Department of Industrial Engineering and Management

Fire Risk and its Management in Cruise Vessel Construction Projects

Pekka Räisänen

Aalto University

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Fire Risk and its Management in Cruise Vessel Construction Projects

Pekka Räisänen

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Abstract

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Abstract

The purpose of this research was to identify and describe the project fire risk in the cruise vessel building industry, to assess the size of risk and to explicate responses. The theoretical approach was based on project management, general fire risk management and shipbuilding literature. The study was carried out with seven shipyards of four European shipbuilding companies, which represented 85 - 90% of the world building capacity. The research approach consisted of twelve improvement and benchmarking action cycles with the shipyards over three years, which produced extensive quantitative and qualitative empirical material. Many of the findings were used to improve building processes at the yards.

The practical findings include 14 categories of contributing factors for ignition, three types of consequences, 27 key metrics for risk assessment and 141 responses to fire risk. The empirical data included a unique, very large set of fire incident statistics, which covered 221 fire incidents on 22 vessels. From the empirical material, it was derived that four out of five fires were due to hot work, and that most of the fires were extinguished by personnel on-board with portable extinguishers. It was estimated that large fires of over one million euros in damages occur every 100 – 200 fire incidents.

The thesis provides new information to the discipline of shipbuilding fire risk management in risk identification, assessment and responses. In particular, hot work on-board, management of moveable fire load, personnel behaviour, detection and alarm, suppression, confinement of fire by closing all major openings, and evacuation were found to be important. Furthermore, unconventional commissioning of the ship's own sprinkler systems early in the building process was found to be especially important, and was estimated to reduce the risk of a large loss by an order of magnitude.

The thesis contributes to general project risk management by demonstrating how data from complex construction projects can be used in setting up systematic risk management practices. The action research method was applied in mutual safety benchmarking of rival shipbuilding companies, which has been very useful in obtaining the results, and is recommended for similar problems in other industries. Further fire risk research is suggested in the effects of workforce, the effects of shipbuilding process, the benefits of automatic suppression and the analysis possibilities offered by the European fire incident statistics database.

Keywords shipbuilding, project risk, fire risk, cruise vessel, ignition prevention, management of consequences of fires

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Tiivistelmä

Tutkimuksen tarkoituksena oli tunnistaa ja kuvata projektien tulipaloriski risteilyalusten tuotannossa, arvioida riskin suuruutta ja esittää vastatoimia. Riskiä tarkasteltiin projektijohtamisen, yleisen paloriskihallinnan ja laivanrakennuksen näkökulmista. Työ tehtiin neljän eurooppalaisen yhtiön seitsemällä telakalla, joilla oli yhteensä 85 – 90 % maailman risteilyalusten rakennuskapasiteetista. Telakoilla tehtiin kolmen vuoden aikana 12 kehityskierrosta, mikä tuotti suuren määrän kvalitatiivista ja kvantitatiivista aineistoa. Monet työn tuloksista otettiin telakoilla heti käyttöön.

Tulokset sisältävät 14 syttymistekijöiden kategoriaa, kolme seuraustyyppiä, 27 mittaria riskin arviointiin ja 141 mahdollista vastatointa paloriskille. Työssä saatiin aikaan erittäin laaja tulipalotilasto, joka sisältää 221 tulipaloa 22 laivalla. Havaittiin, että noin neljä viidestä tulipalosta syttyi tulitöiden takia, ja useimmiten laivalla olevat henkilöt sammuttivat ne. Aineiston perusteella arvioitiin, että yli miljoonan euron tuhot aiheuttavia paloja sattuu kerran 100 – 200 tulipalossa.

Työ tuotti uutta tietoa laivanrakennuksen paloriskin hallintaan tunnistamalla riskiin vaikuttavia tekijöitä, arvioimalla niitä ja kehittämällä vastatoimia. Etenkin tulitöiden tekemisen, hetkellisen palokuorman (varsinkin roskien) käsittelyn, henkilöstön taitojen, palojen havaitsemisen, hälytysten, sammutuksen, palo-osastoinnin sekä evakuoinnin havaittiin olevan tärkeässä asemassa. Laivan omien sprinklerijärjestelmien käyttöönoton huomattiin olevan erityisen tärkeää, ja arvioitiin olevan mahdollista pienentää suuren tulipalon riskiä suuruusluokaltaan kymmenenteen osaan aiemmasta.

Työ tuotti myös yleiseen projektien riskienhallintaan liittyvää tietoa. Siinä esitettiin, kuinka mutkikkaan rakennusprojektin aikana voidaan kehittää systemaattista riskienhallintaa. Toimintatutkimuksen taustana oli keskenään kilpailevien telakoiden yhteistyö turvallisuusasioissa, mikä havaittiin tehokkaaksi tavaksi hankkia tietoa. Tällaista lähestymistapaa suositellaan myös muille teollisuudenaloille. Lisätutkimuksia suositellaan erityisesti työntekijöiden, laivanrakennusprosessin, automaattisten palosammutusjärjestelmien ja laajan eurooppalaisen tulipalotietokannan suhteen.

Avainsanat laivanrakennus, projektiriski, tulipaloriski, risteilyalus, syttymien ehkäisy, tulipalojen seurausten pienentäminen

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Preface

In recent years, the size and complexity of cruise vessels have increased remarkably, and their building process demands ever-increasing risk management. Fortunately, this is very clear for the participants of the process, and development is continuous. The present study is one part of this development effort. The cruise vessel operator Royal Caribbean Cruises Ltd wanted to study the fire risks of vessels under construction, and provided a link to four European shipbuilding companies, currently STX Finland, STX France, Fincantieri in Italy and Meyer Werft in Germany. The shipbuilders joined the research by providing most of the information, excellent cooperation and an encouraging atmosphere for the work.

I wish to express my gratitude to my supervisor, Professor Karlos Artto of the Department of Industrial Engineering and Management at the Aalto University School of Science and other members of the faculty for their encouragement and patience. The advice from Professor Jaakko Kujala of University of Oulu is greatly appreciated. Dr Juha Leimu, Dr Tuomo Karppinen and Professor Kalle Kähkönen read the manuscript, and thanks are due to them for their comments and constructive criticism.

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I also wish to thank those colleagues at Turku University of Applied Sciences who have supported my work, especially Mr Veikko Välimaa, and Mr Timo Vuoriluoto. A special mention is due to Mr Kai Saarinen who has run the Ship Laboratory excellently and provided me with spirited support through the dark times.

Royal Caribbean Cruises Ltd has provided the crucial funding in co-operation with Turku University of Applied Sciences, for which I am grateful. The support of Merenkulun Säätiö, Otto A. Malms Stiftelse and Keelbolt Association is also gratefully acknowledged.

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Kuusisto, June 2014
Pekka Räisänen

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List of symbols and abbreviations

APM	Association for Project Management
AR	Action Research
CAT	Chantiers de l'Atlantique (Currently part of STX Europe as STX France)
DNV	Det Norske Veritas
HSE	Health, Safety and Environment
IMO	International Maritime Organization
JLM	Jos. L. Meyer GmbH (Meyer Werft)
KMY	Kvaerner Masa-Yards (Currently part of STX Europe as STX Finland)
NFPA	National Fire Protection Association
OSHA	U. S. Occupational Safety & Health Administration
PMI	Project Management Institute
PMBOK	Project Management Body of Knowledge
PRAM	Project Risk Analysis and Management
PRM	Project Risk Management
RM	Risk Management
S.I.G.	Safety Interest Group of the four shipbuilding companies that was formed during the research
STX Europe	Mother company of shipbuilding companies STX Finland and STX France
RCCL	Royal Caribbean Cruises Limited

Definitions and some shipbuilding vocabulary used in the study

Available response is a response that: 1) addresses one or more fire risks that are important for a cruise vessel shipyard, either by their frequency of occurrence or by their consequences, and 2) can be expected to allow successful implementation of shipyard processes

Building block – Assembly of steel structural parts, which form a volumetric shape

Bulkhead – Transversal or longitudinal ‘wall’ in a ship

Burnable – Capable of burning

Classification societies – International independent organisations that provide services for ensuring quality and safety for ships

Established fire – A fire that has escalated beyond control and that can be dealt with locally with portable extinguishers

Fire incident – Fire on-board, where at least a fire extinguishing blanket or portable extinguisher has been used for suppression

Flag state – The state of registration of a ship

Flammable – Capable of burning with flame

Fuel – Burnable material in general, used synonymously with the term "fire load"

Fuel oil – Fuel for the ships machinery

Grand block – a collection of building blocks, typically a few hundred tonnes in weight

Gross tonnage (GT) – a dimensionless figure related to the total enclosed volume of the vessel, so that roughly 3 m^3 (older definition) of volume corresponds to one tonnage unit.

$GT = (0{,}2 + 0{,}02 \times \log_{10} V) \times V$, where V = volume of the enclosed rooms [m^3]

Hot work – Flame cutting, torching, welding and grinding

Hull erection – Assembly of grand blocks in a dry dock or a slipway

Impact of fire – Consequences of fire

Keel laying – Positioning of first block in dry dock, start of ship assembly

Large fire – A fire that causes a material loss of €1 million or more

Newbuilding (ship) – Ship under construction

Outfitting – Installation of equipment on-board, a general term for installing items that are not structural parts of the hull.

Operational management – Managers shown between the company top management and the workers in the organisational charts

Owner - Ship's owner

Penetration – Typically a flange or muff assembly where pipes or cables go through the deck or bulkhead, can be made water-, gas- and fireproof

Pre-outfitting – Installation of equipment early in the building blocks, prior to hull erection

Risk – Potential for realisation of unwanted, adverse consequences to human life, health, property and environment – see discussions on subchapters 2.1.1 and 2.2.1

Risk size is defined in the study as an unknown function of generic terms as

$$Risk\ size = f(observed\ frequencies\ of\ fires, contr.factors\ of\ ignition, consequences).$$

The terms 'risk size', 'observed frequencies', 'contributing factors of ignition', and 'consequences' in the definition reflect the mixed quantitative-qualitative nature of the available information at the shipyards

Sea trial – Trial run of the vessel on sea under shipyard command for testing the performance of the ship and its systems in real conditions

Sister ship – Similar vessels that follow a prototype vessel in a production series

Author's contribution

The participating companies have kindly provided much of the qualitative and quantitative research material for the thesis as explained in particular in Chapter 3. Most of the proof-reading in English has been sub-contracted to Mr Tim Glogan. Otherwise, the writing, the analyses, and the conclusions are the work of the author.

1 Introduction

Risk of fire is one of the risks related to industrial projects: in particular, complex construction projects such as buildings, industrial sites, power plants or ships require special attention. In this study, the focus is on fires connected with the building process of large cruise vessels. Their fire risk management is particularly demanding compared with more steel-structure dominated ship types such as tankers. For example, cruise ships contain much outfitting work (installation of parts such as machinery, piping and cabins) that increases the risk on the vessels due to increased fire load and concurrent ignition sources. Therefore, managers in cruise vessel projects need knowledge of practices that can be used in fire risk identification, its assessment and in responses. The literature of project risk management provides a good description of the general project risk management process and procedures of risk identification and assessment, but offers few detailed descriptions of potential responses specific to fire risks. The aim of the study is to address this and focus narrowly on responding to fire risk in cruise vessel projects.

In the following sub-chapters, research background and motivation is outlined. This is followed by short introductions to shipbuilding milieu, the cruise vessel shipyards, shipbuilding process and the organisations that are involved in project fire risk management. Finally, the scope and objectives of the research are discussed.

1.1 Research background and motivation

The majority of shipbuilding companies that build cruise vessels have experienced destructive fires in their past. Large fires on cruise ships under construction, e.g. in 1999 (RCCL 1999a), (RCCL 1999b) and in 2002 (CNN 2002) have emphasised the need for project fire risk management; small fire incidents occur regularly in yards. This investigation originates from the initiative of the world's second largest cruise vessel operator, Royal Caribbean Cruises Ltd. RCCL was a client of three shipbuilding companies: Chantiers de l'Atlantique (St. Nazaire, France, currently STX France), Kvaerner Masa-Yards (Turku and Helsinki, Finland, currently STX Finland) and Meyer Werft (Papenburg, Germany). In the spring of 1999, after a major fire on the first vessel of the "Voyager"- series at the Turku yard (RCCL 1999a), Royal Caribbean Cruises Ltd (Kulovaara 2000) decided to increase its fire risk management auditing at the yards and start improvement negotiations with all three yards.

RCCL also saw a need for research on the subject. Consequently, in June 2000 RCCL and Turku University of Applied Sciences (formerly Turku Polytechnic) of Finland agreed to fund a 36-month research project, where the researcher worked as a member of the RCCL building team. The outset of the research was to study the practices of fire risk management and to explicate the state of the art for fire risk management at cruise vessel shipyards. The research was based on close co-operation with the previously mentioned shipyards, which were eager to participate, and provided the research material. The research process was designed around effecting changes at the yards and the monitoring of progress, and allowed the consolidation of a useable theoretical framework on the way. Fire risk is a product of the organizations involved in the shipbuilding process, and "theory" in this context consists of the physical, behavioural and organizational models and factors which describe and influence the phenomenon. The goal was to identify and assess the problem, and explicate responses to fire risk that are available for project managers of cruise vessel building projects, and, possibly, to suggest some improvements. In addition, the purpose of the study was to provide views for further research and development.

The first contacts of the researcher with the participating shipyards indicated that fire risk is linked to the performance of the various parts of the building organisation. Possible viewpoints could be individual workers' safety performance (Saarela 1991), safety actions of the operational management (Schroll 2002, p. 38), or work by strategic top management (Schroll 2002, p. 34). For this study, the natural viewpoint was dictated by the availability of ample interactions with the managers at operational level: project managers, safety managers and departmental managers of the owner's and building organisations. They do not execute single work tasks, such as welding, or form company strategies, but participate in the operational work between these functions. For the purposes of getting a good overall view of practical responses, this was fortunate. The operational managers have knowledge, both of the hands-on work of their subordinates and of the strategic thinking of their superiors, in addition to their own areas of operational responsibility. Furthermore, they have the power to make changes in local fire risk management practices.

Cruise vessel construction is typically a project-oriented business, and consequently background information for the study was found in project risk management literature as well as in shipbuilding literature. For fire risk in particular, a solid background in fire safety discipline was available.

1.2 Cruise vessel shipyard operation

At the time of the investigation large part of the world's cruise vessel building industry was concentrated in Europe (Lloyd's Register statistics of November 2000, cited by Lauttamäki 2002, p. 10): about 90% of the world capacity was located in Finland, France, Germany, and Italy. According to OECD statistics (OECD 2002), in 2001 these countries delivered 16 passenger ships, a total gross tonnage (GT, related to the volume of the ship, see Definitions) of 1,034,000. A typical 90,000 GT cruise vessel had approximate dimensions of about 290 m in length, 32.2 m in breadth (maximum for transiting the Panama Canal) and about 38 m in height from keel to top deck, and cost approximately €350 – 450 million. The trend has been towards increasing ship sizes.

The four largest European cruise vessel building companies were Fincantieri in Italy, Meyer Werft in Germany, STX Finland (formerly Kvaerner Masa-Yards), and STX France (formerly Chantiers de l'Atlantique) with their shares of world deliveries shown in Figure 1.1.

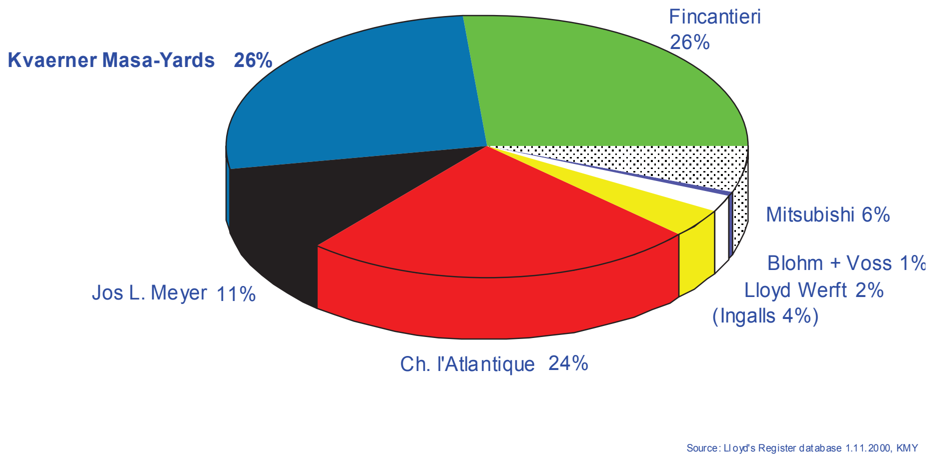

Figure 1.1 Cruise vessel deliveries 2000-2005 according to Lloyd´s Register statistics of November 2000 (Lauttamäki 2002)

1.2.1 Shipbuilding process

A modern shipbuilding process centres around an assembly dock, where partially outfitted (see Definitions) building steel structures (blocks) are assembled on a optimised schedule (Taiminen 2000). For lifting into the dock, these are combined in grand blocks, which consist of several building blocks and sub-assemblies from equipment manufacturers and subcontractors, and weigh 300 - 600 tonnes, depending on the building method and lifting equipment (Gustafsson 2000). Some views of the process are discussed below.

After the building contract has been signed, typical milestones of a ship project are: 1) the start of production, 2) keel laying, where the first building block is laid on the building dock, 3) launching, where the ship is floated for the first time, 4) sea trials, where the systems are tested at sea, and 5) delivery (Holmström 2000). Such milestones may have a special meaning contractually so that part payments or decision timetables are tied to them. How close to each other these milestones are depends on the ship type as well as the layout and process arrangement of the shipyard.

The building process of a ship can also be described as a hull block construction method (EPA 1997 p. 16, National Research Council 1996 p. 45). It is based on dividing the building process according to the steel structure fabrication stages in five to six levels, e.g.: 1) purchasing and pre-assembly,

2) two stages of sub-assembly, 3) assembly and outfitting, 4) erection, and 5) system completion and test and trial. The keel laying, sea trials and delivery belong to levels three to five. This division is rather general and emphasises the steel processing. For outfitting-intensive cruise vessels, more detailed views are available.

A more descriptive process model can be used to incorporate the concurrency of the activities, which involve support processes (Andritsos & Perez-Prat 2000), see the flowchart shown in Figure 1.2. The sub-process of steel assembly is concurrent with the activities of prefabrication of parts and pre-outfitting of systems, which are carried out during the construction of three-dimensional (3D) blocks and during the hull erection phase. Naturally, the extent to which outfitting and steel work are carried out and overlap varies in practice.

