for Maritime Transport</td>
<td>Analysis of empirical archival data, qualitative use of risk analysis technique, use of historical accident data for quantitative descriptions</td>
</tr>
<tr>
<td>RQ4: What are the main categories of contributing factors to packaged dangerous goods release on ships and where do they originate in the transport chain?</td>
<td>PIV: Analysis of accidents and incidents occurring during transport of packaged dangerous goods by sea</td>
<td>Analysis of quantitative and qualitative archival data.</td>
</tr>
</tbody>
</table>

The research strategy of archival analysis was suited to both addressing the descriptive aspects of the studies carried out for each paper, i.e. describing and quantifying the risk, and also the explanatory components that focused on identifying contributing factors or causes. The research strategy and analysis methods used to address the research questions are presented in Table 3.1. Archival sources can produce both quantitative and qualitative information (Yin, 1994), and that was the case for this thesis. Quantitative estimates were produced for some of the papers, and qualitative models explaining the phenomena under study were produced for other parts of the work.

### 3.2 Data sources

Analysis of existing empirical data was a key research strategy used in all of the papers. A variety of sources was used to address the research questions. The primary data sources were worldwide maritime casualty databases, national maritime casualty databases, a national database of dangerous goods release incidents, and an inspection database, as shown in Table 3.2. The data sources included both quantitative data, such as the amount of material accidently
released, and qualitative data, such as text fields containing “description of events”.

**Table 3.2 Main accident, incident, and inspection databases used for the papers**

<table>
<thead>
<tr>
<th>Information source</th>
<th>Type of occurrence included in source</th>
<th>Papers using sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>World casualty databases covering world fleet of merchant vessels of 100 gross tons and above:</td>
<td>IMO requests member Administrations to submit information for all “very serious” and “serious” casualties. Information on other casualties and incidents may also be submitted if it is considered that there are important lessons to be learned. LRFP and LMIU include both serious and non-serious ship casualties.</td>
<td>Paper I (LMIU)</td>
</tr>
<tr>
<td>• IMO’s Global Integrated Shipping Information System (GISIS) Marine Casualties and Incidents Module</td>
<td></td>
<td>Paper III (GISIS, LRFP)</td>
</tr>
<tr>
<td>• Lloyd’s Marine Intelligence Unit (LMIU) Casualty Database</td>
<td></td>
<td>Paper IV (GISIS, summary of LMIU)</td>
</tr>
<tr>
<td>• Lloyd’s Register – Fairplay (LRFP) Casualty Module</td>
<td></td>
<td></td>
</tr>
<tr>
<td>National casualty databases:</td>
<td>• accidents and incidents • spillage or leakage of dangerous goods (SOS database) • release of harmful substance that may have caused serious injury or damaged the health of a person (MAIB database)</td>
<td>Paper III</td>
</tr>
<tr>
<td>• Swedish Sea Accident Database, SOS (SjöOlycksSystemet)</td>
<td></td>
<td>Paper IV (MAIB only)</td>
</tr>
<tr>
<td>• UK’s Marine Accident Investigation Branch (MAIB) Marine Accident Database</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coverage: accidents and incidents on own-flagged vessels in all waters and vessels of all flags in national territorial waters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>US Hazardous Materials Incident Reporting System (HMIRS)</td>
<td>• Dangerous goods incidents involving a spill or threat to spill • Discovery of undeclared dangerous goods during transport</td>
<td>Paper II</td>
</tr>
<tr>
<td>Coverage: national, includes incidents occurring in all transport modes and phases.</td>
<td></td>
<td>Paper III</td>
</tr>
<tr>
<td>Inspection programme for Cargo Transport Units (CTUs) carrying dangerous goods: Swedish Coast Guard Inspection reports</td>
<td></td>
<td>Paper IV</td>
</tr>
<tr>
<td>Coverage: national</td>
<td>Non-compliance with regulations for transport of dangerous goods by sea. Some undeclared dangerous goods cases are also included.</td>
<td>Paper I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Paper III</td>
</tr>
</tbody>
</table>

Information from all three worldwide ship casualty databases - IMO’s GISIS casualty module, the LRFP casualty module, and LMIU casualty database - was used for the studies. These databases cover all flag states and all geographic areas. The GISIS casualty module includes data provided by IMO Member States, which are requested to submit information on “very serious casualties”
and “serious casualties” (IMO, 2008c). “Very serious casualties” are those where there have been total loss of the ship, loss of life, or severe pollution (IMO, 2008c). “Serious casualties” include those that do not qualify as “very serious” but involve fire, explosion, collision, grounding, contact, etc. that has resulted in the ship being unfit to proceed, or in pollution, and/or the ship has required outside assistance (IMO 2008c). Information on “less serious casualties” and “marine incidents” should be submitted if it is considered that there are important lessons to be learned. Both the LRFP database casualty module and the LMIU casualty databases contain records of casualties occurring worldwide to sea-going merchant vessels of 100 gross tons (GT) and above. These contain more records than the IMO GISIS, which is relatively new. Casualties categorised as “serious” and “not serious” are included. For the LRFP, accidents are categorised as collision, contact, hull/machinery damage, wrecked/stranded, fire/explosion, foundered, missing, war loss/hostilities, and miscellaneous. Similar categories are used in the LMIU database, and these are described in IMO MSC (2007b).

Two national maritime casualty databases provided information for the study. The MAIB database from the UK and the Swedish SOS database were searched for accidents and incidents which involved dangerous goods and the records of these incidents were reviewed. For the SOS database, reports were obtained for a ten-year period from 1999 to 2008 for Swedish-flagged cargo ships (including ro-ro) and ro-ro passenger vessels in all waters, and foreign-flagged cargo ships and passenger vessels in Swedish waters. Occurrences in the categories fire; leakage; pollution/discharge; injury/poisoning/death; and other accidents and occurrences were reviewed. For the UK’s MAIB database, case information was provided for all accidents and incidents where there had been an escape of harmful substance of this type as well as any other accident types where dangerous goods were noted to be involved. Records from 1998 to 2008 were reviewed for the studies.

The HMIRS database includes records of hazardous materials (dangerous goods) releases, “threats to release”, and “undeclared shipments of dangerous goods with no release” that occur during transport of dangerous goods in the US. Although it is a national database, the transport volumes represented are quite large. For example, the volume of containers transported to and from the US accounts for 9% of worldwide container traffic (US Department of Transportation, Research and Innovative Technology Administration, 2011). The HMIRS was the largest source of incidents found for the study of dangerous goods release, and there is no similar international database of dangerous goods transport incidents available. The worldwide ship casualty databases are focused on incidents where there has been ship damage or a fatality, and do not include dangerous goods releases with limited damage or injuries. The HMIRS is a public database that was accessed on-line for this study (http://www.phmsa.dot.gov/hazmat/library/data-stats/incidents). The data is self-reported by carriers of dangerous goods who are required by federal regulation to file a report (Battelle Memorial Institute, 2009). Incidents which must be reported include those where there has been an unintentional release of a
dangerous good or the discovery of undeclared dangerous goods. All transport modes are included in the HMIRS database, but only water transport incidents were investigated for this study. Full details of the information reported are available in (Catapult Technology Ltd., 2005).

Cargo transport unit inspection reports and data from the Swedish Coast Guard for the period 2006 to 2008 were also reviewed for the study on undeclared dangerous goods. The Swedish Coast Guard has the authority and responsibility for inspecting cargo transport units within port areas in Sweden to check compliance with transport regulations. An average of 962 units per year was inspected during this period and the original paper reports were reviewed. This provided information on non-compliance with regulations.

Other sources of information for the research included:

- marine accident investigation reports: websites of the Australian Transport Safety Bureau, the Transportation Safety Board of Canada, the Finnish Accident Investigation Board, the German Federal Bureau of Maritime Casualty Investigation (BSU), the Hong Kong Marine Accident Investigation and Shipping Security Policy Branch, the U.S. Marine Board of Investigation Marine Casualty Reports, the U.K. Marine Accident Investigation Branch, and the Danish Maritime Authority were searched for any cases involving dangerous goods release.