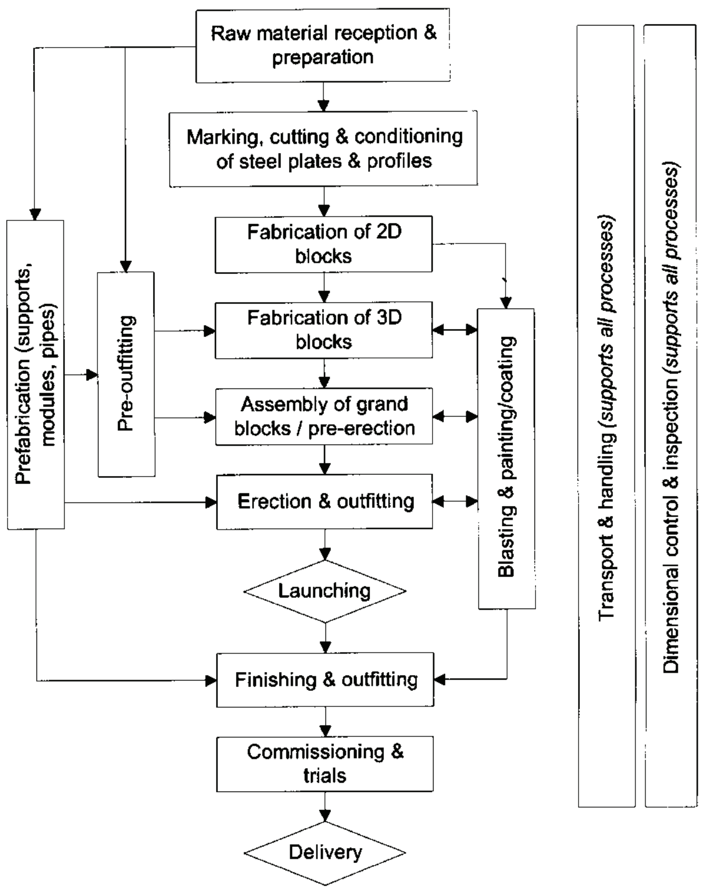

Figure 1.2 Generic shipbuilding process (Andritsos & Perez-Prat 2000 p. 32) © European Communities

A more refined picture of the shipbuilding process may be obtained by further subdivision of the production activities (e.g. benchmarking studies that have been published on Asian (Baba 2001) and on European shipbuilding (First Marine International 2001, p. 8 to 20)). The process can be subdivided into 1) Steelwork production, 2) Outfit manufacture and storage 3) Pre-erection activities, 4) Ship construction and outfitting, 5) Yard layout end environment, 6) Design, engineering and production engineering, 7) Organisation and operating systems, 8) Human resources, 9) Purchasing and supply chain, and 10) Marketing. If the listed items are compared with Figure 1.2, it may be noted that the support and activities that are not steelwork-related have even more emphasis. Shipyard production may also be organised according to its functions or zones (Koenig et al. 2002). For passenger vessel building, a zonal approach, where a restaurant, for example, forms an independent outfitting area for all disciplines (functions), is favoured by some yards (Holmström 2000) due to less interdependence of part-processes.

All the shipyards that participated in the research had processes that fit the descriptions above. Naturally, the individual process descriptions at the yards are more detailed and specific: a cruise vessel may take about two to three years to build from first steel cutting operation to delivery to the owner. In a prototype vessel, the production is preceded by a planning stage, which typically may take a year and continues during building. The production time is variable as, for example, contractual matters, financing, production capacity, the yard's expectations of future workload and regulatory deadlines govern the production schedules. Decreases in time-to-market and building time have led to increased concurrence in activities. In addition to increasing concurrence within a project, the yards often strive to build several ships simultaneously at varying degrees of construction to promote balanced use of production facilities. Simplified, there are two major milestones for the ship delivery process in the building dock: keel laying and delivery. The milestone of keel laying is possible when the design work and the production of the first steel structures have advanced sufficiently for the placement of the first building block in the dry dock (Interactions with Moisio 2000, Longeroche 2001). After this, the assembly of the hull and superstructure often proceed rapidly, with concurrent outfitting and interior work. Some months before completion, a sea trial is carried out to test the vessel systems on open sea. The production process ends at the delivery of the vessel. The yards monitor the degree of completion of a vessel as percentages of completion of the sub-projects (Interactions with

Pitkänen 1999, Moisio 2000, Longeroche 2001) and, translate this into weeks of building time. From a fire risk management point of view, concurrent activities lead to an increased amount of structural welding, cutting and grinding (hot work) during outfitting, compared with more traditional production methods of longer duration and a smaller amount of overlapping. This increases the fire risk for the vessel because many outfitting materials are flammable. On the other hand, increased prefabrication and preoutfitting reduces the risk of the assembled ship, as work is transferred to workshops away from the temporary arrangements on-board (Interactions with Moisio 2000, Longeroche 2001, Wähler 2010, Elice 2003e).

The overall production processes on the four shipyards of this study, served mostly as background (Interactions with Moisio 2000, Longeroche 2001, Wähler 2010, Elice 2003e). The focus of the research was on specific sub-processes, such as hot work and waste removal, problems of which were universal across the yards, and which could be discussed openly between the competing yards.

1.2.2 Organisations in a shipbuilding project

Broadly, the organisational structure of a cruise ship building project consists of the yard and its backing organisations, the owner, the classification societies, the yard suppliers and the public authorities. The daily cooperation of these at the operational management and workforce levels has great effects on fire risk management, as decisions on the practical implementation of the safety policies are made there (Interaction with Longeroche 2001). Typically, the ship owner's project management and its hotel, deck, engine, HVAC (heat, ventilation and air-conditioning) and electric specialists have their counterparts in the yard's project team, which represents the yard organisation. For the owner, the project manager or an appointed safety officer usually takes care of safety during building together with the yard safety manager (Interaction with Miorelli 2001).

A typical cruise vessel building organisation of a shipyard is a matrix of project management functions and the functional departments of the shipyard, such as steel production. The term 'functional department' is used here for the main disciplines of the yard, such as steel production, hull outfitting, interior outfitting and machinery installation. The extent and division of departmental and project group responsibilities vary by shipyard. For example, either a project-related area coordinator or functional departments may be responsible for the progress, workforce, purchasing and turnkey deliveries of the building zones.

A characteristic feature at all yards participating in this study was their increased use of subcontractors. Multinational work crews had also increased in number compared with the situation ten years earlier (Interactions with Högblom 2000, Kulovaara 2000, Longeroche 2001, Pitkänen 1999). This affects project fire risk management.

The project team of the shipyard organisation of a yard is typically rather slim, with only a few persons working exclusively in the project management group (Kvaerner Masa-Yards 2001, p. 20). On the other hand, the functional departments may employ several hundreds of persons directly or through subcontracting, and are organised hierarchically at three to four levels: workers, foremen or team leaders, possibly sub-departmental zone coordinators and department management. The workers belong to groups of typically 10 – 30 persons that are led by foremen, who are responsible to coordinators. Each person on-board contributes to fire safety. The management at each level provides the supporting systems, the safety policies and surveillance (Interactions with Degerman 1999, Moisio 2000, Longeroche 2001).

At all yards studied, safety managers and the other members of the risk management personnel belonged to the permanent yard organisation, and cooperated with the production organisation. Safety managers worked to coordinate the departmental and individual risk management tasks and responsibilities. These were explicated in the form of risk management manuals, instructions to subcontractors and training material for the workers in the yards and their superiors (e. g. (Chantiers de l'Atlantique 2001), (Di Pieri & De Marco 2001), (Kvaerner Masa-Yards 1999), (Interaction with Wähler 2002). This body of knowledge was used during the actions of this study, and also served as sources for ascertaining the state of risk management principles at the participant yards at the beginning of the study.

1.3 Scope, objectives, research questions and limitations

Cruise vessel building projects are complicated ventures and their risk management is demanding. In this research, only one of the risks, the risk of fire on-board during construction is viewed. The existing theoretical frameworks of project risk management, fire risk management and general shipbuilding are used to form a suitable approach for practical interventions in the industry. A passenger ship under construction resembles an ever-changing maze of mechanical engineering, carpentry, piping and electrical workshops where flammable material abounds. This environment is the workplace of individuals from the yard and its subcontractors who carry out welding, flame-cutting and grinding. Therefore, both physical and behavioural approaches to project fire risk management are of interest to the study.

The purpose of the study is to provide a general view of fires in cruise vessel construction through identification of the main sources of fire risk, assessment of the frequency and consequences of fires and, finally, to recommend useful responses (controls) to it. The research questions of this study have been formulated accordingly. The first question relates to the sources and nature of fire risk. The second and third questions relate to measuring the of size of risk and finding some baseline metrics for shipyard use. The scope of the fourth one is broader, and allows a wide spectrum of possible answers. The questions are as follows:

1) What is fire risk in cruise vessel construction projects?
and
2) How can fire risk be assessed in cruise vessel construction projects?
and
3) What is the size of fire risk in cruise vessel construction projects?
and
4) What are available responses to fire risk in cruise vessel construction projects?

For addressing the last question, a definition for the concept of available response was needed.

In this study, the term refers to an action that is practically available for a manager in a shipbuilding organisation, where major changes to the existing practices, budgets, organisation or equipment are often not feasible. Typically, the improvement activities are directed to risks perceived to be the greatest by management and that allow brisk mitigation in an environment constrained by time and budgets. Accordingly, in this context an *available response* is a response, which addresses one or more fire risks that are important for a cruise vessel shipyard, either by their frequency of occurrence or by their consequences, and is applicable in a shipyard process. A response can either be very detailed and thus possibly suitable for one shipyard's building process only, or it can be formulated to be more generic and thus applicable to cruise vessel construction in general. Both alternatives are explored in this study and used to address the research question.

The chains of events that lead to fire losses have two distinct parts: the events before ignition and the events during the actual fires. Common ways of managing both are well-known in society. For example, to reduce the possibility of ignition, flammable materials close to heat sources are assessed and removed, and non-flammable materials are used instead. For ignited fires, however, risk management involves assessment of risks to people and property, followed by appropriate protection and fire suppression. Using this two-stepped logic, the research questions address specific embedded aspects of the following two distinct fire risk management possibilities:

A) Management of fire ignitions
and
B) Management of consequences of established fires on-board

The concept of established fire in this context was defined as a fire, which has escalated beyond the point at which it can be dealt with locally with portable extinguishers. The above alternatives also include the project management view of risk management, which states that risk can be mitigated either by reducing the probability of a negative event or by reducing its consequences.

The research took place in a production management environment, which has steered the focus. In the questions above, and in the consequent discussion, the point of view is at operational level, which refers to the scope of work of managers who are responsible for the daily running of projects' risk management, e.g. safety managers, project managers and managers of production departments.

1.4 Structure of the study

The researcher worked for several years for a ship owner as part of a multinational project team, which had the task of building several cruise ships at three shipyards in Germany, Finland and France. During the course of work, interventions with shipyards' managers were made in the fire risk management practices of the yards. Simultaneously, the answers for research questions were sought. The outcome is described in this study.

In chapters 1 and 2, the problem is introduced and some related terms explained. The relevant theoretical background of project risk management, fire risk management and shipbuilding fire safety is reviewed. Chapter 3 discusses research methods and materials, and includes the selection of the research method and the various methods of data collection. The need to find out more about fire safety in shipbuilding leads directly to studies of the involved organizations, where evidence is broad, varied in form and scattered in multiple sources. For such environments, Action Research (AR) method is commonly used. The method requires unusually broad evidence and thorough triangulation of action cycles, methods and research materials, which explains the large extent of Chapter 3 and the Appendixes. In Chapter 4, factors that contribute to and describe the fire risk that were identified during the interactions with the shipyards are discussed. The possibilities for their assessment are also presented. Based on the collected statistics of fire incidents at the participating shipyards, some summaries of frequencies, the causes and the times of fires relative to the building schedule are presented and discussed. Similarly, the empirical findings on responding to fire risk and the feasibility of the responses are reported in Chapter 5. The research questions are addressed summarily in Chapter 6, and, finally, Chapter 7 ends the study with discussion, contribution, validity and reliability of the work. In addition, some suggestions for further studies are given.

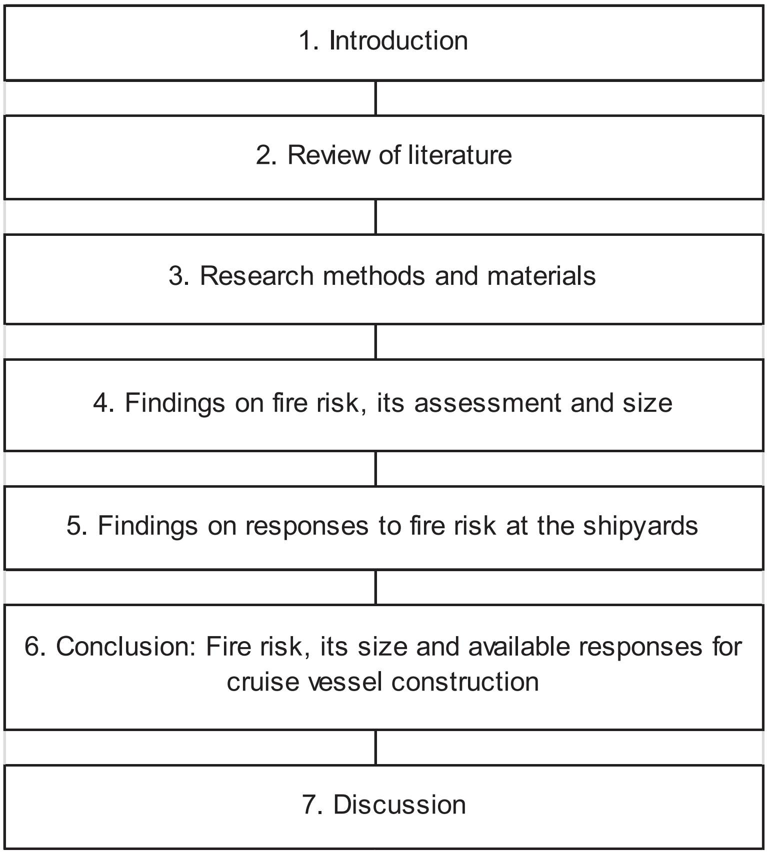

Figure 1.3 Structure of the study

2 Review of literature

The purpose of the study is to discuss the nature of fire risk, and to highlight responses to it in cruise vessel projects. In this chapter, fire risk management is described from project management-, general fire safety- and shipbuilding literature points of view. The findings of these literature reviews include contributing factors to ignitions, possible consequences of fires, as well as responses on work process arrangement that could be available for shipbuilding project management. The findings from references until year 2003 were used in the interactions with shipyards during years 2001-2003. The literature was also important in building the conclusions of the empirical part of the study.

For the specific field of the fire risk management of cruise ship construction projects, there is no obvious, well-published body of knowledge. The literature that relates to ships in operation is of minor value, as the ships under construction often lack the protective measures and trained crew that are available on-board at sea. However, as cruise vessel building is typically a project-based business, project risk management presents a broad and well-established general discipline with suitable concept definitions, which are discussed in sub-chapter 2.1. The discipline of project risk management provides few tools specifically for fire risk. Fortunately, specific details can often be found in the discipline of general fire risk management. They are discussed in sub-chapter 2.1.2. Further, some references to fire safety specific to shipbuilding can be found in its literature. These are reviewed in sub-chapter 2.3. The results of the literature reviews are summarised in sub-chapter 2.4, where summary tables of responses to fire risk can also be found.

2.1 Project risk and its management

In the discipline of project management, risk is an important ingredient, and there are plenty of academic papers on the subject. The practitioners' viewpoint is also well represented in literature. For example, the Project Management Institute (U.S.) has published several editions of 'general practices-documents (Project Management Body of Knowledge, PMBOK) (PMI 1992, PMI 2000). The Association for Project Management (U.K.) has produced sets of best practices (Project Risk Analysis and Management, PRAM) (Chapman and Ward 1997, Chapman 1997, p. 273). An international standard on project management, ISO 10006 (ISO 1997, p. 15) includes a framework for project risk management. For the present inquiry, the focus was on generic project risk management methods and structures that could be useful for managing fire risk in shipbuilding. The findings of the survey are discussed below.

2.1.1 Definitions

In project risk management literature, the definition of the concept “risk” in projects has been discussed broadly, as the actions in risk mitigation are dependent on proper recognition of the target. The earliest views on project risk mostly looked at the negative sides, omitting the possibility of a positive outcome. This has been criticised for limiting the possible views, and a revised vocabulary has been proposed (Ward and Chapman, 2003, p. 102). For example, instead of “project risk” the term “project uncertainty” could be used. This includes the modern view of positive risks, i.e. opportunities (Ward and Chapman 2003). Pender (2001, p. 87) speaks of incomplete knowledge comprising risk, uncertainty and ignorance with underlying fuzziness. A broad definition has been used in PRAM (Ward and Chapman, 2003): “Risk – an uncertain event or set of circumstances that, should it occur, will have an effect on the achievement of project’s objectives”. In the ISO 10006 standard (ISO, 1997, p. 15) the term covers both negative events and opportunities for improvement, and is related either to the processes of the project or its product. All these modern definitions include the negative risks such as fire. Based on the literature, however, the traditional approach of seeing fire risk as a simple “threat to people, property and project objectives” also seems to be sufficient and not too limiting for studying the potential responses to fire risk.

Several ways of categorizing project risks have been used to clarify their management processes. For example, a common categorization refers to project content and to organizing the related risks. The categories are technology, quality, performance, project management, organization, project objectives and external risks (Project Management Institute, 2000, p.131). Another common way is to divide project risks to pure risks (insurable risks), financial risks, country/political risks, and business risks (Artto et al. 2000, p. 8), which allows the relevant risk management tasks to be allocated to suitable parts of the organization. In general context, fire risk can usually be defined as a pure risk that can be partially mitigated by purchasing a suitable insurance. However, in passenger vessel shipbuilding, the insurance market is so small that the shipyards' premiums will increase later, enabling the insurers recover their losses. Thus fire risk in shipbuilding is more like an ordinary business risk, requiring extraordinarily active project management, which is also the point of view of this thesis.

Similarly, the project management processes that can relate to fire risk are interesting. Definitions for the term "project risk management" (PRM) can be found in literature. The early PMBOK (Project Management Body of Knowledge, PMI 1992) defined it thus: "Project Risk Management is the art and science of identifying, assessing and responding to project risk throughout the life of a project and in the best interest of its objectives." The PRAM (Project Risk Analysis and Management, Chapman and Ward 1997, p. 9) view defines the purpose of project risk management as "to improve project performance via systematic identification, appraisal and management of project-related risk". The ISO 10006 (International Organisation for Standardisation, ISO 1997, p. 15) seems to sum up the above as follows: "Management of project risks deals with uncertainties throughout the project and requires a structured approach. The aim of risk-related processes is to minimize the impact of potential negative events and to take full advantage of opportunities of improvement".