- library databases were searched to find further information on marine transport dangerous goods accidents and container ship fires.

- input from experts in design, operation, and regulation of ships: this was obtained in the hazard identification step of the FSA studies which Papers I and II were a part of. The Failure Mode and Effect Analysis (FMEA) technique was used in moderated expert meetings to generate information on hazards, potential causes, and consequences. Records from these sessions were used as a qualitative information source for the risk analysis work described in Papers I and II.

3.3 Methods

The quantitative event tree analysis method was used to estimate risk. The event tree analysis concept was also used qualitatively to portray possible outcome scenarios. The fault tree analysis approach was used qualitatively to develop simple models to portray cause for dangerous goods release and carriage of undeclared dangerous goods. Information from the databases was used both to estimate frequencies and probabilities for the quantitative models, and to generate descriptive statistics and input to the qualitative models.
3.3.1 Risk estimation methods

Quantitative event trees models were developed to evaluate outcomes for the study of risk of fires on container ships (Paper I) and the study of risk of carriage of dangerous goods on container ships (Paper II). Goossens and Cooke (1997) state that event tree modelling has been shown to be “most suitable for modelling hazardous systems on the level of integrated safety functions (and not on the level of components)”. This quality made them particularly useful for the applications in Paper I and Paper II which were modelling outcomes for a generic ship. Branches essentially portrayed higher level safety system success or failure, such as fire detection or fire fighting systems, rather than specifically considering success or failure of a valve or pump. For the container ship fire study, the frequency of the initial event was estimated using number of accidents from the LMIU database as a numerator and an estimate of fleet at risk for the same time period from the same source as a denominator.

For the dangerous goods study, the frequency of initial release for dangerous goods was estimated using incidents recorded in the HMIRS database as a numerator and container ship call data for US ports was used to estimate the denominator. Frequencies were expressed as incidents per ship-year. Quantitative probability data for the event tree branches were estimated based on HMIRS data, literature references, expert judgements, and in some cases simplified assumptions. Outcomes for each accident sequence with respect to human safety were quantitatively described in terms of numbers of fatalities. MS-Excel was used to calculate outcome probabilities and to present the event trees graphically. The total frequency figures and total expected number of fatalities were combined to derive key safety figures such as PLL (Potential Loss of Life) and individual risk per ship-year for each dangerous goods class or sub-class considered. Risk was also portrayed as an F-N (Frequency – Number of fatalities) curve.

3.3.2 Contributing factor assessment

High level causes and contributing factors to dangerous goods release were portrayed qualitatively in fault tree style diagrams. These were identified during review of incident reports in the databases and accident reports obtained from all sources. Factors and “root causes” were also identified at the expert meetings.

3.3.3 Data analysis

Worldwide casualty data: This was used to determine number of accidents per category (i.e. fire/explosion), which was used together with fleet data for the same period to estimate frequencies. The information was also used to provide a breakdown of fire/explosion accidents by area of origin (cargo area, etc.) and for comparing total number of cargo area fires to those involving dangerous goods.
National maritime authority accident data: Reports of accident and incidents where there had been an escape of harmful substances were reviewed to identify contributing factors and produce a distribution of accidents by these factors.

HMIRS data: Incident reports and remarks for each dangerous goods release incident and undeclared dangerous goods incidents for the water transport mode were reviewed to determine applicability for the analysis. Only incidents occurring during the “en-route” transport phase on commercial ships were included. Incidents occurring during loading and unloading were sorted out. A manual review of the textual data was carried out to check that the cases were appropriate for inclusion.

For Paper III, investigating risk of undeclared dangerous goods, all reports coded “an undeclared shipment with no release” were included, as well as those few cases of releases that involved undeclared dangerous goods. For Paper II and IV, those coded as “an undeclared shipment with no release” were not included as the studies were concerned with release information. For all cases, textual data was used to validate and check the accuracy of coded data.

The narrative text was used to provide extra detail and supplement the information in the other data fields. This information was used to identify contributing factors for carriage of undeclared dangerous goods in the qualitative model. To identify contributing factors to dangerous goods release, the narrative text was also used to attempt to determine cause of failure if this had not been identified in the coded field. Both narrative text fields “description of events” and “recommendations/actions taken” were used to provide extra detail and supplement the coded data where necessary.

3.4 Data quality and limitations

Although accident and incident databases are important and useful sources of information, they have limitations resulting from uncertainties regarding underreporting, missing data, and data quality. In addition, if information from different datasets is to be compared, there are often different reporting thresholds that should be considered. Underreporting is a recognised problem with accidents databases both in maritime transport (Hassel et al., in press; Psarros et al., 2010) as well as other transport modes such as road transport (Yamamoto et al., 2008; Savolainen et al., 2011).

National and global maritime casualty databases have been noted to have limitations with respect to information on accident causes and the severity of accidents reported, as well as underreporting. Psarros, et al. (2010) state that the databases may contain detailed information on consequences but there is a lack of information on causes. They also found underreporting of accidents in both the national and international casualty databases that were investigated (10 years of tanker casualty records). They estimated that the upper limit for reporting frequency for tanker casualties to the Norwegian Maritime Directorate was 41%, and for the Lloyd’s Register Fairplay Database, the upper limit was 30%. The authors note that these estimates can only be applied to a specific vessel type and
flag fleet. Hassel et al. (in press) compared casualty data from the international database IHS Fairplay and a set of national authorities for a five-year period beginning 2005. They concluded that on average unreported accidents account for roughly 50% of all accidents that have occurred. Flag states were found to have better reporting of accidents involving their own vessels than third party commercial databases.

For the risk analysis for container ships described in Paper I (Ellis et al., 2008), some known accidents were found to be missing from the LMIU database. In other cases, some inconsistencies were noted when database information was compared to more detailed accident investigation reports, for both the LMIU and LRFP databases.

Papanikolaou et al. (2006) found that information in the international marine accident database from Lloyd’s Marine Information Services was insufficient to populate levels in fault trees below the top event for their analysis of tanker casualties, noting that primary root cause of casualties are rarely defined in such databases. They stated that the research group had to use a mixture of historic data and “expert opinion” to develop their fault trees and event trees. For the studies of dangerous goods accidents and incidents carried out for this thesis, the global maritime casualty databases were limited in that they did not have a requirement or reporting field for identifying the involvement of dangerous goods in accidents and incidents. Textual data in the accident description field sometimes provided this information but not in all cases. Accident investigation reports, where available from flag states, provided conclusive information to confirm involvement of dangerous goods. These were not available for many cases, however.

The national databases used in the studies, the MAIB and Swedish SOS, have requirements for reporting occurrences where there has been spillage or leakage of harmful substances (including dangerous goods and marine pollutants). Both of these countries require reporting of an applicable incident by the vessel master or in some cases ship owner representative. Additional information may be requested or collected by the responsible agency. An accident investigation of reported accidents may be carried out, at the discretion of the national maritime agencies (or inspectorate authorities), resulting in a publically available accident investigation report. Underreporting of accidents is also considered to occur in these national databases (Hassel et al., in press).

Underreporting within the HMIRS database of hazardous materials incidents, which requires self-reporting by carriers, is also recognised. The US Pipeline and Hazardous Materials Safety Administration (PHMSA), which maintains the database, conducts searches of newspaper websites and checks incident records of the National Response Center to identify any incidents that have not been reported by carriers during the specified 30-day reporting period. Carriers involved with unreported incidents are notified that they are required to file a report (Battelle Memorial Institute, 2009). It was noted that for unreported incidents identified by PHMSA, road and rail showed a greater percentage than would be expected based on the modal distribution of incident reports (Battelle
A comparison of fatal truck accidents in the HMIRS with those recorded in the Trucks Involved in Fatal Accidents file (a US database covering all medium and heavy truck fatal accidents) for 2005 found that 59.7% of fatal accidents involving spillage of hazardous materials reported in TIFA were also reported in the HMIRS database (Battelle Memorial Institute, 2009). The TIFA data is collected by interviewers from a number of sources, including the police, and is considered to be of high quality. This matching rate of 59.7% of cases gives some indication of the rate of underreporting within HMIRS, but it was stated that this would likely be considered to be an upper limit for the reporting rate and it is applied only to fatal truck accidents. For other transport modes, and spills with no injuries or fatality rates, the rate of underreporting was not estimated.