The risk management process is usually structured as a feedback loop with separate phases that relate to, for example, acknowledging the risk structure, its assessment, response actions and feedback. Often, the risk management process schedule and scope are designed for each project separately. This can be treated as a separate phase (PMI 2000, p. 129), or for example as separate "definition" and "focus"-phases of the process (Chapman and Ward 1997 and 2003), before commencing the actual risk containment work. The process described by Chapman has response development tasks in identification and assessment phases, and thus has no distinct "response"- phase. PMBOK 2000 (PMI 2000, p. 127) advocates six phases: risk management planning, risk identification, qualitative analysis, quantitative analysis, response planning and monitoring and control. Similarly, PRAM 1997 (Chapman and Ward 1997, p. 48) has nine corresponding but more detailed phases. Chapman and Ward (2004) refer to a risk management process (SHAMPU) of three levels of process, but with three, five and nine phases, respectively. ISO 10006 (ISO 1997, p. 15) has a simple structure. It presents a four-phase project risk management process of identification, assessment, response development and control. Similar simple phase-wise treatment is found in other project literature as well as in other fields. Typical are phases of identifying, analysing and responding to the unplanned events of projects (Rad 2001, p. 3). Patterson and Neailey (2002, p. 366) refer to a five-phase cycle of risk management for the automotive manufacturing industry: identification, assessment – analysis – reduction and mitigation – monitoring, and advocate its use in project risk management. Further examples may be found for example in the processes of Health and Safety in organisations, products or processes, industrial activities or maritime transport (ISO 2002, p. 4; Rouhiainen 1990, p. 14; HSE Executive 2000, p. 19; ISO 1999, p. 5; IEC 2000, p. 15; IMO 1997, p. 16). Broadly, for risk management processes there is a general agreement on the outline content of the process. Simply, the risk needs to be identified, the size of it needs to be assessed and, finally, a response is needed. However, the detailing and assignment of activities to phases may vary (Raz and Michael 2001, p. 10). Later the consequences of the alternative responses may alter the situation, and further management actions may be needed. It has also been noted that risk management process accuracy can be adjusted according to the complexity of the problem (Baccarini, 1996, p. 210, Del Caño and de la Cruz (2002, p. 484). As can be seen above, the process definition alternatives are varied and all have merits, especially in complex risk scenarios. For ease of discussion, the simple process described by International Organisation for Standardisation, (ISO 1997) is useful, and has been used in this study: risk identification, its assessment and the responses to it.

2.1.2 Risk identification, assessment and responses

Project risk identification is a key phase for proactive risk management. Also unidentified risks may emerge during the project, but their risk management must be reactive. Royer (2000, p. 6) suggests that the greatest danger lies in these unmitigated risks, as the recognisable risks have a chance of being controlled during planning. This may be compared with Conroy and Soltan (1998) who quote that 25% of risks may be unidentified at the outset. Ward (1999, p. 333) suggests that, in the identification phase, the focus should be on avoiding the failure to identify any important risk, and warns against excessively early limitation of key risks. ISO 10006 (ISO 1997, p. 15) states that the identification should be carried out at the initiation of the project, at progress evaluations and when significant decisions are being made. Chapman and Ward (1997, p. 55, 95) associated identification with both risks and responses. Typical means of identifying risks by project managers can be listed: documentation reviews, brainstorming, pondering, the Delphi technique, interviewing, SWOT- analysis, checklists, assumptions analysis and diagramming techniques such as system flow charts (PMI 2000, p. 132) (Chapman and Ward 1997, p. 96). Several different types of approaches can be used: historical, divergent and convergent thinking as well as systematic analysis of the process and the product. Risk identification can be limited to cost, time and product risks, but risks related to security, dependability, liability, safety, health and environment can also be important (ISO 1997, p. 15). Rechentin (2004, p. 307) who looks at project management from a health and safety point of view, has criticised PMBOK (PMI 2000) for not emphasising safety as a management objective.

By experience, project managers of large engineering projects such as cruise vessels are aware of the “organisational inertia” and the effects of the counterproductive human behaviour of the participants. Barber (2005, p. 584) has studied these internal project risks (which are due to a project organisation’s or its host’s processes) and concludes that they are difficult to classify, and that common project risk management methods may not be adequate, so advocates further research. Chapman and Ward (1997, p. 96) add that, in addition to searching for risks, they should be classified and primary responses outlined during the identification phase. This is necessary as the risk responses may give rise to “secondary risks”, i.e. new risks due to response actions. The possibility of creating new risks through risk responses implies that the risk process must be iterative, which is the case in the processes that were mentioned earlier. The phase in which secondary risks are studied varies, however. In PMBOK 2000 and ISO 10006, secondary risk management is mentioned first in the “response”- phase. With a broader definition of risk, a key deliverable of risk identification phase(s) may be threats and opportunities, and the consequent planning of responses to these may provide further opportunities (Chapman and Ward 1997, p. 56).

After identification of project risks, risk assessment is used to classify the risks and their effects on the project, determined with sufficient accuracy so that management can make decisions on the relative importance of the risks. In shipbuilding projects, the risk size may remain rather similar from project to project as the project type and site are the same, compared to large civil works, for example. The accuracy of the assessment varies, depending on the need and available data. Chapman and Ward (1997, p. 48) divide the assessment of project risk into four phases: structure, ownership, estimation and evaluation. The testing of simplifying assumptions, using appropriate tools and allocation of responsibilities, is needed. Estimation and evaluation refer to identifying the uncertain issues, making qualitative and quantitative analyses and providing a synthesis of the evaluation (Chapman and Ward 1997), (ISO 1997, p. 16). In qualitative analysis, a typical aim is to assess relatively quickly the consequences and likelihood of risks that have been identified. Typical tools for qualitative analysis are (PMI 2000, p. 135) risk probability and risk impacts in qualitative terms, such as a risk rating matrix based on, for example, expert judgments on likelihood, and on a relative impact scale based on an organisation's values. Project assumptions and data precision can be judged qualitatively. The typical output is overall ranking for the identified risks, the prioritising of risks and the identification of new risks, for example for the quantification of the external and immediate risks and for identifying policy alternatives (Datta and Mukherjee 2001). Risk checklists are commonly used in projects. Risk registers, risk assessment tools based on risk severity ranking and risk databases can also be used (Patterson and Neailey 2002, p. 367). However, the intuition and experience of the project personnel is important as well. Early warnings for project management may thus rank from numerical values to "gut feelings" (Baccarini and Archer 2001, p. 144), (Nikander and Eloranta 2001, p. 385).

Quantitative analysis of project risk can provide a step further in risk assessment accuracy, if good numerical basis is available or can be obtained from, say, calculations, physical testing, pilot projects (Turner 2005, p. 2) or historical data. Naturally, the amount of resources needed and the duration of analysis may increase considerably compared with qualitative analysis. Such things as structured interviews, sensitivity analysis, decision tree analysis and simulation can be used as tools for quantitative analysis, depending on the availability and accuracy of the information (PMI 2000, p. 138). Probabilistic ranking of project risks is quite uncomplicated if only suitable statistical information is available (Chapman and Ward 1997, p. 167). However, obtaining the necessary accurate input data may present problems, especially in prototypes or in short series projects, as in shipbuilding. From the probabilistic viewpoint, project risk variables are stochastic and may change dynamically over time (Jaafari 2001, p. 89) as is the case in shipbuilding projects: the probability of fire breaking out during construction changes with such factors as type of work and workload.

A common way to assess risks is to assign a probability (P) and a quantifiable impact (I) for each identified risk and to compare their products R= P x I to each other. The term R has been called as "concept of risk", "degree of risk", "impact of a risk factor" (Williams 1996, p. 185). A high impact risk may have a very low probability, and thus the product would be small, making the risk seem acceptable. However, the practical view is often that certain risks are unacceptable, the uncertain low probability notwithstanding, and must be mitigated in any case. Williams, for example, criticises Zhi (1995) of the use of the product of probability and impact as a measure of risk, when a set of risks are compared with each other. Instead, the managers should judge the probability and impact separately. The simple probability-impact approach has shortcomings and should be considered in initial identification phases only (Ward 1999, p. 332). Similarly, in a critique of existing general practices, Chapman (2006, p. 307) suggests abandoning this kind of one-dimensional risk-ranking. This has to do with the inherent uncertainty and subjectivity of the variables. In conclusion, from the views above, it seems preferable that the risks should be ranked separately according to their probabilities and impact, rather than using their product for decision support, especially in an industry where production series are short, as in shipbuilding. Further, if information about the probability of a risk is not available for project managers as is common in shipbuilding, studying the factors that influence the risk is a practical alternative.

Chapman and Ward (2004, p. 619) go a step further in using probabilities in project risk assessment, when they advocate the use of "risk effectiveness" to join risk and monetary issues such as cost or profits, which could lead to increased scope and more widespread use of project risk management. In advocating practical viewpoints and a better way of managing project fuzziness, Pender (2001, p. 80) also criticises the basic assumptions of the probability-impact ranking of risks, referring to problems in, for example, randomness, repeatability, human processing capacity limitations, uncertainty, ignorance and project knowledge changes over time. The problem of assigning reliable probabilities to events is present especially in fields where a formal approach is common, such as the reliability engineering of offshore installations, and semi-quantitative solutions may be needed (Aven 2008 p. 769). As discussed above, sophisticated systems have been reported for assessing risk in industry if good input data is available. In comparison, rather simple processes are used in connection with identification, and, in particular, generating the required responses to project risks and their details.

Regarding the varied terminology above that is used in literature, the term *risk size* was defined (see Definitions) for this work, to emphasize that many different qualitative and quantitative ways of assessing the risk were used together in describing the risk in this study.

After identification and assessment of the risks, the managers may need to respond (synonyms: to mitigate or to control), i.e. take action to reduce the effects of the risk on the projects, either the probability of a risk, or its consequences (impact), or both. Fire risk responses in ignition prevention, for example, aim mostly at reducing the probability. In contrast, the responses that concern established fires mostly have the consequences as their target. Chapman and Ward (p. 61) discuss “proactive” and “reactive” alternatives. Proactive responses are often integrated into project planning and reactive responses may be parts of separate contingency planning. One response available for project managers is always inaction (Chapman and Ward 1997, p. 55). They list the response options as modifying objectives, avoidance prevention, mitigation, developing contingency, keeping options open, monitoring, accepting, and remaining unaware. They (1997, p. 94) also emphasise the importance of early identification of available responses. Response practices recorded in standards are avoidance by changes in project plan, transference to a third party, mitigation through reducing the probability and impact of the risk and, lastly, acceptance with possible contingency plans (PMI 2000, p. 140), (ISO 1997, p. 16) (Ben-David and Raz 2001 p. 14). Hillson (2002, p. 238) divides the response planning into risk strategies. For negative risks, four main strategies are possible: avoidance, transfer, mitigation or acceptance. These also provide the practitioner with general directions for seeking responses for the risks at hand.

The responses that need to be developed range from simple to complex, depending on the nature of the risk and the need for proactive and reactive contingency plans. The cyclic nature of response planning is prominent (Chapman and Ward 1997, p. 129). Responses can generate chains of new risks and new responses. The term secondary (tertiary, etc.) risk is used. This concept is well-known by reliability engineers, but may be less known by project managers (Chapman and Ward 1997, p. 131). Proactive responses are often the target of risk managers, and reactive responses are needed when unknown project risks emerge, or when known risks have deliberately been left to chance. When the responses are developed and ready, implementing them and monitoring changes in risks are needed to complete them (Ward 1999, p. 335, ISO 1997, p. 16, PMI 2000, p. 144). In ISO 10006, this phase is called project risk control. In the dynamic environment of project management, changes occur constantly, and risk management must follow accordingly. The changes affect the risks, their interactions and thus their mitigation. Risks that were deemed minor at the start of the project may escalate during project progress, and regular reviews and flexible responses are needed. In cruise vessel construction, this is particularly true, as the series are short, and prototype problems can prevail.

According to Conroy and Soltan (1998), risk management theories available for line management are of limited value to project managers. They base their view on experiences from process industry plant building, and advocate a non-probabilistic, simplified approach. It is clear that resources available to the project manager of a nuclear power plant or a passenger ship building project are vastly different, and a relatively uncomplicated approach may be practical at a typical passenger vessel shipyard. Chapman and Ward (1997, p. 64) refer to the risk management process as a formalisation of the common sense of project managers and advocate a “keep it simple”- approach as risky issues can be complex. This view is a relief for practising operational management, who are short of time and resources. Interestingly, Pavlak (2004, p. 5) even compares the work of the project manager to fire-fighting and distinguishes between proactive work (i.e. avoiding fires) and the complementary activity of troubleshooting (extinguishing fires).

A typical result of proactive risk management is a strategic plan for risk management, which includes methods, key persons, budgeting, schedule, types and thresholds of risk analysis and reporting (PMI 2000, p. 130). In the simplest form, the scope and schedule of risk management are incorporated into the broader project management process, as is common also in shipbuilding.

Based on the literature review on project risk management, it can be said there are sufficient generic alternatives in methods for identification of risks and in methods for assessment of them for the practitioner and the researcher alike. However, for the practical responses of project managers, detailed knowledge of the risks is needed, which is outside the scope of the project management literature. Fortunately, for fires, there exists a general body of literature on fire risks, their assessment and proven responses, which are reviewed in the following sub-chapter.

2.2 Fire risk management in general fire safety literature

Due to its escalating nature, fire may threaten the objectives of a project with complete failure. Large losses due to fires have occurred throughout history, and general fire risk management is a well-established field. The physical, fire-fighting and human behavioural aspects of fires have been studied broadly. The resulting knowledge is largely independent of field of application, and has been applied to manage fire risks in projects. There are also taxonomies that can be used for fires on cruise vessels, and suitable general knowledge of sources of ignition and responses are available. These are discussed below.

2.2.1 Definitions

The typical fire risk management process as described in literature resembles the project risk management process discussed earlier: Watts & Hall (2002 p. 5-4), for example, see fire risk management as a structured approach to identify fire hazards, to judge their consequences and (possibly) probabilities, to identify control options, to judge the consequences of options and to select protection measures.

In a general context, the term "safety" may mean "freedom from danger" and "risk" can be explained with "possibility or chance of meeting danger" (Hornby & Cowie 1980), but the definition of "fire risk" and related concepts is not consistent among the fire safety community (Watts & Hall 2002 p. 5-3). However, their definition for fire risk is "potential for realisation of unwanted, adverse consequences to human life, health, property and environment", which refers only to the negative side of the risk, as there are few practical "opportunities" or positive risks that need consideration. Similar definitions are common in fire risk management literature. Definitions of "fire hazard" combine both ignition and consequences (Kallioniemi et al. p. 19, Watts and Hall p. 5-4). These resemble the view of risk that dominated project risk management discussions throughout the early development of the discipline: a deterministic, controllable threat.

Logically, fire risk management objectives, to prevent harm to people and property can be accomplished either through risk management of ignition or through risk management of fire consequences after failure in ignition prevention. These alternatives categorise the two main types of risks of interest for this research and they also sum up the simple alternatives for managers. Risk management for ignition and much of the preparations for reducing the consequences of established fires are proactive. Naturally, reactive risk management is also needed during fires.

Several terms have been used in literature to describe fire risk that include the factors that relate to ignition and the consequences of fires, such as "variables influencing life safety and egress" Rasbash 2004, p. 24, “ignition sources” (Zalosh 2003 p. 18, Schroll 2002 p. 12), “necessary elements for fires” (Schroll 2002 p. 9), and “prerequisites for fires” (Kallioniemi et al. 2001 p. 8). These terms encompass the generic ‘causes of fires’. For the purposes of this study, the above terms were summarised as *contributing factors of ignition* which emphasise the complex interactions of human, organisational and technical issues that are present in shipbuilding projects. For ‘damage’ in fires, terms such as “consequences” (Thomson 2002 p. 28, Watts and Hall p. 5-4, Zalosh 2003 p. 6), “impact” (Watts 2000) and “losses” (Schroll 2002 p. 1) have been used. The term *consequences of fire* was adopted for this study as it seemed to be in rather general use, whereas the term “impact” (e.g. Watts 2000) was found to be less in use in fire safety than in project risk management literature.

Several approaches have been postulated to categorise, design and organise fire risk management, especially to provide design criteria or to establish the levels of risk for humans in buildings (Rasbash 1977, 1980, Stollard & Abrahams 1999, p. 15, Shields and Silcock 1987 p. 413, Watts 2000). Similarities to project risk literature can be found if the responses are viewed as “proactive” or “reactive”, or if responses are seen as targeting either risk frequency or its consequences. The reasons for fires can also be attributed to natural phenomena, human carelessness, technological failure and deliberate fire-raising and combinations of these (Stollard and Abrahams 1999 p. 22). Ignition sources can also be categorised by type of source: mechanical (e.g. friction, compression), electrical, chemical (combustion, decomposition, spontaneous heating, other chemical reactions) or nuclear (Schroll 2002 p. 13). Risks can be classified according to controls or to practical solutions. Examples: fuel limitation, communication, escape, containment and extinguishing (Stollard and Abrahams (1999). This principle can be elaborated further (Thomson 2002, p. 35) and responses arranged according to structural features, sources of ignition, combustible materials, fire safety checks, equipment and plan maintenance, electrical and gas installations, fire safety checks and reviews of risk assessment, where responses refer to preparations, i.e. the normal operation mode of the industry. Furthermore, other responses can be planned for emergency operation, such as means of escape, fire detection, fire-fighting, lighting, evacuation, fire limitation and liaison with local fire brigades. Evacuation is challenging because people often do not act rationally in an emergency.

As discussed above, the possibilities for categorisation are many. A common fire risk management approach is visualised simply in the fire safety concepts tree (National Fire Protection Association 1986), (Shields and Silcock 1987, p. 424), (Watts 2000), (National Fire Protection Association 2002), which has also been used in several applications (Donegan 2002, p. 5-11, Larsson 2000, p. 19), also in the marine field (International Maritime Organization 2001b). The background of the tree (main branches below, from Watts, 2000) is in system dynamics studies. It has been formed of the two alternatives for fire control, and has been used as a basis to develop new trees with quantitative models of more complete views on fire spread routes and ignition processes (Rasbash et al. 2004, p. 426). It is specifically useful in handling responses, as the branches represent the logical categories of responses that are relevant either before or after ignition.

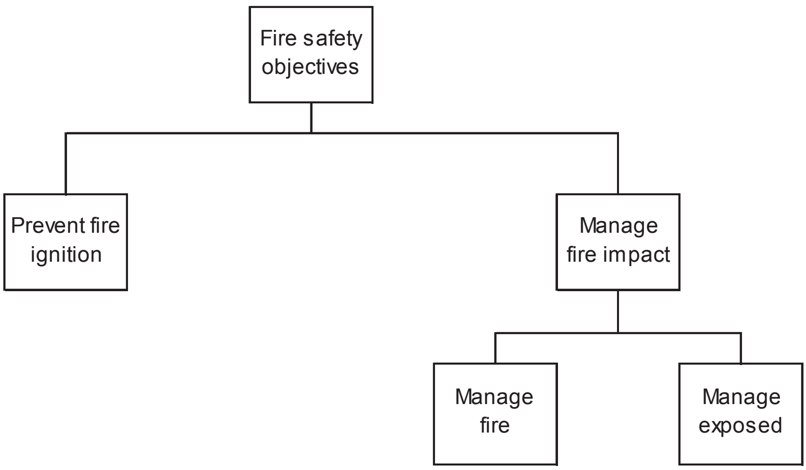

Figure 2.1 The principal branches of the fire safety concepts tree (adapted from Watts 2000), i.e. the response categories related to before and after ignition. Note that Watts uses the term "impact" for consequences.

Risks in both branches can be managed with the simple process in use in both project and fire risk management fields: risk identification, assessment and response.

Generally, ignition of fires may be identified simply as an unwanted combination of three necessary elements; ignition energy source, oxygen and fuel (e.g. Planer 1979). More complicated models of combustion also exist (Sax 1979 p. 234) but are less common. The simplification ignores such factors as spontaneous ignition and decomposition reactions, which, however, do not cause a significant number of fires in general (Hall 1999, Hall 2003a, Hall 2003b, Hall 2003c, Karter 2003, ODPM 2003, ODPM 2002). The importance of the chain reaction of burning (important for some extinguishing methods) is also not emphasised. With these simplifications (Babrauskas 2003, p. 7), the occurrence of fire can usually be treated as a function of the amount of burnable material in a compartment, access to sufficient oxygen and availability of an ignition source (Magnusson & Rantatalo 1998, National Fire Protection Association 1984a, p. 312-4, Netterstrom 1972, p. 199, OSHA 2003e, Robinson 1984, p. 1049, Schroll 2002, p. 72, Thomson 2002, p. 115). The basic physics and chemistry of fires are summarised in Appendix A for completeness. However, it should be noted that fire risks in general literature are often viewed in terms of the normal operation of the system, for example a building or a production plant with the designed safety systems operational, and a trained crew in charge, which often is not the case in shipbuilding.

A simple taxonomy of risks of ignition and the responses to them can be formed with possible controls of sources of energy (heat) and fuel. This is applicable in most fires where sufficient oxygen is available for burning, and the effects of special controls such as for oxygen-enriched atmospheres are omitted.

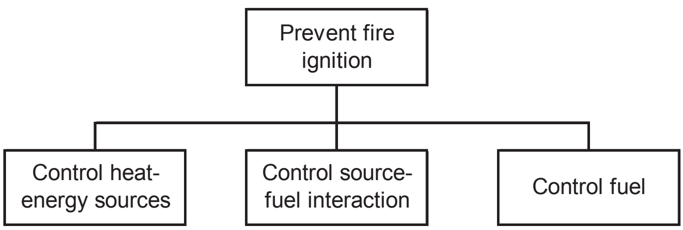

Figure 2.2 Response types in the "prevent fire ignition"- branch of the fire safety concepts tree (adapted from Watts 2000)

The other branch of the tree in Figure 2.1 illustrates the need to manage the consequences of an established fire, either by directly controlling the fire (e.g. by extinguishing) or protecting the exposed persons and property from fire effects as far as possible.

Another side of fire risks is the safety of people and property after ignition in an established fire. These can be classified by, for example, occupants, features of the structure, means of escape, means of detection, alarm and extinction, smoke control and potential fuels (Rasbash et al 2004, p. 24), control of the fire, or the protection of people and property at risk (Watts 2000). The latter uses a simple taxonomy of responses in "managing the impact of fire", see Figure 2.1 on page 24, and the following Figure 2.3 as well as Figure 2.4.

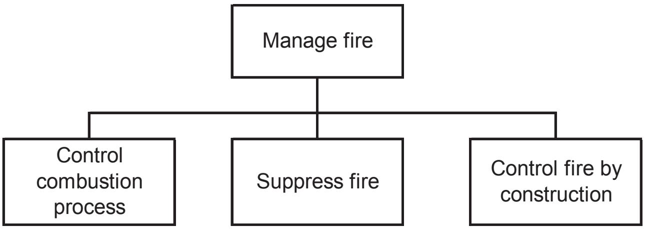

Figure 2.3 Response type alternatives in the "manage fire"- branch of the fire safety concepts tree of page 24 (adapted from Watts 2000)

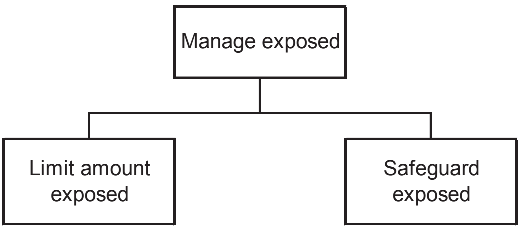

Figure 2.4 Response type alternatives in the "manage exposed"- branch of the fire safety concepts tree on page 24 (adapted from Watts 2000)

The taxonomy described in Figure 2.1, Figure 2.2, Figure 2.3 and Figure 2.4 has been used as the background in this study for identification and assessment of fire risk, as well as finding the responses to fire ignition and established fires. For classification of responses, the consequences (Rasbash et al. 2004, p. 12, Schroll 2002, p. 1, Zalosh 2003, p. 6) to the "exposed" have been divided into three parts (Schroll 2002, p. 1) in this study and then the consequences named accordingly: *human damage in fire*, *material damage* and *secondary damage*. The findings from literature are discussed in the following, with some comments relating to the practical arrangements. Finally, the responses are summarised in the tables of subchapter 2.4 on pages 43 to 49.

2.2.2 Identification of fire risk

During the history of general fire risk management, the identification of risks has grown with negative experiences. This has led to the creation of general knowledge on risks of heat energy sources and flammable materials (Cote and Bugbee 1988, p. 51, Industrial Insurance Ltd. 1970, 1978, 1998a, Kavanian and Wentz 1990, p. 165, Sax 1979, p. 236, Schroll 2002, p. 12, Stollard and Abrahams 1999, p. 23, Thomson 2002, p. 24, p. 108, Zalosh 2003, p. 2). In addition to general knowledge on fires, experiences have also resulted in research on risk identification in very specific cases (e.g. ship engine rooms, Häkkinen et al 1997, p. 3, Marine Safety Agency 1997). Typical contributing factors to ignitions are human error combined with hot solids, shock, impact, open flames and electric phenomena (Babrauskas 2003, p. vii and 497) and fuels, such as gases, dust clouds, liquids and solids. Furthermore, the following factors have also been identified for industry processes: machinery producing sparks, drying or heat treatment plants, heaters, the handling of flammable liquids and gases, welding and cutting (e.g. Industrial Insurance Company 1978, p. 8, Kavanian and Wentz 1990, p. 165). Such historical knowledge of factors that affect fires has been used to identify the direct risks, and the risks due to responses. In the following sub-chapters, the identified common generic fire risks are discussed together with assessment methods and responses.

2.2.3 Assessment of fire risk

Formal fire risk assessment has its roots in the insurance reviews of the 19thcentury (Watts and Hall 2002, p. 5-4, Watts 1992, p. 28). The aim of assessment is to allow the clarification and ranking of the alternatives for risk mitigation. The processes that are used resemble those used in project risk management. Watts and Hall classify fire risk assessment methods into four categories: 1) qualitative methods of fire risk checklists and narratives, 2) quantitative methods, 3) fire risk indexing and 4) probabilistic methods. The latter two have also been referred to as ranking (semi-quantitative) and quantitative methods (e. g. Magnusson & Rantatalo 1998 p. 9). Furthermore, the quantitative analysis can be refined into computer simulation and stochastic modelling of a fully quantitative analysis. An approach where some numerical data is used to score hazards and safety features in an empirical comparative quotient may offer a compromise between effort and accuracy. These kinds of methods are termed fire risk (or safety) indexing, rating schedules, point schemes, ranking, numerical grading or scoring

(Watts 2002, p. 5-125, Ramachandran 1999, p. 365, Howarth and Kara-Zairi 1999, p. 367). Quantitative analysis can be divided into deterministic (e.g. physical fire models), stochastic (e.g. fire spread and escape models), and probabilistic (e.g. logic trees) (Rasbash et al. 2004, p. 22, Ramachandran 1999, p. 365, 368). All the approaches above are used for a similar purpose: to judge the fire risk of a system and make informed decisions. Varying levels of accuracy of quantification are needed, as the cost and complexity of the evaluation are weighed against its accuracy (Magnusson & Rantatalo 1998 p. 9).

In fire risk management research, a recent trend is to develop methods that can be used to assess the “safety performance” of a structure. The level of accuracy, number of assumptions needed and the calculation effort needed vary considerably. For example, risk analysis can be divided into three levels: reference to existing rules and regulations, deterministic calculations used to compare alternatives in relation to each other, and calculation of the actual probability of risk (Magnusson and Rantatalo 1998).

Probabilistic fire risk analysis aims to provide a comprehensive view of the size of the risk: the hazards and their frequency of occurrence are quantified. New risks with low probabilities may also be revealed, in contrast to the previously mentioned ranking and scoring methods. For quantification, a combination of paths of analysis may be available. Relevant historical data may be available, and the event frequencies and probabilities may be estimated by synthesis of, for example, expert judgment, logic trees and human reliability analysis (Barry 2002, p. 5-188, Ramachandran 1999, p. 375). The required factors can be obtained from literature or field surveys. For example, a quantitative view of fire load can be obtained by surveys, and the results can be compared to permitted permanent fire load (e.g. the SOLAS regulations, International Maritime Organization 2001c, p. 2) or usual fire loads in a building. Typically, these kinds of methods have been used in chemical and nuclear industries, and are increasingly being used for building design with improving statistics and modelling techniques (Keski-Rahkonen & Björkman 1999 p. 8, Beard and Santos-Reyes 1999 p. 352, Santos-Reyes and Beard 2001 p. 360).

In the fire risk management design of operating cruise vessels, this approach is also gaining momentum (International Maritime Organization 2001b, 2004), (Maccari & Vergine 2003). This approach requires knowledge about the probability of ignition, probability of fire escalation and of quantification of the impacts (i.e. consequences):

$$Fire\ risk\ magnitude = f(probability, impact)$$

A probabilistic approach referred in such formulas and the term 'risk magnitude' are often linked together, and the use of the term may imply certain formal rigour to the reader. To avoid this connotation, the generic term *risk size,* as mentioned in discussion on project risk on p. 20 (see also Definitions), was used throughout the thesis. The definition emphasizes that many different qualitative and quantitative ways of assessing the fire risk were used together in describing the risk in this study.

The broad selection of alternative fire risk assessment methods described above can provide good tools for evaluating the importance and frequency ignitions and consequences in cruise vessel construction and thus contributes to addressing the research questions. In a hectic project environment, simple and robust assessment methods are useful.

2.2.4 Responses to fire ignition

Responses to risk of ignition (Watts and Hall 2002, p. 5-49) are typically based on the elements in common fires: ignition energy, oxygen and fuel. From literature, typical heat sources in industry were found to be electricity, auto-ignition, heating systems, hot work, light energy, machinery, impacts and tobacco smoking. The frequency of each is dependent on the type of industry. For example, fires due to auto-ignition are rarer in steel manufacturing than in composite manufacturing where resins can cause exothermic reactions. Furthermore, the use of heating systems is naturally dependent on the climate and location of the manufacturing facility.

One of the common heat sources in manufacturing where metalworking is needed is hot work (welding, torching, flame cutting and grinding). This is very well represented in literature (Babrauskas 2003, p. 506, Cowley 2002, p. 198, Industrial Insurance Ltd 1998a, Industrial Insurance Ltd 1998b, National Safety Council 1980, OSHA 2003a, OSHA 2003c, OSHA 2003e, Schroll 2002, p. 91, Thomson 2002, p. 113, Van Brunt 1984, p. 453, Veriö 1978, p. 145). U.S. municipal fire department statistics (National Fire Protection Association 2000b) on non-residential fires due to hot work, excluding grinding, note that 44% of fires are due to flame cutting, and 31% due to welding, and many of the remaining fires are due to other torching activities. Hot work may also deprive personnel of many of the most usual signs of fire threat, such as smoke, warning by others and noise (Cote & Bugbee 1988, p. 22). For example, a lone welder may continue his work unaware of a fire nearby.

Tobacco smoking is a common cause in workplaces in general (Thomson 2002, p. 111), (National Fire Protection Association 1984a, p. 312-5) and its control is an important factor in frequencies across industries. Electric machinery such as blowers, heating systems and transformers cause fires through short circuits and seized bearings (Babrauskas 2003, p. 683-686, 755, 849; Thomson 2002, p. 78, 135; Zalosh 2003, p. 322). Arcing, overheating and short circuits are typical in heavy usage and in the start-up of systems. Systems that are on without surveillance increase the risk of escalation. Zalosh (2003 p. 17) refers to NFPA statistics in emphasising that electric ignition sources are the most common source of fires in manufacturing facilities in general. Sparks can be produced by such things as friction, collisions or electricity. Often they are harmless sources of heat without the proximity of fuels, but they have the capacity to ignite delayed fires, which in the absence of observers can escalate. Tool selection also plays a part in ignition prevention. For example, using explosive-proof electrical appliances and safe heating systems (Van Brunt 1984, p. 454) is important.

In addition to heat, discussed above, fuel is needed for fire ignition, which can be divided into permanent and moveable fire loads. Permanent fire load consists of burnable matter in a fixed position such as wooden wall linings. For many fields, such as construction and mass transportation, rules on allowable limits of flammability of materials are common, and their usage is related to required protection measures. Movable load includes all other fire loads. This includes a temporary fire load present at a specific time only, for example during the construction of a building. However, in temporary construction, material may be flammable and is controlled locally at the site. Human actions at the workplace are particularly important in heat-fuel interaction. Management of waste and gas leaks are typical examples. The severity of an escalated fire is also dependent on the fire load (Hall & Ahrens 2002). Flammable liquids, vapours, gases and dust are particularly dangerous fuels for fires as their spread can be unexpected, flammability may be high, and explosions may even result. Avoidance of low flash point adhesives is also important (Van Brunt 1984, p. 454).

Human actions are important in ignition (e. g. (Hall 1999), (Hall 2003a), (Hall 2003b), (Hall 2003c), (Karter 2003), (ODPM 2003), (ODPM 2002)), as well as controlling heat and fuel (Figure 2.2). Personnel actions that relate to safety performance are the focus of the general safety management discipline, where literature on the importance of human factors in safety is extensive, for example Reason (1999, p. 235), Petersen (1996, p. 247) and Glendon & McKenna (1995, p. 8). For fires in general, deliberate errors (arson) are significant sources of ignition. Location and surveillance obviously play an important part in arson. For example, in U.S. statistics published for buildings under construction (National Fire Protection Association 2000a), the largest cause of ignitions are incendiary or suspect fires. Their proportion is about 40%. Similarly, Stollard & Abrahams (1999, p. 23) quote U.K. statistics for deliberate fire-starting in non-dwellings in 1996 as 48%. Thomson (2002, p. 108) attributes arson to over 50% of major fires in U.K. industry. On the other hand, for industrial buildings in Sweden, Heikkonen (1994, p. 9) quotes a 0.6% rate of ignition by arson in large fires. Obviously, the extent of statistics and local circumstances contribute largely to the results. This makes statistical comparisons between industries and locations difficult.

In addition to heat and fuel, the third necessary ingredient for fires is oxygen, but it is not present in the taxonomy of Figure 2.2. In most cases there is enough air for a fire to start: sufficient air must be present for people to prevent the danger of suffocation, and thus air is available for fire as well. In addition, oxygen leaks from tool supply may increase fire risk. The limiting of oxygen may be used in firefighting, for example CO_2 systems for engine room fires (International Maritime Organization 2001, p. 165), but they also cause a new hazard, as the oxygen content must be reduced below the level needed for breathing. Drafts and flows of combustion gases provide oxygen for fires, and fire doors and draft stops are installed to reduce the effects. During construction, temporary measures may be needed (Sax 1979, p. 239).

From literature, simple practical responses for generic risk management of ignition can be summarised as effective housekeeping, restrictions on tobacco smoking, controlled hot work, fireproofing of structures, good installation and maintenance of heaters, safe handling of flammable liquids and gases, restricted use of electric appliances, well-planned machinery maintenance, and general fire safety training of the workforce. The identified contributing factors and responses to ignition that were found in literature are collected in the summary tables of this chapter on pages 43 to 46. These were later used in the interactions with the shipyards.

2.2.5 Responses to established fires

Typically, identified fire risks in established fires are not discussed directly in generic fire literature, but in connection with their potential responses. The risks relate broadly to damage to humans and property, and the severity of consequences depends largely on the extent of escalation of fire (Watts and Hall 2002, p. 5-2). Practices for extinguishing and protecting people dominate literature, and often apply to specific cases. Design solutions for fire safety and risk-reducing construction are also prominent in literature. Responses to established fires relate to managing the fire and the exposed people and property (as illustrated in Figure 2.1 on page 24), for example control of hazardous materials, design, operational extinguishing systems, availability of detection systems, prompt alarming, preventive maintenance and fast evacuation (Cote and Bugbee 1988), (Industrial Insurance Ltd. 1997), (Planer 1979) (Howarth and Kara-Zaitri 1999), (Proulx 2003). Below, some common responses are discussed.

Fire detection, alarming and suppression capability are essential for fire safety (National Fire Protection Association 1984a, p. 312-6, Sax 1979, p. 241, National Fire Protection Association 1984b, p. 462, Rasbash et al. 2004, p. 227, Shields and Silcock 1987, p. 319), and specific rules exist in many fields, similarly for passenger vessel operation requirements (International Maritime Organization 2002, II-2, Reg. 8). One of the most common responses to fire risk in industry is automatic suppression systems, and specifically sprinklers. Their feasibility is based on continuous protection and the early extinguishing of fires. The feasibility has been studied broadly in literature. For example, Sax (1979, p. 242) refers to U.S. statistics where they extinguished or held in check 96% of the fires in the sprinkler-protected areas. Cowley (2002, p. 147) has reported figures as high as 99.8%. Zalosh (2003, p. 118) refers to insurance companies' statistics of 332 large fires in storages, where average loss per fire was about five times smaller for facilities with sprinklers than for those without.