The PHMSA does quality control checks of submitted reports to look for inconsistencies such as invalid commodities or spill volumes that exceed container volumes (Battelle Memorial Institute, 2009). Carriers are contacted for additional information or clarifications when discrepancies or data irregularities are identified in the submitted reports.

The database limitations described above likely influenced the study results but efforts were made to address these where possible. For the study on container ship risk, data from the international LMIU casualty database was used for initial event frequencies in event tree models, but expert judgment and information from ship operators and classification societies was also used as inputs. Still, the initial event frequencies were likely low, given estimates of underreporting by Hassel et al. (in press) that have recently been published. The risk analysis of dangerous goods transport on container vessels used input data from the HMIRS database to estimate release rate frequencies. This database is also noted to have some underreporting, although the degree for the maritime transport mode is not known. A release rate frequency was also estimated from data obtained from a container ship operator, to ensure the estimate based on HMIRS data was reasonable, and was found to be about 38% higher. For probable loss of life due to accidents involving dangerous goods release on container vessels, the risk determination was done both using HMIRS data and modeling and by using information from IMO databases combined with fleet statistics. Thus two different data sources were used and compared. The study on undeclared dangerous goods used a range of data sources, both qualitative and quantitative, and produced primarily qualitative results, so would be less influenced by underreporting. The study of factors contributing to dangerous goods release used data from two national databases and international data from IMO to produce breakdowns of contributing factors. Underreporting leads to uncertainty about whether all relevant incidents were included and contributing factors identified but the use of three data sources ensured that a larger group of incidents with a broader range of severities is included.
3.5 Validity and reliability

Aven and Heide’s (2009) paper on the reliability and validity of risk analysis states that reliability is “concerned with the consistency of the “measuring instrument” (analysts, methods, procedures). In other words, how repeatable are the results given similar measuring instruments. Jonker and Pennink (2010) state that if the study is reliable, it has been done consistently and the same results would be generated if the study was repeated. Aven and Heide (2009) explain that validity is “concerned with the success at “measuring” what one set out to “measure” in the analysis.” Thus validity is concerned with how close the measurements come to reality. Arbnor and Bjerke (1997) describe validity as “the quality of the knowledge being developed”.

Open databases were used for the studies and data selection methods were explained in each paper which should ensure that other researchers would begin with similar inputs. Subjective judgment and assumptions were used when building the event tree models and at times when assigning probability to some of the branches, and these are documented to provide transparency to the analysis. The use of other assumptions could result in different outcomes even if the same method was used by other researchers.

Data triangulation, defined as the use of variety of data sources in a study (Tashakkori and Teddlie, 1998), was used in the studies. All three main worldwide ship casualty databases were investigated, for example, to identify relevant accidents and incidents and confirm information for Papers II, III, and IV. For Paper I, the LMIU database was the main source. Two different national databases were used when investigating contributing factors to onboard release of dangerous goods (Paper IV). Cargo transport inspection data was also used to provide supplementary information for Paper III. Information from ship operators was also part of the data. Triangulation with different data sources was considered important for validity of results.

Triangulation with multiple analysts is described by Patton (2002) as using multiple analysts to reduce potential bias. Expert audit review is identified as a type of approach to analyst triangulation. Two of the studies, reported in Papers I and II, were reviewed internally within the project of which they were a part (the EU SAFEDOR (Design, Operation, and Regulation for Safety) project) by independent experts who were not directly involved with the work. Both of these studies were risk analysis components of Formal Safety Assessments that were subsequently submitted to the International Maritime Organization. The FSA studies were then reviewed by an international FSA Experts Group. This review included a check of the validity of the input data and its transparency. The experts group consists of representatives from 19 member governments and 7 non-governmental organizations (IMO MSC, 2010a). For the container ship FSA study, the group noted some areas for potential improvement and noted some issues with input data from the available casualty databases (IMO MSC, 2010a). One area for improvement was noted to be the inclusion of highly ranked scenarios in the hazard identification phase regarding working conditions during lashing but working conditions during loading were not part of the scope, as
noted by the SAFEDOR team response ((IMO MSC 2010b). Regarding input data, it was noted that only the LMIU database was used for initiating frequencies and branch probabilities were based on expert judgment, simple formula, and assumptions, with the acknowledgement that these could be improved in the future if new information becomes available. For the FSA study on dangerous goods transported in the holds of open-top container ships, the committee noted the work was done in line with the FSA guidelines (IMO MSC, 2010c) and no comments were raised on input data.
4 SUMMARY OF APPENDED PAPERS

This chapter summarises the appended papers and discusses the connections and links between them. The main purpose, approach, and findings of each paper are summarised. The contributions of each paper towards addressing the various research questions are also described.

4.1 Links between papers

Paper I, a risk model for the operation of container vessels, is an overview, high-level study that considers risks with all aspects of operation, with the relevant area for this thesis being the fire accident category. This higher level study involved construction of an event tree consequence model for cargo area fires, and identified some of the particular issues and problems with cargo fires on container ships. Important areas where further study was required were identified and this lead to some of the work carried out in Papers II, III and IV. Of particular interest were fires involving dangerous goods, and the problem of undeclared dangerous goods was raised. Paper II, also a higher-level FSA, took an in-depth look at carriage of dangerous goods on container ships. The particular interest area of carriage of goods requiring on-deck stowage was investigated. Accident and incident reports reviewed for this study found that many of the identified causes could be considered to originate on the “land” side of the transport chain, prior to loading the goods on a ship. Paper III was a study of the problem of undeclared dangerous goods, which was raised in Paper I, and investigated the extent of the problem, contributing factors, and potential consequences. Paper IV carried out a quantitative investigation of factors contributing to on board release of dangerous goods and assessed where along the transport chain they originated. This was an in-depth study expanding on the qualitative review of release factors in Paper II. Paper IV also had an overall goal of quantifying the contribution of dangerous goods releases to overall container ship accident rates. Links between the papers are shown in Figure 4.1.
Figure 4.1 Links between the papers

The first two papers focused on the ship, as shown in Figure 4.1. Risk models were limited to ship operations and consequences for the ship and crew from ship accidents. Although Papers III and IV also had a primary focus on ship safety, they considered activities further up the transport chain. These were assessed from the perspective of identification of potential factors contributing to dangerous goods release incidents on board. All studies were limited to safety risks of the sea transport link and did not consider the safety risks during land transport and intermediate storage.

A simplified version of a multi-modal transport chain, shown in Figure 4.2, illustrates the focus of the studies with respect to the links and nodes. A more complex version of the chain could involve transshipment and additional sea transport links. Papers I and II are focused only on marine transport operations. Papers III and IV have marine transport safety as a focus and also consider how factors and activities occurring during preparation of the goods for transport may affect safety of maritime transport operations. Each of the four papers is summarised in the following sub-sections.
4.2 Paper I: A Risk Model for the Operation of Container Vessels

4.2.1 Purpose

The overall purpose of the study was to develop a high-level risk model of container ships to estimate the current risk profile of container vessel operation and provide a basis for identifying and evaluating potential risk control options. The study summarised in Paper I formed part of a Formal Safety Assessment (FSA) report (IMO MSC, 2007b) that was submitted to the IMO’s Maritime Safety Committee. Each of the main accident categories considered in the study (collision, contact, grounding, fire/explosion, and heavy weather) was investigated by one paper author, and all contributed to overall discussions of how the results could be integrated to produce a risk profile for container ships. The dissertation author investigated the fire/explosion accident category, and it is this work that is relevant to the thesis. The dissertation author also participated in the work of summation and presentation of overall results (all categories summed) and discussion of risk control options.