Rasbash et al. (2004, p. 237) discuss their feasibility in limiting damage and quote several studies. They find the reduction significant. For example, for metal goods manufacturing they quote statistics for average fire sizes in a normal 1,500 m² building approximately five times larger without automatic extinguishing than with. For mechanical engineering facilities, the average fire areas were about nine times larger without automatic suppression. Although automatic systems are very effective in reducing the size of fires, they increase the risk of water damage. Sprinkler releases due to misconduct may occur (Sax 1979, p. 243). In freezing conditions, the systems should be protected. Keeping piping dry, heating and insulation of the systems can be used for protection. Anti-freeze-solutions have also been studied (Arvidson and Månsson 1999). Detection without automatic suppression may delay the start of suppression compared to a fully automatic system. This can be seen in general building insurance premiums where typically only minor discounts are available if detection is used without a automatic extinguishing system (Ramachandran 1998, p. 104).

For manual suppression, fire needs to be detected, a signal communicated, action decided upon, the fire site responded to and sufficient suppressant applied (Watts 2000). Short response time is critical, and often the ability to respond rapidly with portable extinguishers is important for preventing escalation, and is widely referenced in regulations and literature (e.g. OSHA 2003d, International Maritime Organization 2002, II-2, Reg. 10.3., Cowley 2002, p. 45, Kavanian & Wentz 1990, p. 178). One way of judging a sufficient number of portable extinguishers is the average maximum fetch distance to an extinguisher according to the U.S. OSHA requirement. The OSHA maximum fetch distance from work to a class-B extinguisher is 15.2 m (50 feet) and for Class A extinguisher 22.9 m (75 feet) (OSHA 2003d). For ships in operation, a sufficient number of portable fire extinguishers in most of the ship spaces on-board an operating vessel is referred to in SOLAS (Ch. II-2, Part A, Reg. 6). The responsible authority is the flag state administration.

Confinement of fire and protecting exposed people and property has a high priority in literature and also in fire regulations. For limiting the risk in established fires, the closing of all adjacent openings is essential both for limiting fire effects for evacuation purposes and for limiting property losses. [Cowley (2002, p. 140), International Maritime Organization (2002, II-2, Reg. 9.4), National Fire Protection Association (1984a, p. 312-6), Rasbash et al. (2004, p. 245), Sax (1979, p. 239), Schroll (2002, p. 100), Zalosh (2003, p. 78)]. An example of the effect of lack of fire integrity on the extent of damage to buildings may serve as an analogy. According to Industrial Insurance Company (1978, p. 9), the typical loss for industrial buildings and warehouses (with a fire load somewhat comparable to the ships in this survey) is 10 - 20% of total loss value if structures are fireproof (i.e. fire doors closed). This can be compared to a typical loss of 50% of the total value for a building under construction, which resembles the situation of a ship with open doors.

According to a state-of the-art study by Ingason and Arvidson (2001), no final conclusions may be drawn concerning the use of smoke ventilation systems during fire extinguishing. There are two conflicting views: one points out the beneficial effects of automatic venting for smoke damage and the escape of exposed persons, and the other the possibility of cooling the environment near the spray heads so that a lower number are activated, resulting in a higher-powered fire.

From the above, it is clear that limiting the effects of heat upon flammable materials is important for preventing ignition and that rapid suppression and protection of people dominates in reducing the consequences of established fires. When fires escalate, evacuation and automatic extinguishing systems are useful as responses. Sprinkler systems are widely used in industry, and provide effective protection for high-risk spaces. These and other responses for managing the consequences of established fires are presented in the summary tables on pages 47 and 48.

2.2.6 Some usual production arrangements as responses to fire risk

In addition to direct responses to fire risks, responses that relate to work process arrangements were found in fire safety literature (Table 2.3). The main themes relate to organised risk management and safety personnel (Industrial Insurance Ltd. 1997, p. 1, Planer 1979 p. 26, and Schroll 2002 p. 27, p. 183). The importance of audits, surveys and inspections in monitoring fire safety in the industrial processes is recognised, especially in the view of the insurers (Industrial Insurance Ltd. 1978, p. 8, Kallioniemi et al. 2001, p. 62, Planer 1979, p. 35, Stollard and Abrahams 1999, p. 33 and Thomson 2002, p. 77). In particular, fire guarding system with regular patrolling of premises at critical times is noted as an integral part of the fire safety process (Industrial Insurance Ltd. 1970, p. 1; 1978 p. 8; 1997, p. 1; Kallioniemi et al. 2001, p. 58). As the personnel is in key role in preventing ignitions as well as in first extinguishing actions, their fire safety training is essential (Industrial Insurance Ltd. 1970, p. 1; 1997, p. 4, Kallioniemi et al. 2001, p. 58, p. 65 and Thomson 2002, p. 84) The clients of industrial companies also play an important role in promoting fire safety in production, and an insurer’s recommendation includes fire safety in contracts (Kallioniemi et al. p. 54) as is common, for example, in the oil industry.

2.3 Fire risk management in shipbuilding literature

The fire safety of operating passenger vessels, including permanent and moveable fire load, is carefully controlled by international regulations (e.g. International Maritime Organization 2001, p. 145-241; IMO 2004, p. 149-285). For this, see the summary of the rules applicable to the vessels of this study in Appendix B. This leads us to conclude that the flammability of ships' materials is generally low and their associated energy content below regulation limits.

During construction, however, fire risk is increased because flammable temporary fire load and heat sources are present, and many of the safety features of an operating vessel are not available. The fire compartments of a ship might not be finished; doors and bulkhead and deck penetrations may be under construction. Fire detection and suppression systems might not be operational. In addition, an abundance of hot work must be carried out. On the positive side are the absence of engine operation and the related fuel oil fire risk until sea trials start. In the following, shipyard fire risk management is discussed in two parts, according to the logical division of preventing ignition and managing the consequences of established fires.

Most potential ignition sources and temporary fuel on-board depend on the actions of the people working on a ship project. Hot work (mainly welding, flame cutting and grinding) is one of the key threats in ships under construction and repair (Netterstrom 1972, p. 197, Veriö 1978, p. 145, Van Brunt 1984, p. 454). This is in line with information from other industries (Matthews 1984, Gilmour 2003). Hot work is also mentioned as a key reason for fires in some national HSE regulations applicable to shipyards, such as in the U. S. Occupational Safety & Health Administration's set of standards (OSHA 2003c) and guidelines (OSHA 2003a), (OSHA 2003b) concerning shipyard safety. These refer to the National Fire Protection Agency standard on welding, cutting and other hot work (National Fire Protection Association 2000c). The classification societies and industrial insurance companies also refer to hot work in their instructions for ship repair (Industrial Insurance Company 1970, 1998). For ignition prevention, typical factors that relate to responses in shipbuilding have been listed as housekeeping, tobacco smoking, hot work, structures, heaters, the handling of flammable liquids and gases, electric appliances, and machinery maintenance. One of the key contributing factors is hot work (mainly welding, flame cutting and grinding). Other identified fire risks in literature are the cabling of generators, heating arrangements, control of flammable material, vehicle fuel and temporary housing. For managing the consequences of fires, a systematic fire risk management programme, suppression, fire brigades, alarms and fire guards are needed (Van Brunt 1984, p. 441-464).

According to the U. S. Occupational Safety & Health Administration (OSHA 2003b), in the United States fall hazards are a leading cause of fatalities at shipyards, but fire is also a major risk. They refer (OSHA 2003a) to the U. S. Bureau of Labor Statistics, which reports that up to 25% of fatalities at shipyards result from fires and explosions ignited due to hot work. Other causes, such as technical malfunction are also important but their percentage of the total is smaller.

It is necessary to avoid concurrent hot work with fire hazardous work such as painting, woodworking and solvent cleaning (Van Brunt 1984, p. 454). For minimising fire load on a shipyard, good housekeeping is vital. General principles apply (Robinson 1984) and at a shipyard a typical problem is discarded packaging material (Van Brunt 1984, p. 454).

For fire risk assessment, analyses of contributing factors, such as heat sources and protection measures are mentioned in literature. If the distributions of contributing factors such as available fuel and the amount of hot work were compared with the scale of the potential project losses as a function of production time, it seems that there may be times of particularly high risk. Figure 2.5 is an illustrative graph from a shipyard (adapted from Äyräs 2003). It seems also that more research is needed as the graph is related to hot work, and other significant ignition sources for large fires are known to exist. However, it is obvious that the size of risk is not static during the construction but changes with project progress.

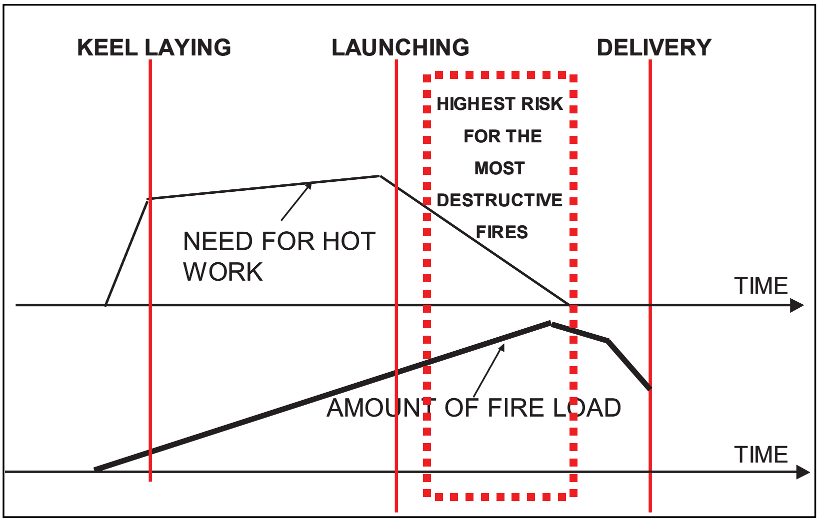

Figure 2.5 Time of highest risk for most destructive fires, adapted from Äyräs 2003

Many of the responses mentioned in shipbuilding literature were connected with managing the consequences of fire, such as fire detection, alarms and extinguishing, as well as protection of people and property, but the details of shipyard arrangements were also commonly mentioned. Response details refer to the arrangement of fire watch systems, fire brigades, maintenance of flame or spark-producing equipment, distribution of portable fire extinguishers, fire hose connections, fire alarm systems, general watch service at the shipyard, as well as surveillance of hazardous behaviour such as tobacco smoking (Van Brunt 1984, p. 454). For managing the consequences of fires, systematic fire risk management programmes and fire detection, alarm and extinguishing are used. Planning for fire guards, escapes and barriers for the protection of people and property are key issues, as is liaison with the local fire brigade. Continuous revision of fire risk management plans, and sufficient availability of portable and water hose extinguishing systems were also mentioned.

The structural stability, fire boundaries and number and construction of fire doors of an operating vessel are controlled by international regulations. In vessels under construction, many of these features are added during the building process, and thus fire risk management due to construction varies with building time. The backbone of steel structure must exist before other work starts, and insulation, fire doors, hatches, fire baffles in ducts, draught stop barriers between decks and inner ceilings are added during the building process. Large passenger ships are mostly steel structures, which have a load-bearing capacity to withstand fire until it has escalated to proportions resulting in the complete destruction of fire zones. Thus the structural stability of the steel part of the vessel is not a primary problem. In addition to steel, aluminium is used on the upper decks and funnels. This has to fulfil the same rules as the steel structures. Its load-bearing capacity when hot is, however, much inferior and protective insulation is often required for compliance with international regulations. During the building stage, not all the insulation and aluminium structural work may be completed simultaneously, diminishing structural stability in a fire. The structural problems and even flammability of aluminium if heated to a sufficiently high temperature have been studied on naval vessels (Walmerdahl 1999 p. 31) (Toppan 2000 p. 1). In cruise vessels, however, the loss of a fire zone or the whole vessel is imminent if the aluminium structures start to collapse and major harm has already occurred before that. Compared to concrete structures in buildings, metal structures allow the spreading of fire to neighbouring compartments in just a matter of minutes if uninsulated (Darwin et al. 1994, p. 71, Gross and Davis 1988, p. 7).

One fundamental difference in structural stability between marine and land-based fires is the capsize possibility of ships due to excess weight and the free surface effects of the water used in extinguishing [e. g. (National Fire Protection Association 1984a p. 312-7, Räisänen & Kanerva 2000 p. 6-3, Rushbrook 1961 p. 408, Stokoe 1964 p. 85, Veriö 1978, p. 38). The allowable amount for water may need to be calculated during fire-fighting.

In addition to the arrangements of the shipbuilding process, basic ship design also affects fire risk. Nowadays "Alternative fire safety design criteria" allow the shipbuilding industry to present individual fire safety designs that differ from the older, rule-prescribed solutions for the finished product (Maccari & Vergine 2003, p. 153). Arguably, this kind of individual designs could also have effects on the fire safety of a ship during the building process. However, the need for elaborate studies case by case makes practical application tedious.

It is notable that much of the literature refers to general shipbuilding. Passenger vessels differ from other ship types, for example in the large amount of outfitting with simultaneous hot work, long escape routes and size and the complexity of the ships, and few references to this specific ship type were found. However, the general principles of shipbuilding fire risk management apply to cruise vessel construction, but the scale is different. The responses collected from shipbuilding literature were added to the summary tables on pages 43 to 49 of the following sub-chapter.

Similarly to general fire safety literature, shipbuilding literature also contains references to responses on production processes, relating to organised risk management and safety personnel, for example through systematic fire risk management programmes and safety plans (Van Brunt 1984 p. 443-444). The responses for shipbuilding relate to the arrangement of fire watch systems and inspections (National Fire Protection Association 1984, p. 4; p. 6, OSHA 2003c, p. 3; Van Brunt 1984, p. 454; p. 462), a constantly manned central control station (National Fire Protection Association 1984, p. 6), as well as surveillance of hazardous behaviour on-board (Van Brunt 1984, p. 453). Again, the central role of safety training of personnel (Schei et al. 1991, p. 206) is highlighted. From literature, it seemed that safety in shipbuilding has developed in leaps and bounds after rare, large fires. For example, due to a fire on an operating ship, it was found that balcony structures were not covered by IMO regulations on fire endurance, and provided a path for a lethal fire (Blenkey 2006). Later, the rules were amended and thus risk was reduced for ships under construction as well.

2.4 Summary and tables of findings from literature

Three literature reviews on project risk management, fire safety and shipbuilding were carried out before interactions with the shipyards started. Of these, many concepts were adopted and a theoretical framework for the research was built. The development of the new framework was rather easy as the disciplines of project risk management and fire risk management were found to have a common simplified basic process: risk identification, assessment and response (control). The disciplines complemented each other well in addressing the research questions. Firstly, in project risk literature, tools for definitions, identification and assessment are well represented but few practical references to detailed responses were found. Instead, they were available in the fire risk management discipline. Secondly, general fire risk (or safety) literature typically related to responses in a stable, operational environment, and the project risk management view was more appropriate for dynamic construction processes. In addition to risk management literature, some complementary information regarding fire specifically in ship construction projects was found in shipbuilding literature. Below, the conclusions that were drawn from the literature at the start of the study are summarised concisely for each research question, with joint tables of contributing factors for ignitions, consequences and responses to them. This information provided the basis for the research actions, and was continuously improved during the empirical work with the participants. The findings of the study are discussed in detail in chapters 4 and 5, and the empirically amended versions of initial tables, Table 2.1 to Table 2.3, are presented as Table 5.5 to Table 5.7.

The first research question relates to the nature of fire risk in general:

1) What is fire risk in cruise vessel construction projects?

Knowledge about fire risk in cruise vessel projects was found in literature on project risk, fire risk and shipbuilding. Drawing from these disciplines, it became evident that a traditional definition of fire risk as a threat to people and property is useful for the formulation of practical responses. Not much quantitative information of 'fire risk probabilities' and 'impacts' was particularly found for shipbuilding, but plentiful references were found for the corresponding qualitative concepts of 'contributing factors for ignition' and 'consequences of established fires', especially in generic fire safety literature. Further, it was found that both these elements are needed to describe the risk, but that useful responses can be derived by studying each one separately. It was also noted that empirical studies at the shipyards could produce some useful qualitative data but eventually allow some quantification for the concepts. The empirical findings are discussed in Chapter 4.

With regard to the risk that relates to ignition, a set of 15 contributing factors to ignition were collected and evaluated. They describe the ignition qualitatively, as no reliable probabilities were found for shipbuilding projects in literature. They are listed in the first column of Table 2.1. Similarly, qualitative information on the other side of fire risk, the consequences of fires, was obtained from literature and grouped into three main categories: human damage in fire, material damage and secondary damage, which are listed in the first column of Table 2.2. All the tables were later used in the interactions with the shipyards. The same tables also include the responses formed from information in literature. This information was used in the beginning of the research before empirical information became available.

The second and third research questions refer to the assessment of scale of risk and suitable metrics for shipyard use:

2) How can fire risk be assessed in cruise vessel construction projects?

and

3) What is the size of fire risk in cruise vessel construction projects?

The literature reviews gave a broad view on the possibilities of assessing the fire risk in cruise vessel construction. Multiple methods that could be used to scale the risk were found and reformed for the problem at hand, ranging from simple semi-qualitative methods to complicated quantitative analyses. Varying levels of the accuracy of quantification are needed as problems vary, but typically the assessment methods viewed the risk in terms of probability and impact. For cruise vessel construction, these are often not appropriate, as available data and analysis capabilities in shipbuilding are limited, compared with the nuclear industry, for example. The terms 'risk size', and 'consequences' were found from literature and used later in empirical work to reflect the mixed quantitative-qualitative nature of the information. The main problem for the current study was that again little quantitative data from literature was found that could describe the actual size of the risk in shipbuilding. Rather, the literature reviews revealed good opportunities for empirical research with the shipyards. Therefore, the empirical work was started directly with basic quantification of the problem.

The fourth question relates to responses for mitigating the risk; these responses are typically decided upon and employed by the line, safety and project managers of the shipyards:

4) What are available responses to fire risk in cruise vessel construction projects?