The purpose of the work carried out by the thesis author in the context of this dissertation was:

- to develop a generic risk model for fire in the cargo area of a container ship
- to develop the risk contribution tree for the fire/explosion accident category, with primary focus on fire in the cargo area, and estimate probabilities of outcomes resulting in human and environmental consequences.
4.2.2 Approach

Historic accident data from Lloyd’s MIU casualty database for the period 1993 – 2004 was used to determine frequency of occurrence for each accident category. Event trees were developed to estimate the consequences from each modelled accident outcome sequence. The study was limited to modelling fully cellular container ships in commercial operations. Sea transit and transit and manoeuvring in restricted waters were considered as well as the loading and unloading phase. Other life cycle phases such as construction, drydocking, repair, and dismantling were not included. For consequence modelling, human consequences were the primary consideration.

For the fire/explosion category, the focus of the study was on cargo area fires and the specific issues with container fires. Fires in other ship areas, such as engine rooms and accommodation areas, were included only on a very general level to ensure the model covered all major accident types. The frequency of the initiating event of fire originating in a container was derived from the LMIU casualty database. Estimates of branch probabilities for the event trees were developed using information from literature sources, review of information in accident database reports, and in some cases assumptions based on expert judgement (described in Appendix I).

4.2.3 Findings

The total risk for human safety for container ship operations, estimated from the event tree modelling and expressed as potential loss of life (PLL) for crew members, was found to be $9.00 \times 10^{-3}$ per ship year. This is the predicted number of crew fatalities expected for one ship year (during the operation of one ship over one year). The fire/explosion accident category represented 16.7% of the total PLL, and had the second largest contribution to the PLL.

The risk profile for container ships was estimated to be within where the IMO states that risk should be “as low as reasonably practical” (ALARP). This justifies investigation and implementation of cost-effective risk control options.

Important in the context of this dissertation, the work summarised in the paper and described in detail in the IMO submission (IMO MSC, 2007b) identified fire/explosion as one of the main accident categories for container ship operations in terms of human safety. Further, it was estimated that 30% of cargo area fires involved containers with dangerous goods. The problem of undeclared dangerous goods was also identified with respect to on board fire fighting and the contribution to increased risk. Fires involving dangerous goods and those involving undeclared dangerous goods were both scenarios that were considered to require further investigation.
4.3 Paper II: Dangerous Goods Transport with Open-Top Container Vessels – Risk Analysis

4.3.1 Purpose

The main purpose of the study was to construct risk models and estimate the risk level for carriage of dangerous goods classified for “on deck stowage only” by the International Maritime Dangerous Goods (IMDG) code for the following situations:

- in the open-top holds of open-top container ships (a novel use of an existing ship type)
- on deck of conventional container ships (the current situation permitted by regulations).

The overall purpose of the Formal Safety Assessment of which this study was a part was to determine whether dangerous goods classified for “on deck stowage only” could be carried with the same level of safety in the open holds of open-top container ships. The risk analysis study allowed a comparison of safety between the two different carriage situations to be made. It also had the goal of identifying scenarios with a higher level of risk where further attention could be focused in the risk control options study.

In the context of this thesis, this paper continued with a more detailed investigation into the risk of dangerous goods transport, following on from the high level analysis of fire in container ship cargo areas.

4.3.2 Approach

An event tree approach was used to model the outcome of the release of a specific dangerous goods class or sub-class. Initial input frequencies for a dangerous goods release were derived from the US Department of Transportation’s Pipeline and Hazardous Materials Safety Administration’s (PHMSA) Hazardous Materials Incident Reporting System (HMIRS) database. This database contains information on dangerous goods release or “threat to release” during transport of dangerous goods. Causes of the initial release were discussed qualitatively.

The risk assessment was carried out for specific classes or sub-classes (divisions) of dangerous goods identified during the hazard identification phase as having the highest risk index. These included classes 1, 2.1, 2.2, 2.3, 3, 4.1, 4.2, 5.1, 6.1, and 8. The analysis was focused on the “en route” phase of transport and did not include loading and unloading activities.
4.3.3 Findings

Risk expressed as potential loss of life (PLL) to crew members was found to be slightly higher for carriage of dangerous goods requiring on-deck stowage in the open holds of open-top container ships, as compared to on-deck stowage on conventional container ships. Scenarios resulting in fire fatalities were dominant for both dangerous goods carriage situations. Open-top container ships had a slightly higher PLL from fire for Class 3, and a much lower PLL for Class 5.1, as compared to on-deck stowage on conventional container ships. The total PLL for fire was quite similar for both carriage situations. PLL for crew by asphyxiation and exposure to toxic substances was twice as high for stowage in open-top hold positions as compared to on-deck stowage, but this accounted for only a small portion of the estimated PLL.

The qualitative review of accident and incident report narratives for dangerous goods release found that many of the identified causes could be considered to originate on the “land” side of the transport chain, prior to loading the goods on a ship. Examples include packing faults, human errors with respect to filling containers and closing valves, and securing within containers.


4.4.1 Purpose

The overall goal of the paper was to investigate the extent and potential consequences of the maritime transport of undeclared dangerous goods. The main objectives of the study described in the paper were as follows:

- to contribute towards the knowledge regarding relative amount, type, and range of potential consequences of undeclared dangerous goods transported by sea
- to identify factors contributing to carriage of undeclared dangerous goods by sea and the potential consequences with respect to ship safety, and develop a qualitative model of undeclared dangerous goods release.

4.4.2 Approach

Cargo transport unit inspection reports and hazardous materials incident data were reviewed to determine the possible extent and potential consequences of undeclared dangerous goods transport. Swedish Coast Guard inspection reports for cargo transport units carrying dangerous goods for a three-year period from 2006 to 2008 were reviewed to gain information on non-compliance with dangerous goods declaration and marking regulations and to search for reports of undeclared dangerous goods. The US Hazardous Materials Incident Reporting System (HMIRS) database was reviewed and reports of undeclared shipments of
dangerous goods were analysed with respect to dangerous goods class and the potential severity of the non-declaration infractions.

Marine world casualty databases, specifically the IMO’s Global Integrated Shipping Information System (GISIS) and the Lloyd’s Register – Fairplay (LRFP), were searched for information on cases involving the release of dangerous goods on board vessels. These provided information on serious casualties. Two national accident databases, the UK’s Marine Accident Investigation Branch (MAIB) databases and the Swedish Transport Agency’s SjöOlycksSystemet (SOS) database were searched for examples of less serious accidents and incidents involving undeclared dangerous goods.

4.4.3 Findings

An analysis of the incident and accident reports found that undeclared dangerous goods enter the transport chain due to factors such as lack of awareness of regulations, mistakes/omissions during cargo transport booking, and deliberate non-declaration. The presence of undeclared dangerous goods does not in itself lead to a release - for the majority of identified cases no release occurred. Incorrect or non-declaration does, however, mean that transport requirements for minimising the risk of dangerous goods releases may not necessarily be applied, thus increasing the possibility of a more serious accident. Extent and type of consequences of releases are related to type and quantity of dangerous goods and the circumstances of the release.

Undeclared dangerous goods were involved in 25% of all serious cargo area fires identified during the period 1998 – 2008 in world casualty databases. They were found to account for six out of a total of 24 serious cargo area fires.

4.5 Paper IV: Analysis of Accidents and Incidents Occurring During Transport of Packaged Dangerous Goods by Sea

4.5.1 Purpose

The study described in this paper had the overall goals of investigating the contribution of dangerous goods releases to overall container ship accident rates and assessing the contributing factors to releases with respect to where along the transport chain they originate. Specific study objectives were as follows:

- to identify and categorise main contributing factors leading to release of packaged dangerous goods on ships, estimate the distribution of each category, and compare the distribution of contributing factors for different data sets, through an analysis of empirical data on accidents and incidents
- to estimate the contribution of dangerous goods releases to total fatality rates resulting from container ship accidents.
4.5.2 Approach

Reports of dangerous goods release incidents occurring during ship transport were obtained from a US HMIRS and UK MAIB databases for an 11-year period covering 1998 to 2008. These national databases provided information on releases resulting in a range of consequences, although the majority were lower consequence incidents and there were no fatalities for any of the cases. The incident reports were analysed to identify and categorise main factors contributing to the dangerous goods releases. Information on serious incidents involving release of containerised dangerous goods obtained from worldwide sources for the period 2006 – 2007 was also assessed with respect to factors contributing to dangerous goods release.