Reviews of fire safety and shipbuilding literature were used to produce a set of responses to shipbuilding project fire risks, which depend on the complexity and severity of the identified risk. It became obvious that well-known domestic fire risk factors such as heat energy sources and flammable materials are also important in industrial applications. Specifically for shipbuilding, some additional risk areas, such as capsize of the vessel during extinguishing and fire safety during sea trials, were discovered. In general, the literature reviews at the start of the research provided a good selection of generic responses that could also be applied in shipbuilding projects. It was noticeable that the disciplines complemented each other well and there were relatively few items that were mentioned in both sets of sources. Three sets of review results were produced: responses to ignition, responses for minimising the consequences of fires and responses that relate to production process arrangements. Responses to ignition were derived from managing ignition energy, fuel or their interaction. 92 responses in 15 categories of ignitions were formed from the two disciplines (second column of Table 2.1). For established fires, responses related typically to suppression process and confinement of fires, as well as to evacuation. 43 responses were recorded (second column of Table 2.2). In addition, indirect production process-related responses were also discussed in the literature, 11 of which were added to the summary tables (second column of Table 2.3). The complete references are listed in Appendixes C and D for general fire safety and for shipbuilding, respectively.

The tables were used with the participants throughout the study, and were revised during the actions with empirical data that became available. These empirically augmented versions of the tables are discussed later in Chapters 4 and 5, and therefore the tables are not addressed in detail here. Here, however are some general observations about the reviewed responses: about two-thirds of the responses concerned ignitions related to hot work, fuel, machinery and electric systems, which stressed the importance of these categories. Accordingly, they were the focus of the first actions and inquiries at the yards. On limiting the consequences, it became clear that secondary damage was not the focus of the reviewed literature, and perhaps better covered in insurance and ship operations literature. However, direct measures against human and material damage were discussed broadly in the reviewed literature. In particular, limiting the spread of fire, extinguishing and evacuation were considered important. Responses that related to work process arrangements focused on the organisation of safety, auditing, training and surveillance.

The summary tables of literature reviews are on the following pages. They contain risk and response features as follows:

- Table 2.1 : 15 categories of common contributing factors to ignition that are linked with 92 responses found in literature.
- Table 2.2: Three types of consequences (human damage in fire, material damage and secondary damage) for established fires and 43 responses.
- Table 2.3 11 responses that relate mostly to managing fire risk by work process arrangements.

The literature review did not reveal directly which of the responses listed in Table 2.1 to Table 2.3 would be suitable for managing fire risk in cruise vessel construction. However, it became clear that concentrating at least on typical fuels, fuel-heat interaction and heat sources on-board cruise ships in the empirical research part of the study would be essential to understand ignitions. Similarly, the responses of suppression, the protection of people and property and functional work arrangements were found to be important in managing the consequences of established fires on-board.

Table 2.1 Summary of 15 categories of contributing factors to ignition and responses formed from shipbuilding and general fire safety literature. Complete literature references are shown in Tables C1 and D1 of Appendixes C and D (continues on the following pages).

Contributing factor to ignition	Responses	Reference type (G= general fire safety literature, S= shipbuilding literature)
1) Arson	Automatic suppression	G
	Good lighting	G
	Guarding of premises	G
	Housekeeping to avoid flammable waste	G
	Restricted access to compartments	G
2) Autoignition	Avoiding incorrect storage and use of chemical products	G
	Managing the use of incompatible chemicals used in the plant	G
3) Electric phenomena	Static electricity: effecting a conductive path between the charged materials	G
	Static electricity: proper grounding of vessel and its temporary and permanent parts, especially pipes	S
	Use of lightning conductors, earthing in general	G
4) Electric systems	Damage control of cabling	S
	Ensuring overheating protection in electric systems	G
	Maintenance of electric systems	G
	Maintenance of thermostats, motors and transformers	G
	Overheating checks with IR equipment	G
	Prevent arcing	G
	Proper design, installation and maintenance of cabling	G
	Proper installation of temporary electric systems	S
	Shutting down of electric appliances when not in use	G,S
	Systematic maintenance of electric appliances	S
	Use of explosion-proof appliances in hazardous areas	G,S

Table 2.1 Summary of 15 categories of contributing factors to ignition and responses formed from shipbuilding and general fire safety literature. Full references are shown in Tables C1 and D1 of Appendixes C and D (continues on the following pages).

Contributing factor to ignition	Responses	Reference type (G= general fire safety literature, S= shipbuilding literature)
5) Explosions, e.g. dust, explosives, gas, and vapors	Avoiding gas leaks and dust accumulations	G
	Explosion-proof machinery	G,S
	Restricted storage on board for highly flammable materials	S
	Special cautions for explosives	G
6) Fire load	Avoiding accumulation of flammable substances in structures and dust clouds	G,S
	Avoiding highly flammable solvents for cleaning and gluing	G,S
	Control of combustible solids by design and work arrangement	G
	Control of flammable material	S
	Control of hazardous materials	G,S
	Good house-keeping in general	G
	Good house-keeping, especially waste logistics	S
	Fuel oil ignition risk	S
	Installing emergency shutoff systems for liquids and gases in piping	G,S
	Limitation of fixed and moveable fire load	G
	Maintenance of gas distribution systems	G
	Minimal storages in production, no packaging materials in production	G
	Odorizing of gases to help in leak detection	G
	Precautions during fuelling	G
	Removal of flammable scaffolding parts	S
	Removal of flammable waste, waste logistics	G
	Restricted use and storage of combustible materials onboard	S
	Safe handling and storage of flammable liquids and gases	G,S
	Unpacking flammable packaging before materials are taken aboard	S
	Use of non-combustible construction materials, furniture and decorations	S
	Use of non-sparking tools near flammable materials	G
	Use of safety precautions with fuel oil or lubrication oil in connection with hot machinery	S
	Use of temporary flameproofed coverings over materials	S

Table 2.1 Summary of 15 categories of contributing factors to ignition and responses formed from shipbuilding and general fire safety literature. Full references are shown in Tables C1 and D1 of Appendixes C and D (continues on the following page).

Contributing factor to ignition	Responses	Reference type (G= general fire safety literature, S= shipbuilding literature)
7) Friction	Maintenance of rotating machinery, e.g. gears, belts and bearings	G
	Overheating checks with IR equipment	G
8) Heating, drying and heat treatment	Good housekeeping near heaters	G
	Functional overheating protection in equipment	G
	Maintenance of blowers and heating systems	G
	Special caution for unatteneded heating systems	S
9) Hot surfaces and open flames	Avoiding work with open flames, protective procedures	G
	Thermal isolation of hot surfaces from fuels	G
10) Hot work (welding, cutting, grinding, torching)	Disconnecting gas and electricity when not in use	S
	Effective hot work procedures	S
	Fire watch system	G
	Flammable waste management systems	G
	Gas concentration measurements before hot work	G
	Hot work permit system	G
	Hot work safety exam and card	G
	Hot work supervision plan	G
	Instructions for hot work in special circumstances, e.g. in tanks	G
	Measuring gas content in room before hot work	S
	Precautions during fuelling of ship systems	S
	Systematic maintenance of gas systems	S
	Training	G
	Use of protective coverings	G
	Use of non-sparking tools near flammable materials	S
	Using alternative methods instead of hot work	G,S

Table 2.1 Summary of 15 categories of contributing factors to ignition and responses, formed from shipbuilding and general fire safety literature. Complete literature references are shown in Tables C1 and D1 of Appendixes C and D (continued from the previous pages).

Contributing factor to ignition	Responses	Reference type (G= general fire safety literature, S= shipbuilding literature)
11) Machinery	Equipment maintenance	G
	Isolation of spark-producing machinery from fuel	G
	Jacketing of high pressure oil lines	G
	Maintenance of flame or spark producing equipment	S
	Maintenance of rotating machinery	S
	Risk management of combustion engines	G
	Safe location of compressors	G
	Safe parking of motor vehicles	G
	Systematic procedures for using motor vehicles on board	S
12) Painting	Good housekeeping with solvents and waste	G
	Precautions for hot work, cleanliness, ventilation and chemical reactions	S
	Proper earthing of substances	G
	Use of suitable non-sparking equipment	G
13) Sea trials	Proper engine operation	S
	Tested fire alarm, detection, public announcement and extinguishing systems	S
14) Smoking of tobacco	Education of fire safety	G
	Inspections	G
	Smoking restricted with designated smoking places	G,S
15) Miscellaneous	Avoiding ignition by shock and impact with material and tool choices	G
	Avoiding light energy ignitions by education	G

Table 2.2 Consequences of established fires and relevant responses, formed from shipbuilding and general fire safety literature. Complete literature references are shown in Tables C2 and D2 of Appendixes C and D (continues on the following page).

Consequences of established fires	Responses	Reference type (G= general fire safety literature, S= shipbuilding literature)
Human damages in fire	Clear escape routes	G
	Closing of temporary and permanent openings	G
	Communication of alarms	G
	Confinement of fire by barriers	G
	Early division of the ship into functional main vertical fire zones, and separation of rooms by structural and fire bulkheads and decks	S
	Early manual detection, alarming and suppression	G
	Ensuring structural stability in fires	G
	Escape and fire-fighting routes built early and kept functional	S
	Fire compartments	G
	Fire integrity of vertical casings, staircases and ventilation ducts built early	S
	Functional fire detection, alarming and public announcing systems	S
	Installation of windows early in the production process	S
	Keeping fire doors always closed	S
	Possibly smoke ventilation	G
	Practiced evacuation procedures	G
	Reviews of personnel risks and safety culture	G
	Safety training	G
	Sufficient extinguishing capacity	G
	Sufficient safety personnel capacity	G
	Temporary closing of vertical ducts during building process, especially cable ducts	S
	Use of automatic detection and extinguishing systems	G
	Use of portable extinguishers by all employees	G

Table 2.2 Consequences of established fires and relevant responses, formed from shipbuilding and general fire safety literature. Full references are shown in Tables C2 and D2 of Appendixes C and D (continued from the previous page).

Consequences of established fires	Responses	Reference type (G= general fire safety literature, S= shipbuilding literature)
Direct material damages in fire	Availability of portable extinguishing systems close to work locations	S
	Avoiding smoke and water damages by fast suppression	G
	Avoiding structural collapse with isolation	G
	Fast responses with portable extinguishers	G
	Fire brigades	G
	Fire detection, alarming and suppression capability is essential for fire safety	G
	Fixed suppression systems in machinery spaces	G
	Functional fire suppression, both temporary and ship's own system, preferably automatic	S
	Good liaison with local fire brigade	S
	Prevention of accidental CO_2-release in engine rooms	S
	Sufficient fire pumps, hose connections, pressure and water supply	S
	Sufficient supply of pressurized water to premises	G
	Trained shipyard fire brigade available fast	S
	Use of temporary detection and alarming	G
Secondary damages	Avoiding loss of information by backup	G
	Avoiding lost production by rapid suppression	G
	Avoiding delayed deliveries to customers by reserves in schedule	G
	Avoiding damages to environment by containment	G
	Isolation of conductive surfaces for structural stability and to prevent fire conduction to adjacent compartments	S
	Making pump capacity available for draining of suppression water	S
	Removing obstacles from drainage paths	S

Table 2.3 Summary of production process arrangements as responses to fire risk formed from shipbuilding and general fire safety literature. Full references are shown in Tables C3 and D3 of Appendixes C and D.

Arrangements for managing fire risk	Responses	Reference type (G= general fire safety literature, S= shipbuilding literature)
Process arrangements for managing fire risk	Alternative fire safety design criteria	S
	Arrangement of fire watch systems and inspections	S
	Audits, surveys and inspections	G
	Constantly manned central control station	S
	Fire guarding system	G
	Fire safety training of personnel	G
	Including fire safety in contracts	G
	Organized risk management and safety personnel	G
	Safety training of personnel	S
	Surveillance of hazardous behaviour onboard	S
	Systematic fire risk management program and safety plans	S

The risk characteristics and responses summarised in the tables in this sub-chapter were used in the interactions with the shipyards, where they provided the necessary background information and seeds for new solutions. In addition, the literature reviews provided taxonomy for the risk management of ignition, established fires and process arrangements. During the actions, it was found that the separate category ‘Friction’ of literature reviews was unnecessary in studying shipbuilding: the empirical data on effects of frictional phenomena were found to fit the categories ‘Machinery’ and ‘Electric systems’ better, and the ‘Friction’- category was left out. This taxonomy was subsequently used for gathering empirical evidence on fire risk, its assessment and responses in the subsequent actions with the participating shipyards. The different types of evidence and the methods of acquiring them are discussed further in the following chapter.

3 Research methods and materials

Already at the outset of the study, the participants knew much about fire incidents in shipbuilding projects. Mostly the fires were extinguished by the personnel on-board with a portable extinguisher, and often there was potential for larger disasters. Therefore, all yards had established procedures for examining the root causes of incidents and some systematic method for recording them in confidential databases. However, no comparisons for similar operations in other countries were possible. To overcome this shortcoming, for this study the four shipbuilding companies agreed to provide their data to the researcher for joint analyses. This unique opportunity provided fertile ground for actions of inquiry and improvement. The focus of the research was broadly in the fire risk management process, from identification to assessment and responses, in two main areas: contributing factors of ignition and management of the consequences of fires.

The selection of the research methods of the study was based on the fact that the researcher was in a position to initiate changes in fire risk management at most of the participating shipyards as a client's (RCCL) representative. The fact contributed to the paradigm of this research, which is largely hermeneutic (Phillips 1987), i.e. internal to the research problems, which are not strictly causal, but are formable by the actions of the participants. Based on other fields of social system research, and in particular organizational studies, the inductive theory generation approach is expected to be fruitful in such a situation, but the right amount of detachedness from the topic is debatable (Argyris 1980, Riordan 1995, Bradbury & Reason 2002). Case-based inductive theory generation ("theory generated less during the actions than after it") and action research-based ("theory generated cyclically during the actions") inductive theory generation are usual alternatives (Gummesson 1991, Yin 1994). In this research, there was a need for theoretical input from three disciplines for theory generation (project, fire and shipbuilding risk management). In this context, the term "theory" is related to the physical, behavioural and organizational models and factors which describe and influence fire risk and its management in shipbuilding. As research of the topic was at its early stages, generating new views for future research was also considered important. Further, many types of qualitative and quantitative information were available rather than one type of data. Action research (AR) has been successfully used in similar situations for theory generating, and for spawning questions for further beneficial research (Eden & Huxham 1997, p. 532). An alternative, case-based inductive research, was considered to be better suited in generating theory frameworks in situations where there are some representative cases, and some definite theoretical background is already available for testing by the researcher. Regarding the above, and the practical need for development of sufficient theoretical background during the interventions, action research was found to be a suitable method for the inquiry.

An important characteristic separating action research from other methods of organisational inquiry is its emphasis on the researcher becoming an active participant in the organisational change process (Eden & Huxham 1997). Most often, this results in a cyclic action–reflection–theory generating process (Elden & Chisholm 1993, French & Bell, 1984) after the researcher has first obtained a pre-understanding of the subject (Argyris 1980, Riordan 1995, Bradbury & Reason 2002). In the cycles, the researcher enters to change actions with the participants and studies the effects. Next follows a methodical reflection phase, and the AR cycle is concluded with an explication of the theoretical and practical outcome. The method is somewhat controversial, and has been widely criticised for lack of rigour and objectivity. It does not offer confined experiments or repeatability, and is by nature affected by the presence of the researcher. Its proponents, on the other hand, point to its potential for revealing the true values of the participants (Hawk 2002). It is sometimes believed that action research allows access to more powerful and sustainable participant actions, because participants get deeply involved in the active theory generation. This may be because it is said to be "concerned with systemic relationships rather than with single theories" (Eden & Huxham 1997, p. 532). For ensuring methodological rigour with the action research approach, good documentation of action cycles and triangulation with multiple data sets and multiple information acquisition methods are needed (Eden & Huxham 1997 p. 538-540, see also Appendix E). Therefore, the discussion on research design and materials of this study is rather long, with even more details in the Appendixes. The overall research design is described in sub-chapter 3.1. Next, the triangulation and the details of materials and methods are discussed in sub-chapter 3.2 and sub-chapter 3.3, respectively. Further, the documentation of the action cycles is discussed at some length in sub-chapter 3.4. The chapter ends with a brief summary in sub-chapter 3.5.

3.1 Research design

The research originated from the need to increase fire safety in the large cruise vessel building industry. The action research inquiry that was used in connection with the changing processes of the participant organisations followed the outline of Eden and Huxham (Figure 3.1).

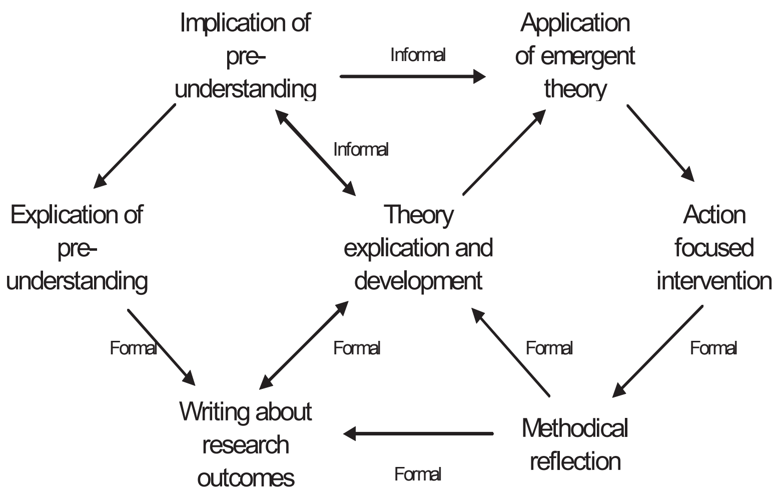

Figure 3.1 The generic process of action research (Eden and Huxham 1997)

The key parts of the graph above represent a generic view of action research phases (French & Bell 1984, p. 111, Riordan 1995): pre-understanding, theory exploration and development, as well as action interventions. The cycles include reflection and explication as well as application of the emergent theory. The cyclic and concurrent nature of the method is underlined by the directionality of the arrows. There are four interacting loops of actions around the central theme of “theory explication and development”. After “pre-understanding” on the left side of the process is obtained, only the two loops of “action focused intervention” and “writing about research outcomes” remain. The process is flexible, and for this study can be presented in a simplified format as shown in Figure 3.2., in which the reflection – theory explication – application – writing- loops of Figure

3.1 are not shown separately but are rather included in the twelve action cycles. Within the action research process of the study, multiple research methods were applied according to the type of information that became available during the process. The process and its constituent methods are described in Figure 3.2 and discussed on following sub-chapters.

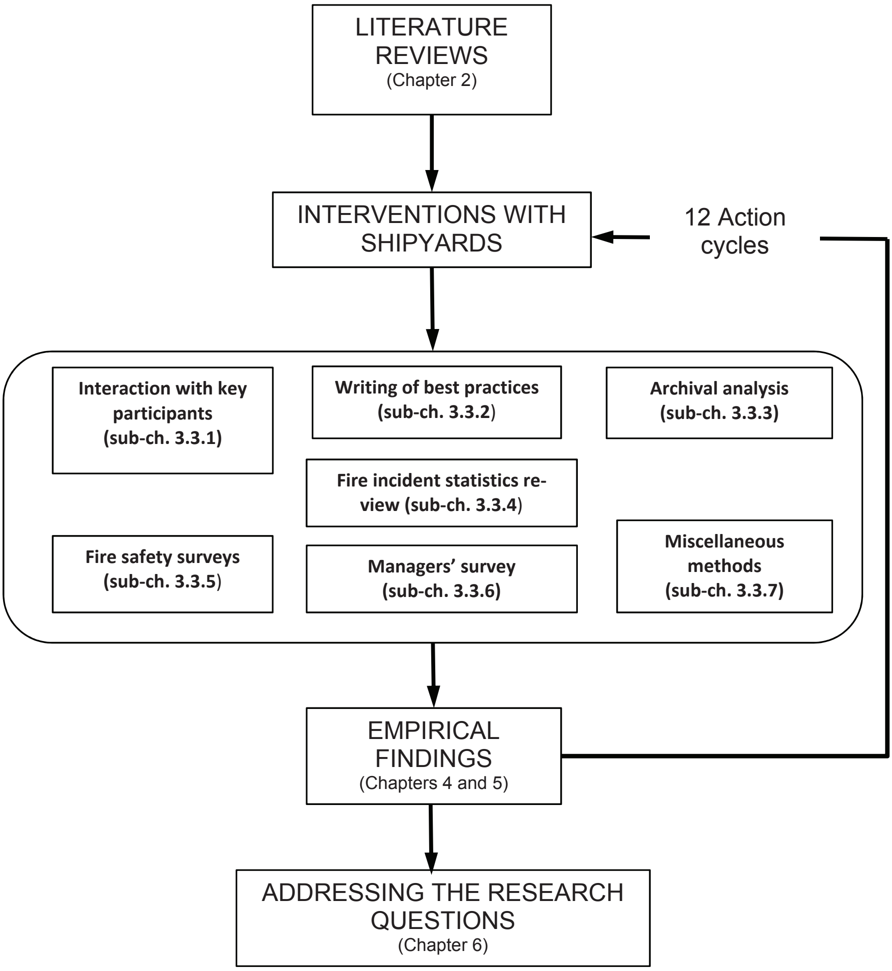

Figure 3.2 The overall research process of this study, and the main methods used for obtaining information during the action cycles

In this study, a pre-understanding of the problem was formed before the twelve action interventions started. It was obtained from literature, interviews with participants, preliminary fire risk management audits and the fire incident statistics of one of the shipyards. From these, it could be derived that the work should be concentrated in the whole risk management process of the shipyards, through studies of 15 (later 14) categories of contributing factors to ignition and three types of consequences (human, material and secondary damages). The pre-understanding was explicated as tables of risk-related issues and available responses for managing the fire risk (Table 2.1 to Table 2.3) and as RCCL internal documents (Räisänen 2000, 2001a, 2001b). These documents were used in preliminary discussions with two shipbuilding companies. Later, the action interventions during the research process involved first three and then four shipbuilding companies. There were three principal ways available for the researcher to induce improvements: written client's recommendations or requests for active measures to improve fire risk management, meetings with the participant organisations and workshops with the key personnel. The information on fire risk and responses initially found in literature was updated continuously during the interactions with qualitative and quantitative data, which provided the basis for addressing the research questions.

After the literature studies, the risk and the responses were described with the metrics and other information that were available at the time. The estimates improved when new information became available during the action cycles. Each action had a formally documented start status ("Theory explication" in AR terms of Figure 3.1). Targets for action cycles were determined qualitatively as "main topics of actions". They were explicated for each shipyard separately, and later, when the co-operation of the shipyards increased, also as their joint action topics. The outcomes were documented after each action cycle ("methodical reflection" in AR terms). The documentation and topics are summarized in Table 3.5 on p. 83.

As stated earlier, rigorous documentation of action histories is necessary for the reliability of the conclusions (Eden and Huxham 1997) due to the flexible and unformatted nature of the AR method. In this study, documentation consists of catalogues of the relevant documents and recordings of the history of the actions. Documentation is discussed separately in subchapter 3.4. The history and the details of the process of obtaining the pre-understanding and the action cycles are described in Appendix F. A short summary of history is given below.

At the outset of the research actions 1999-2000, the intervention and research design was based on RCCL auditing of three shipbuilding companies. The company hired a safety consulting company, Baltic Ship Safe Ltd, (BSS) to make audits; the findings were reported to the three yards and improvement demanded of them. The need for some kind of metrics was found early in the process, and a checklist with some metrics was developed for the audits. During this time, information for forming the pre-understanding for the research was gathered. The methods were literature reviews, safety audits, analysis of the fire incident reports of the RCCL vessels under construction and participant interviews. Some archival analysis was done for the pre-understanding: reports and records of major fires and some fire incidents were available (e.g. Liland 1991) from some yards, to augment the view gained from literature and interaction with participants. About a year later, the intervention design was changed (explicated in Räisänen & Fetten 2001), and the action cycles of the research began to include closer co-operation with the yards. A Safety Interest Group (S.I.G.) of three shipbuilding companies in Finland, France and Germany was the result, where problems, best practices and statistics were shared. The researcher has since acted as the secretary of the group. The members were the safety managers, fire chiefs and some production logistics personnel of the yards. Later, in 2002, the Italian Fincantieri shipyards at Monfalcone, Marghera and Sestre joined the research, increasing the coverage to 85 to 90% of the world capacity. Each action cycle was numbered from 1 to 12 in approximate chronological order, and named according to the event ending the cycle, typically a Safety Managers' Meeting.

Table 3.1 The 12 research actions and their participants

	Action	Participants
1	Owner's and their consultants' fire safety interventions 1999-2001 (Pre-understanding)	Royal Caribbean Cruises Ltd, (RCCL), Baltic Ship Safe (BSS), Det Norske Veritas (DNV); the three shipbuilding companies
2	Starting meeting of safety managers co-operative in November 2001	RCCL, two shipbuilding companies
3	Fire safety workshop with one of the yards January 2002	RCCL, one shipyard, BSS
4	Visit of safety manager of yard BBB at yard AAA March 2002	BSS, two shipbuilding companies, RCCL
5	Meeting of safety managers at yard CCC in April 2002	RCCL, three shipbuilding companies, BSS
6	Meeting of safety managers at yard BBB in May 2002	RCCL, four shipbuilding companies
7	Meeting of safety managers at yard AAA in September 2002	RCCL, four shipbuilding companies
8	Meeting with firemen of one shipyard in December 2002	RCCL, fire personnel of one shipyard
9	Meetings with outfitting foremen of one yard and its subcontractors spring 2003	RCCL, four groups of outfitting foremen of one yard and its subcontractors
10	Meeting of safety managers in March 2003	RCCL, four shipbuilding companies, one other ship owner, three classification societies
11	Inquiry of management opinions of fire risk	RCCL ship project management, one yard top management, DNV
12	Event tree and discussion on sprinkler usage	RCCL, four shipbuilding companies

Each shipyard and the owner's consultants carried out their parts of the improvement actions at their own pace. Besides the direct action cycles of Table 3.1, there were three separate actions that contributed to the overall view of the problem:

1) The yearly waste volumes of one yard were obtained and analysed

2) An event tree estimation of sprinkler effectiveness during the building process was calculated and presented to the participants.

3) Survey of expert managers' estimates a rather long time after the actions in 2011.

Both qualitative and quantitative research approaches were used, which are discussed further in the following sub-chapters.

3.2 Use of triangulation in the study: varying research methods and materials

Triangulation is a term used, for example, in navigation for determining position by making observations of distances or angles to known objects, and intersecting the lines of position thus obtained. In management research, the definition has been used to mean the application of two or more research methods to the same problem (Gummesson 1991, p. 121). This can be extended to a broader definition, which involves multiple data-collection technologies, theories, researchers and methodologies. Further, the mixing of qualitative and quantitative methods may produce a more complete picture of the phenomenon (Jick 1979, p. 603). Eden and Huxham (1997, p. 536) refer specially to the opportunity of triangulating in action research, between the action cycles, and using it as a dialectical device.

In this study, the themes in fire risk identification, its assessment and available responses recurred throughout the action cycles. Eventual controversial findings of various methods were consequently taken up in the interactions with the participants, and proved to be an effective dialectical tool, as referred in Eden and Huxham (1997, p. 537). The repeated comparison of the participating shipbuilding companies and their yards with their fiercest commercial competitors provided a particular opportunity for theory generation and development of practical responses. In fact, with such a large group of participants, there was an abundance of research data, and the interpretation of especially qualitative data during the action cycles took great effort. However, this ensured that the findings benefited the actions in real time.

In this study, triangulation with multiple researchers or multiple theories has received minor attention for practical reasons. Instead, the multiple sources of information dictated that several different research methods were used within the action research, which provided for unusually comprehensive triangulation in methods and materials. In Figure 3.3, these are outlined. There were three qualitative (see discussion in sub-chapters 3.3.1 to 3.3.3) and three quantitative (sub-chapters 3.3.4 to 3.3.6) main research methods.

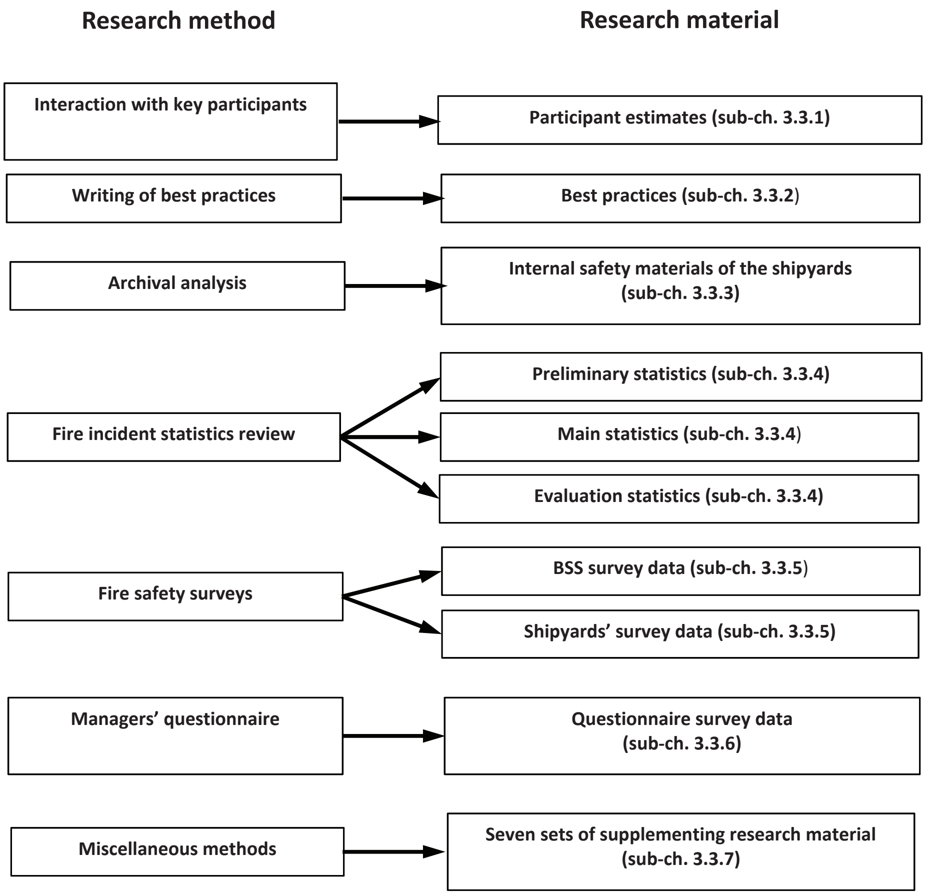

Figure 3.3 Research methods and materials in the action cycles, see relevant sub-chapters for discussion

3.3 Research material

As illustrated in Figure 3.3., nine main sets of research materials were used during the action cycles. Further, these were supplemented with seven sets of data from miscellaneous sources. In the actions of the research process, the evidence from all sources formed a constantly improving mosaic view of fire risk and responses at the shipyards. It was possible directly to divide much of the obtained data either into the 15 (later 14) ignition-related categories derived from literature or into types of consequences of established fires (Table 2.1 to Table 2.3). The information was continuously recorded by the researcher during the actions with the yards, and the categories adjusted if needed. Data was also extracted from the written material received during the research, especially for participant estimates. During safety interest group meetings, a working document on best practices (Räisänen et al. 2002) was created and revised. In addition to gathering information, the aim was to announce the state-of-the-art and future goals, published internally at the four yards. In addition, the shipyards had considerable amounts of their documentation on fire risk management practices made available for study. A highly efficient way of learning about fire risk and its management, especially about ignition prevention, were the fire incident statistics of the participant shipyards. These included a groundbreaking joint fire incident statistics that was formed during the study of data from four European shipyards from late 2001 to early 2003. Most of the incident records also included short descriptions of the incidents, which provided qualitative data and an insight into the circumstances on-board. Information was also obtained from fire safety surveys, which were provided throughout the research period by RCCL's safety consultants at three yards, and one yard's fire guards. The close co-operation with the shipyards' expert managers prompted a questionnaire survey of risks and response feasibility, which helped in addressing the research questions.

In order to meet the confidentiality requirements of the yards, the presented research material of the thesis has been made unidentifiable when needed for publication, e.g. the shipyard identification letters are varied and redistributed from topic to topic.

3.3.1 Participant estimates

The definition of 'participant estimate' in the study was rather broad. It included not only many kinds of short fire safety-related records from participating companies but also information from single persons in the industry. There were 34 records of information, which are listed in Table 3.2. In addition, the participating companies had broad safety documents, such as manuals, for internal use, which are discussed separately in sub-chapter 3.3.3.

The sources of information were data from participating companies, interviews and discussions with knowledgeable persons in the industry, safety personnel meetings and a workshop. Interviews and discussions were used as sources predominantly at the beginning of the research, whereas written material and records of the improvement meetings became available mostly later in the process. All the persons listed in Table 3.2 had very good knowledge of the topics. They were safety managers of shipyards, clients, consultants and insurers. Eight of the participating persons (sources 6 to 11, 13 to 14, 21 to 26 and 28 to 33) were directly responsible for fire safety management in shipbuilding, either for the yard or for the owner. The interviews and discussions were typically of one to two hours in duration, and revealed the state of the art as well as prompted new development avenues. The topics ranged from strategic issues to specific fire safety details. Otherwise much of the records consisted of concise (some pages) safety-related information materials produced by the participant organisations. In the tables of information sources on the following pages, many records are self-explanatory; however, the source term 'interview' needs specification. It refers to a semi-structured interaction, arranged for the purpose, with written recording, based on meeting notes or tape recordings, and the content later evaluated by the interviewee. The source of 'discussion', respectively, accounts for a less strictly prepared event, recorded in writing during or after interaction, with no later content evaluation by the object person. Further, there were constant formal and informal interactions with the personnel of the owner and of the yards (e.g. interactions with Degerman 1999, Elice 2003e, Furic 2007, Grosso 2011, Högblom 2000, Kulovaara 2000, Laine 2000, Lebaron 2010, Longeroche 2001, Mäkelä 2000, Moisio 2000, Moore 2000, Miorelli 2001, Paasikivi 2000, Pitkänen 1999, Servanto 2001b, Wähler 2002, a total of 17 named informants).

The information on fire risk and responses was extracted from the written documents and researcher's notes regularly during the action cycles. The qualitative data on fire risk, its assessment and responses were recorded, classified in the result tables, and added to preliminary answers for research questions. The data was used in constant triangulation with other types of information. In addition to the formal input listed, the safety managers of the yards provided continuously practical feedback for assessment of intervention alternatives. They also eagerly delivered complementing material for addressing the research questions, and offered data for triangulation of the conclusions of the study.

Table 3.2 Sources of information for unpublished participant estimates. Tables are arranged alphabetically by stakeholder name. Full source data is found in the References at the end of this study. (continues on the next page).

	Source	Author, interviewee or participant	Research material topic and format	Are research material contents evaluated by the object of interaction (e.g. the interviewee)
1	Meeting	Aker/Kvaerner EHS Champions 2002	Vulnerability to ignition of vessel types, researcher's notes	No
2	Memorandum	Äyräs 2003	Hot work safety presentation	Yes, content produced by object
3	Memorandum	Bergen Hull Club 2000	Quality Assessment Form	Yes, content produced by object
4	Memorandum	Det Norske Veritas 1999	Fire inspection review	Yes, content produced by object
5	Discussion	Egeland 2000	Meeting notes, written summary	No
6	Memorandum	Elice 2003a	Safety slides	Yes, content produced by object
7	Memorandum	Elice 2003b	Evaluation of fire risk	Yes, content produced by object
8	Memorandum	Elice 2003c	Fire incident photos	Yes, content produced by object
9	Memorandum	Elice 2003d	Cruise ship particulars	Yes, content produced by object
10	Memorandum	Furic 2003a	Cruise ship particulars	Yes, content produced by object
11	Memorandum	Furic 2003b	Fire prevention presentation	Yes, content produced by object
12	Memorandum	Hauge 2000	Fire control in passengerships	Yes, content produced by object
13	Interview	Holmberg 2003	Fire safety comparison of the three shipyards, taped interview and written summary	No
14	Oral presentation	Holmberg 2002	Shipyard safety issues, researcher's notes, minutes of the meeting	Yes
15	Discussion	Jakobsen 2002	Fire safety onboard, researcher's notes	No
16	Memorandum	If and Vesta Insurance 2000	Management review	Yes, content produced by object
17	Discussion	Kanerva 2000	Fault trees in passenger vessels, researcher's notes, written summary	No

Table 3.2 Sources of information for unpublished participant estimates. Tables are arranged alphabetically by stakeholder name. Full source data is found in the References at the end of this study (continued from the previous page)

	Source	Author, interviewee or participant	Research material topic and format	Are research material contents evaluated by the object of interaction (e.g. the interviewee)
18	Discussion	Kulovaara 2000	RCCL safety strategy, fire incident origins, use of fault trees in passenger vessels, researcher's notes, written summary	No
19	I nterview	Kulovaara 2002	Effect of vertical shafts to fire safety, hot work, researcher's notes, written summary	Yes
20	E-mail reply to questions	Logistics Manager, Yard AAA	Volumes and density of waste	Yes, content produced by object
21	Interview	Longeroche 2001	Fire safety, taped interview and written summary	Yes
22	Interview	Miorelli 2001	Fire safety, taped interview and written summary	Yes
23	Memorandum	Moisio 2003a	Fire safety co-operation summary	Yes, content produced by object
24	Memorandum	Moisio 2003b	Hot work co-operation summary	Yes, content produced by object
25	Memorandum	Moisio 2003c	Management attention co-operation summary	Yes, content produced by object
26	Memorandum	Moisio 2003d	Cruise ship particulars	Yes, content produced by object
27	Discussion	Moore 2000	Risk management, researcher's notes, written summary	No
28	Memorandum	Servanto 2000	Fire safety inspection sheet	Yes, content produced by object
29	Memorandum	Servanto 2001a	Fire risk assessment of a ship	Yes, content produced by object
30	Discussion	Servanto 2001b	Status of fire safety at three shipyards, researcher's notes, written summary	No
31	Memorandum	Servanto 2002	Evaluation of shipyards	Yes, content produced by object
32	E-mail	Wähler 2003	Cruise ship particulars	Yes, content produced by object
33	Discussion	Wähler 2004	Commissioning of safety systems, researcher's notes, written summary	No
34	Memorandum	Yard AAA, 2002	Logistics reorganization	Yes, content produced by object

3.3.2 Joint document on best practices

An important product of the co-operation between the shipyards' safety managers was the Best Practices document for fire safety that was written and continuously revised by the researcher with input from the participating companies' safety managers (Räisänen et al. 2002) throughout the action cycles. The document versions were produced for the internal use of the owner and participating shipyards. Twelve versions were produced during the actions. Four versions were subjected to participant scrutiny at Safety Interest Group meetings, and others were working versions. From the research point of view, the aim of the documents was to provide one additional way of explicating the findings of the action phases. Also, the writing process was used as a dialectical tool, with which fire safety-related information was inquired about and generated. The information was extracted during the revision rounds not only directly from the resulting document versions but also from the development comments of the participants. The obtained information was classified in tables of risks and responses, and used to amend the emerging answers for research questions. The last version related to this research (Räisänen et al. 2002) had 27 pages. Its table of contents is reproduced in Figure 3.4. The document included the participating shipyards' consensus view on shipyard fire risk management arrangements (preventing ignition and managing consequences of fires), as well as shipyard organisation and attitudes relative to fire safety (general management, shipyard design, production and safety management, production employees and safety culture in general).