Information on ship casualty events resulting in fatalities on board container ships during the period 1998 – 2008 was also analysed to identify the overall involvement of dangerous goods in fatal ship accidents on container ships.

4.5.3 Findings

The main contributing factors for the majority of releases noted in the HMIRS and MAIB databases had origins in portions of the transport chain occurring prior to loading of the goods on the ship. The most common types of contributing factors identified in the HMIRS data set were problems with packaging and containment and with loading of goods into cargo transport units. These factors were also prevalent in the MAIB cases and the set of serious incidents identified from worldwide sources. Self-ignition of cargo, however, was also a contributing factor for these two data sets, particularly for more serious accidents.

Accidents involving packaged dangerous goods were estimated to account for 15% of all fatalities which occurred as a result of container ship casualty events during the period 1998 to 2008. Dangerous goods self-ignition or ignition of undeclared dangerous goods was identified as a contributing factor for each of the fatal accidents on board container ships during the period studied. Activities connected with documentation and preparation of the goods for transport contributed to each of the accidents.

Activities in the supply and transport chain prior to loading dangerous goods on the ship were found to contribute to the majority of serious and non-serious release incidents involving containerised dangerous goods.
4.6 Summary of findings

A summary of the main findings of the appended papers with respect to how they address the research questions is provided in Table 4.1.

Table 4.1 Summary of papers’ findings related to the research questions

<table>
<thead>
<tr>
<th>Research Question</th>
<th>Research findings from the appended papers</th>
</tr>
</thead>
</table>
| RQ1: What is the risk of accidental fires on container ships and specifically what is the risk of cargo area fires? | • The risk of accidental fire/explosions for container ships was estimated to be $1.5 \times 10^{-3}$ potential crew member lives lost (PLL) per ship year, which was 16.7% of the total PLL estimated for container ship operations. (Paper I)  
• Cargo area fires contributed 26% to the total risk as represented by PLL of crew for the fire/explosion accident category. (study carried out for Paper I)  
• A review of ship casualty database records showed “fire/explosion” to be the accident category with the largest number of human fatalities for container ship casualties for the period reviewed (1993-2004). (Paper I).  
• 32% of serious fire/explosion incidents on container vessels were found to originate in cargo areas, for an 11-year period ending 2008. (Paper III) |
| RQ2: How much does the carriage of dangerous goods contribute to the risk of container ship operations? | • Potential loss of life (PLL) per ship year resulting from dangerous goods release was estimated using event tree models to be $3.68 \times 10^{-4}$ for carriage in on-deck stowage on a conventional container ship. (Paper II)  
• Accidents involving packaged dangerous goods were estimated to account for 15% of all fatalities which occurred as a result of container ship casualty events during the period 1998 to 2008, and thus have an important influence on the risk of container ship operations. (Paper IV)  
• Chains of events of dangerous goods releases that included fire were the dominant type of scenario that resulted in fatalities for both open hold carriage on open-top container ships and on-deck stowage on conventional container ships. (Paper II) |
<p>| RQ3: What are the contributing factors to and potential consequences of | • Lack of awareness of regulations, mistakes/omissions during cargo transport booking, and deliberate non-declaration are contributing factors that can result in the carriage of undeclared dangerous goods. (Paper III) |</p>
<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
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</thead>
</table>
| undeclared dangerous goods carriage by sea?                              | • Potential consequences of carrying undeclared dangerous goods include fire, explosion, loss of life, and material damages, but there are many cases with no release or consequences. (Paper III)  
|                                                                         | • Accidents involving undeclared dangerous goods were found to account for 25% of the 24 cargo area fire casualties and 8% of all shipboard fires during an 11-year period from 1998 to 2008. (Paper III) |
| RQ4: What are the main categories of contributing factors to packaged dangerous goods release on ships and where do they originate in the transport chain? | • The main categories of contributing factors were found to be:  
  o Container/Packaging deficiencies and filling errors  
  o Poor securing, bracing, and blocking, and preparation of the cargo transport unit  
  o Loading / Unloading at the port  
  o Cargo self-ignition. (Paper IV)  
|                                                                         | • The majority of on board dangerous goods releases had main contributing factors that originated prior to the goods being loaded onto the ship. (Paper IV)  
|                                                                         | • Other ship accident categories such as collision or grounding, or heavy weather and extreme ship motions, rarely resulted in dangerous goods releases. (Paper IV)  
|                                                                         | • Self-ignition or ignition of incorrectly declared dangerous goods was identified more often as a contributing factor for the serious accidents involving dangerous goods release. (Paper IV) |
5 ANALYSIS AND DISCUSSION

This chapter provides an analysis and discussion of the main findings of the appended papers as they pertain to the research questions. Contributions of the work are summarised.

5.1 Risk of container vessel fires

The risk of accidental fires on container ships and the relative importance of cargo area fires were determined in the larger context of a study to estimate the risk level for all major accident types for container vessels. This type of overview study facilitated comparison between accident types to allow future prioritisation of safety improvement measures.

A quantitative estimate of risk for container ship operations was developed based on 11 years of data from the LMIU database, covering the world fleet, and on modelling using a combination of data and engineering judgement. All major ship casualty accident categories were included. The risk for human safety from fire/explosion accidents on container ships, expressed as potential crew member lives lost per ship year (PLL), was estimated to be $1.5 \times 10^{-3}$, which was 16.7% of the total PLL estimated for container ship operations, as shown in Table 5.1. The three major accident categories were found to be collision, fire/explosion, and grounding.

**Table 5.1** Summary of risk for human safety (expressed as PLL per ship year) from container ship operations, for main accident categories

<table>
<thead>
<tr>
<th>Accident Category</th>
<th>PLL per ship year (crew)</th>
<th>% of total PLL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision</td>
<td>$6.11 \times 10^{-3}$</td>
<td>67.9</td>
</tr>
<tr>
<td>Contact</td>
<td>$1.25 \times 10^{-4}$</td>
<td>1.4</td>
</tr>
<tr>
<td>Grounding</td>
<td>$1.24 \times 10^{-3}$</td>
<td>13.7</td>
</tr>
<tr>
<td>Fire/Explosion</td>
<td>$1.50 \times 10^{-3}$</td>
<td>16.7</td>
</tr>
<tr>
<td>Heavy Weather</td>
<td>$3.10 \times 10^{-5}$</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$9.00 \times 10^{-3}$</td>
<td>100</td>
</tr>
</tbody>
</table>
For the fire/explosion accident category, the model was focused on cargo fires, with general estimates for other ship areas estimated from historical data. The sequence of events and conditions that were the basis for the event tree model for estimating consequences is shown in Figure 5.1.

**Figure 5.1** Simplified chain of events and conditions affecting event outcomes for fires beginning in the cargo area of a container vessel (adapted from Forsman et al., 2006).

The initial event for the consequence model is cargo fire ignition. Container stowage location was considered an important condition for estimating probability of fire detection and fire fighting effectiveness. Closed cargo holds have fixed fire detection and automatic extinguishing systems and it was considered that fires beginning in holds would have a higher probability of detection and successful fire fighting. Fires in containers carried on deck require manual detection through crew patrols and access to containers for manual fire fighting can be difficult with large container stacks, thus a lower probability of successful fire fighting is expected. Fire spread can vary depending on flammability of cargo, characteristics of adjacent cargo, availability of oxygen, and effectiveness of fire fighting efforts. Dangerous goods cargos carry additional hazards to the crew due to toxicity, corrosiveness, explosivity, and other specific characteristics and quantity and involvement of these goods will affect final consequences. Availability of search and rescue teams if needed, assistance from nearby vessels, weather conditions, and sea state can influence...
the success of evacuation and fire fighting assistance. The quantitative event tree model developed based on Figure 5.1 is shown in Appendix I.

The distribution of fire/explosion events on container vessels by on board location was determined in Paper III (Ellis, 2010) through an analysis of reports in the LRFP database casualty module for the 11-year period 1998 – 2008. The distribution was estimated for the 75 serious or very serious events reported in the database and is shown in Figure 5.2. The cargo area was the location for fire initiation for 32% of the events. This is relatively close to an earlier estimate of 24% by Povel, et al. (2008), which was based on older data from the period 1993 – 2004 from the LMIU database.

![Figure 5.2 Distribution of fire/explosion incidents on container vessels, 1998-2008 (75 incidents), by location of initiating event (summarised from data in Ellis, 2010)](image.png)

The cargo area is second to the machinery area for total number of fires, and is thus important from an overall risk perspective, as the quantitative risk analysis showed that fire/explosion is the second largest accident type contributing to risk on container ships in terms of human safety.

### 5.2 Influence of carriage of dangerous goods cargo on container vessel risk

The study on risk of container vessel fires described in Paper I determined, through an investigation of LMIU casualty data combined with a search of published accident reports, that 30% of cargo fires had dangerous goods involvement (for the period 1993 to 2004). The next study, described in Paper II, was carried out to determine how the carriage of dangerous goods contributes to accident consequences and the risk level of container ship operations. This was done by constructing a risk model using an estimated initial frequency for
dangerous goods release, and constructing event tree models to estimate consequences. The frequency of dangerous goods release per ship year was estimated using data from the HMIRS database for the water transport mode for the 15-year period 1993 to 2007, along with container ship call and fleet statistics. Using data for container ship calls in the US and an estimate of average number of calls per container ship, an estimate of 0.0325 dangerous goods releases per ship year was estimated. Dangerous goods release rates from a smaller container ship operator were also obtained to check that the estimate was within a reasonable range. Approximately two incidents per year were estimated for a fleet of 44 vessels, resulting in an average release rate of 0.045 incidents per ship year. This agrees well with the estimate obtained from the larger HMIRS database and fleet statistics. The majority of the releases did not result in serious consequences.

Consequences to crew were modelled using event trees. A probable loss of life per ship year resulting from dangerous goods release was estimated to be $3.68 \times 10^{-4}$ for carriage in on-deck stowage on a conventional container ship. On-deck stowage conditions were assumed because the work was part of a study task within the EU SAFEDOR project that had the goal of comparing carriage of dangerous goods in the holds of open-top container ships with conventional on-deck stowage. Thus the goal was to find a common basis for comparison. An F-N curve, Figure 5.3, portraying group risk as a frequency-fatality plot, plotting frequency (F) of events involving N or more fatalities, was plotted using results of the event tree modelling. F-N curves that were estimated during the container ship risk analysis for other accident scenarios are also plotted in the figure for comparison to the potential contribution of dangerous goods releases to the overall risk of container ship accidents.
Figure 5.3 F-N curves for major container ship accident categories (adapted from Ellis et al., 2008)

The estimated frequency of one or more fatalities from dangerous goods fires is approximately 22% of the estimated frequency of one or more fatalities from all fires, as shown in Figure 5.3 (note the logarithmic scale). For accidents with fewer fatalities, dangerous goods fires are estimated to be more frequent than fatal accidents from grounding and contact accidents. Accidents involving larger numbers of crew fatalities were not as dominant for dangerous goods fires. Larger numbers of crew fatalities were estimated to be more likely for other accident types where sinking or capsizing may be involved, such as collisions, contacts, or heavy weather incidents. Fire accidents that have resulted in total loss of a container ship have taken longer times to develop, for example the loss of the Hanjin Pennsylvania in 2002 (Munich Re Group, 2006) due to an explosion and fire resulted in only two crew fatalities at the time of the initial explosion. There was time for the remainder of the crew to be rescued after they were unable to control the fire (DNV, 2003).

Further work carried out in Paper IV (Ellis, 2011) estimated a frequency for fatalities from dangerous goods fires on container vessels. Container ship accidents resulting in fatalities during the period 1998 to 2008 were identified from IMO databases and lists of serious and very serious accidents. Contributing factors were investigated for each of the identified casualties through searches of accident reports and other literature sources because worldwide ship casualty databases contain limited information on causes. Dangerous goods involvement
was identified in 3 out of 11 fatal container ship accidents (27%), accounting for 5 out of 34 fatalities (dead or missing) resulting from these 11 accidents. Using world fleet statistics, a fatality frequency of $1.4 \times 10^{-4}$ per ship year was estimated for accidents on container ships involving dangerous goods. This is 15% of fatalities from all container ship casualties during the period 1998 to 2008.

A comparison of the estimated fatality rate for container ship accidents involving dangerous goods to the modelled probable loss of life of $(1.4 \times 10^{-4}$ compared to $3.68 \times 10^{-4}$) shows that they are within the same order of magnitude, but the modelled value is higher. This is thought to be the case due to the conservative estimates regarding the effectiveness of fire fighting and detection. The model assumed effectiveness values for on-deck stowage, whereas some dangerous goods may be carried in holds with automatic firefighting and detection, which may be more effective than manual systems on deck. Some dangerous goods must be carried on deck according to the IMDG code. For other goods carriage under deck may also be permissible. In general, “on deck only” stowage goods are those which require constant supervision, accessibility, or where there is risk of explosive gas formation, development of toxic vapours, or unobserved ship corrosion (Hengst and Molenaar, 1995).

The research provided some quantitative estimates of dangerous goods release frequencies and fatality rates resulting from dangerous goods accidents. The latter was estimated using both modelling and historical data, and was presented in terms of ship years. No other previous literature sources had provided these types of quantitative estimates of risks involved with carriage of dangerous goods cargo on container vessels.

### 5.3 Undeclared dangerous goods

Undeclared dangerous goods have been identified as a cause or contributing factor in some serious accidents on container ships. The fire and explosion on the *Sea-land Mariner* in 1998, which resulted in two fatalities and extensive ship and cargo damage, was stated to have been caused by undeclared polymeric beads which evolved flammable vapours (Maritime Administrator, Republic of the Marshall Islands, 1999). Serious fires on the *Sea Elegance* in 2003 (South African Maritime Safety Authority, 2004) and the *Zim Haifa* in 2007 (Stuart, 2007) were attributed to undeclared calcium hypochlorite.

Contributing factors to and potential consequences of maritime transport of undeclared dangerous goods were determined through a review of inspection reports, HMIRS incident reports, information from ship casualty databases, and a search of accident reports. A conceptual qualitative model, shown in Figure 5.4, was developed following analysis of accident and incident reports. The model shows factors contributing to marine transport of undeclared dangerous goods and potential events resulting from this.
A group of “faults” contributing to the “event” of undeclared dangerous goods being offered for transport is shown on the left side of Figure 5.4. Factors such as lack of awareness of regulations, mistakes/omissions during cargo transport booking, and deliberate non-declaration were found to be “faults” that can result in the carriage of undeclared dangerous goods.

Once undeclared dangerous goods have entered the transport system they may potentially be discovered through random inspections, although the rate of inspections is quite low on an international basis. Undeclared dangerous goods may either be transported without incident or be released during transport. The majority of undeclared dangerous goods reported in the databases reviewed for the study had been transported without incident when they were discovered.

As noted in the cases mentioned previously, some undeclared dangerous goods have been released during transport and have been associated with serious consequences such as fire, explosion, loss of life, and material damages. During the eleven-year period from 1998 to 2008, six serious fire/explosion accidents involving undeclared dangerous goods in containers were identified from a review of accident databases, reports, and literature review. There were 75 serious or very serious fire/explosion accidents reported in a world casualty database for container vessels during this same time period. These are shown according to location of initiating event in Figure 5.5.
Figure 5.5 Distribution of fire/explosion incidents on container vessels, 1998-2008 (75 incidents), by location of initiating event (summarised from data in LRFP, 2009), showing incidents involving undeclared dangerous goods (Ellis, 2010)

The six accidents involving undeclared dangerous goods account for 25% of the 24 cargo area fire casualties and 8% of all shipboard fires in total. The number of serious cargo area fire/explosions is quite small but undeclared dangerous goods could still be considered to be a significant contributor to serious fires in cargo areas of container ships.

5.4 Factors contributing to release of dangerous goods during maritime transport

Factors contributing to the release of dangerous goods during maritime transport were further investigated as part of the study described in Paper IV (Ellis, 2011). Non-declaration of dangerous goods had been identified for some serious releases as described previously. Further investigation was carried out to identify other factors for both serious and non-serious releases.

Other studies had indicated that activities occurring on shore could be important in terms of contributing to on board losses or accidents. Wang and Foinikis (2001), in their formal safety assessment of container ships, observed that shore error accounts for a high percentage of all major loss incidents. Mullai (2007) stated that many marine accidents involving dangerous goods have causes and contributing factors originating in other systems, and gives an example of packaging faults. His statements were based on qualitative assessment of four case studies.

The analysis carried out in the current study found that the majority of dangerous goods releases resulted from faults that originated prior to ship departure. Contributing factors originating on the “land side” are shown in Figure 5.6.
Figure 5.6 Basic fault categories for accidents/incidents where release of dangerous goods is the primary event in an accident (Ellis, 2011)

Only a small percentage of releases followed another primary accident type such as a collision or grounding, or resulted from damage caused by storms and extreme ship motions. For the U.S. database investigated, the HMIRS, about 2% of releases resulted from extreme ship motions during storms. The majority of other releases could be associated with failure causes that were grouped into the main fault categories shown in Figure 5.7.

Figure 5.7 Distribution of generalised causes contributing to release of dangerous goods in HMIRS water transport mode incidents, n = 83, 1998 - 2008 (Ellis, 2011)
The majority of identified causes originated early in the transport chain, as shown in Figure 5.7, prior to the dangerous goods being loaded on to the ship.

Faults introduced early in the transport chain also represented the majority of contributing factors to dangerous goods releases identified in the 14 cases from the MAIB database for the period 1998 – 2008. The two categories containment/packaging and poor securing of cargo inside the cargo transport unit (CTU) were contributing factors in 57% of the cases. Cargo self-ignition was identified in three cases.

Contributing factors to a group of worldwide serious incidents involving release of containerised IMDG dangerous goods on board container ships during the period 2006 – 2007 were also assessed. Problems with containment and packaging, including packaging that was not gas-tight, a rusty metal drum, and a slow-leaking tank, were a contributing factor in 50% of the releases. Cargo self-ignition due to warm temperatures was identified for 30% of the releases, one of which involved undeclared dangerous goods. Thus the contributing factors for serious releases were similar to those for the groups of less serious releases identified in other databases.

Activities in the supply and transport chain were thus found to be very important for on board safety, as the majority of serious and non-serious release incidents involving containerised dangerous goods had contributing factors that originated with these activities.

5.5 Summary of main contributions

Main contributions of the thesis are summarised as follows:

Risk of container vessel cargo fires: the work provided a quantitative estimate of cargo fires on container ships based on world casualty information and event tree modeling. The risk of cargo fires was compared to other container vessel accident types, which was useful for development and assessment of risk control options in further work.

Risk of dangerous goods carriage on container vessel operation: a quantitative risk estimate, expressed as potential loss of life per ship year, was developed based on historical release frequencies and event tree consequence modeling. A quantitative estimate of dangerous goods release per ship year was also estimated based on release data and container ship call estimates. A fatality rate for container ship accidents involving dangerous goods was estimated based on empirical data for comparison to the modelled risk estimate.

Undeclared dangerous goods: a conceptual qualitative model showing contributing factors and potential consequences of marine transport of undeclared dangerous goods was developed. This type of model can be useful for identifying areas where measures for reducing risks could be considered. The contribution of undeclared dangerous goods to serious cargo area fire casualties was quantitatively estimated.
Factors contributing to the release of dangerous goods during maritime transport: Factors contributing to the release of packaged dangerous goods on board ships as identified in two accident and incident databases were reviewed and categorised according to main transport chain activities. A distribution of contributing factors according to the main categories was produced using the database records. Activities in the supply and transport chain prior to loading dangerous goods on the ship were found to contribute to the majority of serious and non-serious release incidents involving containerised dangerous goods.

The main results of the work make both theoretical and practical contributions to the area of maritime transport of dangerous goods. From a theoretical perspective the work provides improved understanding of the risks involved with the transport of packaged dangerous goods. Factors contributing to release of dangerous goods are identified and categorised to enhance understanding of risk contributions along the supply and transport chain. Further understanding of the risk of undeclared dangerous goods transport was contributed through the development of a conceptual qualitative model. From a practical perspective, the results of the work provide information that can be useful for improving safety. The distribution of factors contributing to on board release of dangerous goods shows that most originate prior to loading on board ships. Thus efforts directed at ensuring the dangerous goods are adequately packed, labelled, and declared before loading should result in reduced release incidents. Improved knowledge of the contribution of dangerous goods to cargo area fires should also be helpful from a practical perspective for developing measures to reduce fire damages.
6 CONCLUSIONS AND FURTHER RESEARCH

This thesis consists of a series of studies on the safety risks associated with carrying containerised goods by sea, starting with an investigation into the overall risk of fires on container ships, continuing with studies on the risk of dangerous goods carriage, and finishing with an investigation into the factors contributing to the release of dangerous goods on board. The work started at a higher overview level, with the study on container ship cargo area fires, and became more focussed on the specific safety risks of dangerous goods carriage as questions arose from the initial work.

A literature review identified concerns with cargo area fires and dangerous goods accidents on container ships, and also the lack of studies and analyses in this area. The work conducted for this thesis was an effort to fill in some of the gaps and lead to improved understanding in the area, with an ultimate goal of contributing to a higher level of safety.

6.1 Main conclusions

The container ship risk analysis modelling work determined that the fire/explosion accident category was the second largest contributor to overall human safety risk, accounting for 16.7% of the risk expressed as potential loss of life (PLL) for crew members. The fire/explosion category had the most crew fatalities reported for the period 1993 – 2004, as determined through the review of reported casualty data. The risk analysis study, part of a Formal Safety Assessment, contributed to the knowledge in the area, as no previous study of container ship risks had been found in the literature. It provided an overall view of the risk level and a basis for focussing further investigations on specific aspects of container ship safety.

An analysis of ship casualty statistics found the cargo area of container ships to be the location for fire initiation for 32% of fire/explosion events. Dangerous goods cargo involvement was identified for 15% of crew fatalities resulting from container ship casualties during the 11-year period from 1998 to 2008. A dangerous goods release rate for carriage of packaged dangerous goods was estimated to be 0.0325 per ship year, using data from the US Hazardous Materials Incident Reporting System (HMIRS) database for the water transport mode for the 15-year period 1993 to 2007, together with container ship call and fleet statistics. No previous literature sources had provided quantitative estimates of release frequencies and fatalities from packaged dangerous goods carriage. The relatively high percentage of crew fatalities for ship casualties where
dangerous goods are involved indicate that improvements in safety regarding dangerous goods could have an effect on overall safety.

Undeclared dangerous goods were found to be involved in 25% of all serious cargo area fires reported for container ships during the period 1998-2008. A review of inspection and incident reports showed that there are many cases where the presence of undeclared dangerous goods does not in itself lead to a release, but because transport requirements and regulations may not be followed due to the lack of knowledge about the goods by crew members, there could be the possibility of more serious consequences. A conceptual qualitative model was developed based on analysis of accident and incident reports. Lack of awareness of regulations, mistakes/omissions, and deliberate non-declaration to avoid extra costs and restrictions were identified as factors contributing to non-declaration of dangerous goods. Many of the identified incidents did not result in releases or consequences, although there were some serious fire accidents identified. This work contributed to describing and exploring a problem that had been documented in some articles but had not previously been quantified or modelled.

An investigation of factors contributing to the release of dangerous goods during maritime transport found most to originate prior to the goods being loaded on to the ship. Failure causes that could be categorised as deficiencies in packaging and containment or failure occurring during loading of cargo transport units were associated with 91% of dangerous goods release incidents on board vessels reported in the HMIRS database for the period 1998 to 2008. These factors were also found to be dominant in the UK’s Marine Accident Investigation Branch (MAIB) marine accident database cases for the same period and a group of serious incidents identified from worldwide sources. Self-ignition of cargo was also found to be a factor, particularly for the more serious incidents. For three fatal container ship fire/explosion accidents involving dangerous goods release identified from worldwide ship casualty information, self-ignition or ignition of incorrectly declared dangerous goods was identified as a contributing factor. This study contributed new information on the type and distribution of faults contributing to on board releases of dangerous goods, from the perspective of where along the transport chain the faults may have originated and differences based on incident severity. The findings point to the importance for maritime safety of ensuring that dangerous goods are correctly prepared and documented for transport, and the influence of these activities on shipboard dangerous goods releases.
6.2 Areas for further research

The research carried out for this thesis contributed further information on shipboard releases of packaged dangerous goods, including identifying contributing factors such as undeclared dangerous goods and shore side faults. A lack of worldwide data on dangerous goods releases and limitations on accident cause information in the ship casualty databases was identified, and this prevented detailed investigations of underlying factors. The International Maritime Organization has implemented stricter reporting requirements so in the future there may be more empirical information available, particularly for the more serious accidents. This will be helpful to future studies.

Regarding undeclared dangerous goods, information was scarce for this and again, more inspections and reporting would provide the basis for further study. This would allow quantification of the problem and would also be useful for development of risk control measures. The review of the reported results of cargo transport unit inspection programs showed that non-compliance with dangerous goods transport regulations is common and the rate of non-compliance has not changed significantly in recent years in most countries. Underlying factors for non-compliance and measures to increase compliance rates are other areas where additional study would be of interest.

Faults occurring prior to goods being loaded on to ships were identified as contributing factors for the majority of shipboard releases. Risk control measures to reduce the incidence of these faults should be investigated. More training and control of shore side personnel responsible for initial loading of the goods has been identified by those in the maritime industry but enforcement and implementation of this on a worldwide level could be both costly and difficult. Measures undertaken at the port or by ship operators may also be something that should be considered, but these also come at a cost. Further study and investigation of the costs and benefits of risk control measures is necessary to find effective and efficient solutions to improve on board safety.
7 REFERENCES


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APPENDIX I – EVENT TREE MODEL FOR CONTAINER VESSEL FIRE DEVELOPED FOR PAPER I

Details of the event tree model for container vessel fire are provided in this appendix. This model was part of the risk model for operation of container vessels described in Paper I. Part of the information presented below was also published in the study report “FSA – container vessels; Details of the Formal Safety Assessment” (IMO Maritime Safety Committee, 2007), which provided detailed information on the study described in Paper I.

Container vessel fire event tree model

The event tree model for container vessel fire was focussed on cargo area fires involving containers, as shown in Figure AI.1. Branches were also added to the event tree for fires originating in the engine room and other areas because they contribute to the overall number of fires on board, but they were represented only at a very general level. The initiating event frequency for the fire/explosion event tree was estimated from LMIU data, as described in Paper I (Ellis et al., 2008), to be $3.55 \times 10^{-3}$ events per ship year. From a total of 109 fire/explosion incidents in the data set, 51% originated in machinery spaces and 24% originated in cargo areas. Of the fire/explosion incidents originating in the cargo area, 20 were categorised as fires, 3 were categorised as an explosion with subsequent fire, and 3 were explosions where it was not clearly specified if there was a subsequent fire. The more detailed portion of the model was developed for the “fire only” incidents (representing 20/108, or 19% of all fire/explosion incidents for the data set).

Probabilities for each of the various branch points along the event tree were estimated based on available data or engineering judgement and assumptions, and are described as follows for each branch point statement:

Fire is detected before it spreads beyond initial container: It was assumed that 70% of the time the fire would be detected before it spread beyond the containers, based on the following:

- 50% of containers for the reference ship are carried in holds with fire/smoke detection systems. It was assumed that any fires beginning in holds would be detected before the fire spread.
Figure A1.1 Event tree on container vessel (1 of 2)
Figure A1.1 Event tree fire on container vessel (2 of 2)
• 50% of containers are carried on deck: it was assumed that the crew would detect a fire before it spread for approximately 40% of the cases.
  \[40\% \times 50\% = 20\% \text{ of total.}\]

**Container is in hold with CO\textsubscript{2} or water spray:** For the reference ship used for this risk analysis, it is assumed that 50% of the containers are carried in closed cargo holds with hatch covers and an automatic fire fighting system. The remaining containers would be carried on cargo hold hatch covers or on deck.

**Automatic fire fighting is effective:** It was assumed that an automatic firefighting system would be effective in 50% of cases.

**Hazardous goods are in containers affected by fire:** A review of the accident descriptions for the cargo fire incidents in the LM IU database indicated that at least 9 out of 27 were likely to have dangerous goods involved. Hazcheck Systems (2003) reported that there had been nine major fires involving dangerous goods on container ships in recent years, which supported the information found in the data review. Based on the data review, it was assumed that 30% of fires on a container ship would have dangerous goods present in containers affected by fire.

**All dangerous goods have been properly declared and marked:** Some limited data on compliance monitoring in Sweden of dangerous goods transported by sea was reviewed (Melander, 2001). Based on this information, an estimate of 80% was used. If dangerous goods have not been declared, there is a risk that they have been stowed under inappropriate conditions (perhaps under deck when they should be stored on deck, perhaps in an area that is too warm, or perhaps next to incompatible goods). If dangerous goods have not been declared, it is more likely that inappropriate fire fighting measures will be attempted and that crew injuries/fatalities will occur. It was also assumed that a fire would spread more quickly if undeclared dangerous goods were onboard.

**Effectiveness of manual fire fighting:** Manual fire fighting on a container ship is difficult due to problems of container accessibility, limited crew experience with fire fighting, and equipment limitations. No statistics were available so the following assumptions were made regarding the effectiveness of manual fire fighting:

- No dangerous goods involved: 20% effectiveness of fire fighting assumed
- Correctly declared dangerous goods: 10% effectiveness assumed
- Undeclared dangerous goods: 5% effectiveness of manual fire fighting assumed.

**Fire fighting assistance from other vessels or land possible to control the situation:** Povel (2005) stated that 32% of reported fire/explosion incidents occurred in port areas, 57% occurred at sea, and 12% were reported as “unknown”. It was assumed that for most accidents in port areas that fire fighting assistance would be available quickly. In a small percentage of fires at sea timely
assistance may also be available (the container ship Sea-Land Mariner was assisted by the USS Wasp following an explosion and fire in a cargo hold (Maritime Administrator, Republic of Marshall Islands, 1999)). For the event tree analysis it was assumed that in 35% of cases timely fire fighting assistance can be obtained.

Fire extinguishing / vessel towing possible: It was assumed that in most cases (95%) the fire would eventually be brought under control and the vessel towed and salvaged. The high number was assumed because even in cases with severe fire and explosions, such as for the Hanjin Pennsylvania container vessel accident, the vessel was eventually brought in to a port, although in this case it was declared a constructive loss. None of the fire/explosion in cargo area cases in the database involved total loss of the vessel.

Timely evacuation and rescue of crew possible: As for the question above, it was assumed that in most cases this would be possible. For all of the 26 fire/explosion in cargo cases in the LMIU database investigated for this study, the crew was rescued. However, it is conceivable that in some situations out at sea or in severe weather, or where fire has spread to the accommodation area, that not all crew may be rescued. The following assumptions regarding evacuation were made:

- Vessels with no dangerous goods: Assumed that for 99.5% of the cases the timely evacuation and rescue of crew would be possible.
- Vessels with dangerous goods: Assumed that timely rescue would be possible in 98% of the cases. With dangerous goods on board the fires are likely to progress more quickly, there is the potential for explosions, and crew may also be affected by toxic gases and smoke.

The portion of the event tree related to fires in the cargo area contains a total of 57 accident sequences resulting in various outcomes, as shown in Figure AI.1. The potential loss of life (PLL) from cargo area fires was obtained by multiplying the calculated frequency for each scenario by the number of expected fatalities and summing the values obtained from all scenarios. The PLL for cargo area fires (scenarios 1 to 57) was calculated to be $3.9 \times 10^{-4}$. The PLL for all fire/explosion branches, including fires originated in other areas is $1.5 \times 10^{-3}$.

References


APPENDIX II – APPENDED PAPERS

Paper I

Paper II

Work published in:

Paper III

Paper IV