Several versions of the Best Practices were produced after the research in an EU-funded project. Although the contents of the document were confidential, a version of the Best Practices document was used as a starting point when the conference publications (Räisänen et al. 2003a, 2003c) were prepared for explicating the findings of the co-operation and research to the industry on behalf of the Safety Interest Group of the participating shipyards. These documents contain the condensed best practices in hot work, fire load handling, fire door closure, detection and extinguishing, as well as fire patrolling, alarming and education. Further, they emphasized the organized risk management feedback process for the key issues, and advocated the safety culture. In this thesis, the best practices underlie the discussion of Chapters 4 and 5.

1. Introduction ... 3
1.1 Observed frequency of fire incidences and their causes ... 3
1.2 Shipyard design, production and safety organization ... 3
1.3 Definitions ... 4

2. Shipyard fire safety arrangement ... 6
2.1 Preventing fire ignition ... 6
2.1.1 Controlling heat-energy source(s) ... 7
2.1.2 Control heat-energy source – fuel interaction ... 9
2.1.3 Controlling fuel ... 10
2.2 Managing fire impact ... 12
2.2.1 Managing fire ... 12
2.2.2 Managing exposed ... 15

3. Organization and attitudes ... 16
3.1 General management ... 17
3.1.1 Status of safety issues in the formal and informal organization ... 17
3.1.2 Organizational learning systems ... 18
3.1.3 Project fire risk management ... 18
3.1.4 Measurement of safety attitudes ... 18
3.1.5 Communication, success factors, statistics, and databases ... 19
3.1.6 Safety budget ... 20
3.2 Shipyard design, production and safety management ... 21
3.2.1 Arrangement of work ... 21
3.2.2 Incident reporting ... 21
3.2.3 Design and logistics of flammable waste removal and flammable liquid storage ... 22
3.2.4 Safety training ... 23
3.2.5 Support, enforcement and surveillance by the safety organization23
3.2.6 Hot work permit system ... 24
3.3 Production employees ... 25
3.3.1 Fire safety rules ... 25
3.4 Safety culture ... 26

4. Conclusion ... 27

Good practices of passenger vessel shipyard fire risk management v.12.doc

Figure 3.4 Table of contents of a version of the Best Practices document (Räisänen et al. 2002).

3.3.3 Internal safety materials of the shipyards

The shipyards' own safety material presented possibilities for obtaining a view of the fire risk management of cruise vessel construction with archival analysis. The sources included (Table 3.3) the safety manuals of all four participating shipbuilding companies, as well as some other literature and videos of the yards (Chantiers de l'Atlantique 2001), (Di Pieri & De Marco 2001), (Kvaerner Masa-Yards 1999, 2000, 2001 and 2003), (Wähler 2002a and 2002b). Again, the analysis was carried out during the action cycles, and relevant information was extracted for amending the cumulative evidence on fire risk and responses. The analyses especially contributed to knowledge of systematic risk management, attitudes and management practices.

Table 3.3 Sources of internal safety material of the four shipbuilding companies and evaluation by the source. Full source data is found in the References at the end of this study.

	Source	Author	Research material topic and format	Are research material contents evaluated by the object of interaction (e.g. the interviewee)
1	Memorandum	Chantiers de l'Atlantique 2001	Safety Manual	Yes, content produced by object
2	Memorandum	Di Pieri and De Marco 2001	Safety information	Yes, content produced by object
3	Memorandum	Kvaerner Masa-Yards, 1999	Occupational health manual	Yes, content produced by object
4	Memorandum	Kvaerner Masa-Yards, 2000	Ship operation manual	Yes, content produced by object
5	Memorandum	Kvaerner Masa-Yards, 2001	Quality guide	Yes, content produced by object
6	Memorandum	Kvaerner Masa-Yards, 2003	Safety plan	Yes, content produced by object
7	Memorandum	Wähler 2002a	Subcontractor instructions	Yes, content produced by object
8	Video	Wähler 2002b	Safety training	Yes, content produced by object

3.3.4 Fire incident statistics

Three sets of fire incident statistics were used in the research. These are discussed below and summarized in Table 3.4 on page 67. The first set, (named Preliminary Statistics) was used in the earliest research actions. It came from one shipyard's own information for the years 1998 to 2001 (Interactions with Fire Chief, Yard AAA 2000), (Interactions with Fire Chief, Yard AAA 2001), and included simply the number of fire alarms within the gates of the shipyard per year, percentages of ignition cause and fuel of the fires. There were 227 incidents. One of the incidents in the first set was a major fire that had caused significant damage. Further, a subset of these fire incidents had more specific details for fires on-board: time, date, location on-board, and full event histories for each fire incident. The set included 47 incidents.

The second set of information (named Main Statistics) covered the fire incidents on-board or in the immediate vicinity of the vessel (e.g. a paint gun on the quay by the vessel) of the four shipbuilding companies. This set of data was extensive, and also included the incident histories. It provided clearly the most significant contribution to the research. For this data, a format for analysis was developed by the researcher in co-operation with the Safety Interest Group of the shipyards (S.I.G.), which was also formed in this research. The S.I.G. discussed the items to be recorded, based on their view on relevance, availability and ease of use. Finally, date, time, location on-board, fuel, ignition cause, the company responsible for the incident (subcontractor) and the incident history were selected as the input variables. To rule out the smallest of incidents of which scant data was produced, *fire incident* was defined as '*fire on-board, where at least a fire extinguishing blanket or a portable extinguisher has been used for suppression*' (see Definitions). The main statistics set included a total of 221 fire incidents, two of which had escalated into major fires. There were 22 ships represented in the main statistics, which was collected mostly during year 2002 and for a small part during year 2003. The ships included in the data and their delivery dates are listed in Appendix G. The set contained all data mentioned above for each incident, except 90 incident histories and 79 records of the companies responsible for the fires. This was mostly due to unfinished internal recording procedures at some of the participating yards. The set was used in most of the later actions, and summaries were discussed at all safety interest group meetings. The set was also important in making conclusions for this study. During the actions, the initial statistics developed into the statistics reporting system that was still (2014) in use at the S.I.G. participant shipyards and included approximately 1,200 incidents at the time of writing. The statistics input form is shown in Figure 3.5.

FIRE INCIDENTS IN PASSENGER SHIPS AT SAFETY CO-OPERATION YARDS 2002

Statistics for ship and the immediate area around it

For shipyard safety co-operation members internal use only

Fill all three tables with your data, save with name "Shipyard safety report Yardname date.xls", e.g "Shipyard safety report CAT 1.10.2002.xls" and send to p

See definitions and codes on the header fields by placing the mouse on top

Do selections for your own viewing by pushing on the arrow buttons in the header fields

	Date	Time	Yard	Ship number	Location deck	Area id	Fuel	Ignition cause	Subcon tractor	Incident grade	Incident story
1	23.1.2002	22:30	CAT	656	10	FZ6	WT	F	ABB	2	Write incident history here
2			JLM				GL	W		1	Write incident history here
3			KMYH				PI	G		2	Write incident history here
4			KMYT				PS	E		3	Write incident history here
5			MA				C	O		4	Write incident history here
6			MO				O			2	Write incident history here
7			SC							3	Write incident history here
8											
9											
10											
11											
12											
13											
14											
15											
16											
17											
18											

Figure 3.5 The final fire incident statistics input form for the S.I.G. (Räisänen 2002m, unpublished).The categories of fuel and ignition energy are shown (WT = waste, GL= gas leak, PI=permanent material already installed, PS= permanent material stored on-board, C= chemicals, O= other) (F= flame cutting, W=welding, G= grinding, E= electric, O= other)

In addition to the above statistics, a third set (named Evaluation Statistics) of approximately similar data from 2001 was available from two of the yards. There were 66 fire incidents. The data was used in evaluating the larger set, but was not included in it, or distributed to all members of the Safety Interest Group. This was due to confidentiality issues.

Table 3.4 The three statistics of the research

Name of statistics	Collection time	Organization	Collection area	No. of incidents
Preliminary Statistics	1998-2001	One shipyard	All fires in the shipyard	227
Main Statistics	2002, partly 2003	Four shipbuilding companies	Ships and the immediate area around them	221
Evaluation Statistics	2001	Two shipyards	All fires in the shipyard	66

In selecting the methods of analysis, it was found that simple review approaches suited the available data better than rigorous statistical treatment. The reason was that the situation in the industry was dynamic, and the incident records gave a relatively short glimpse of fires on-board compared to the time-frame of the total production flow of the four shipbuilding companies. A typical time for finishing a large cruise vessel at the yards was around two years and the research time was three years. There were many ships in construction, at various stages of readiness, and thus most of the incident data covered only part of their production time. Also, fire risk management development associated with the research efforts reduced the number of fires per vessel considerably in many of the yards. Further, shipyard organisations learn from experience with prototypes, which usually causes fewer production errors in later similar vessels (sister ships), which influenced the outcomes. For the above reasons, no in-depth statistical modelling was deemed necessary or feasible for the research. The term 'statistics' in this text refers rather to review of numerical data of the incidents and its visualisations used in action interventions. Good coverage to support the actions with the yards was accomplished nonetheless with comprehensive calculation of relevant quotients, such as the ratio of hot work-related incidents to all fires. There are good opportunities for further research in this matter, though. At the outset of the research, there were no established statistical methods for visualising the occurrence of fire incidents relative to project timing, nor relative to ship size, important for comparisons of ship projects and shipbuilding companies. To overcome this shortcoming, during the first few action cycles a simple presentation format was developed to make the variables of project timing and ship size non-dimensional.

The shipbuilding process and schedule can be described in many ways, as discussed in sub-chapter 1.2, but the key project milestones for fire incidents were found to be the keel laying and the delivery. All fire incidents on-board were found, as expected, to occur between these milestones. The dates of these key milestones of all the ships in construction were used at the outset of the research to the scale of each project time from 'days' to '0 to 100%'. There were problems, however. When the project durations between these milestones were compared among the shipyards, it was confirmed, as expected, that the duration depended not only on the shipyard production capacity and workload, but also on several unrelated factors such as constraints in equipment delivery, international regulations, contract contents and design and building process philosophies. Also, it was noted that the ships may be nominally in production but the progress can be slow due to priorities between ship projects. With this in mind, it was found that actually the fires on-board occur as the project pace increases towards the delivery, typically during the last 1½ years of *active* building time before delivery, irrespective of the formal keel laying date of the ship contract. Therefore, a nominal, fixed production time was selected as the basis for normalisation. To be on safe side, 100 weeks of building time before the delivery was selected as the observation period, with the added benefit of ease of interpretation for the practitioners at the shipyards, as one week corresponds to 1% of the nominal building time in dry-dock and outfitting quay. (Later, it was found that this selection was very suitable as all fire incidents have occurred between 20% and 99% of the non-dimensional time, see Figure 3.6.) For good readability, the numbers of incidents were grouped in 5-week intervals, which correspond directly to the widths of 5% of the columns in the graphs. It was also found that more elaborate methods to link process milestones to fires on board could be devised, with dates such as start of outfitting in compartments, daily hot work coverage, closing of ceilings and sea trials. But these will remain subjects for eventual future research, as one of the main problems is obtaining comparable detailed building process data from the various shipyards for this purpose.

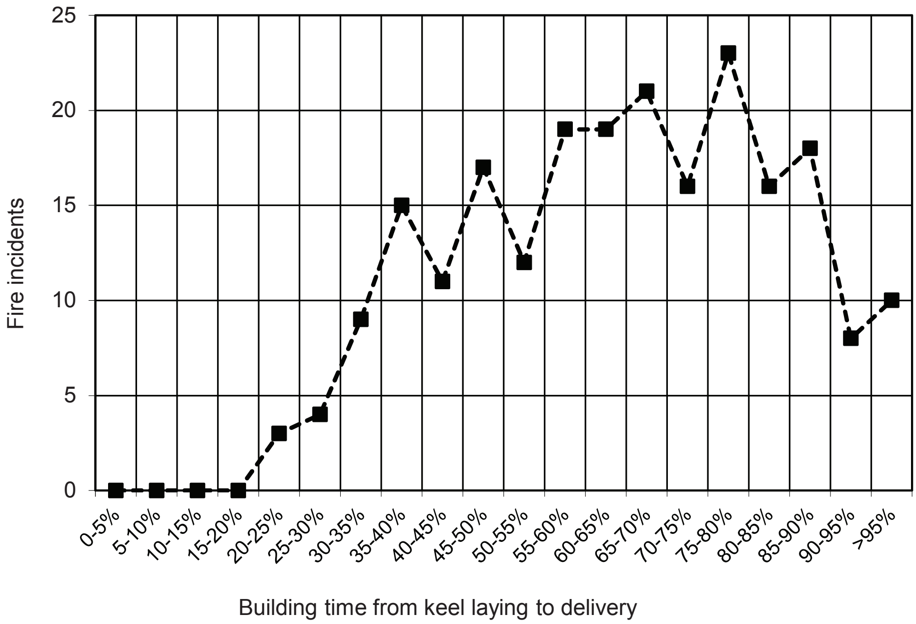

Figure 3.6 Number of fire incidents relative to time from keel laying to delivery of the ships, 2002. The Main Statistics of 221 incidents. One incident is not plotted due to uncertainty in time data. The data is not from complete delivery cycles. (Räisänen 2003e, unpublished)

Some bias is present in the statistics due to the fact that the numbers plotted above are not of complete delivery cycles of vessels, since shipbuilding processes were long compared with the duration of the research, as mentioned on page 67. On the other hand, 22 ships were represented in the statistics at this phase, and they were at varying stages of delivery, which reduces the bias. A graph of the percentage of ships available for each time interval is presented in Figure 3.7.

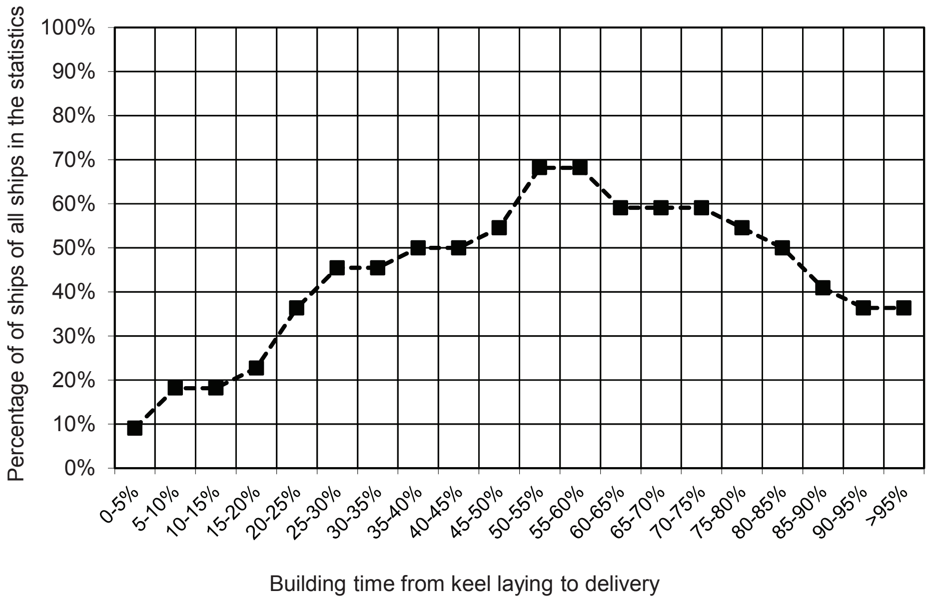

Figure 3.7 Percentage of number of ships included in time intervals of the incident statistics 2002 (of the total of 22 ships) (Räisänen 2003e, unpublished)

For example, the graph above shows that, in 2002, about 70% of the vessels passed the construction phase that relates to the non-dimensional time interval of 50% - 55% of building time. (It should be noted that the number of ships included in a time interval of the graph was not necessarily an integer. The five-week intervals are ship-specific, and observation periods have started or ended randomly during the intervals).

In addition to normalising the building process time, similar questions arose on normalising the number of fires between ships of different sizes. For example, a few fires during the construction process of a small river cruise vessel would indicate much greater fire safety problems for the yard than the same number of fires in the assembly of a large cruise ship. The effect of ship size could not be analysed statistically in this research, again due to the relatively small number of incidents, but factors that relate to fires were studied instead. The most common fuels in the fires on-board (waste, installation materials and gas) and the usual ignition sources (welding, flame cutting, grinding and electrical) were found to be involved in at least 90% of the observed fires (as discussed in detail in Chapter 4). The amounts of these eight 'main ingredients of fires' are related to the size of the ship; larger ships have more welding on-board, for example. For this study, it was deduced that consequently the number of fires that result from these factors could also show similar dependence, and thus the numbers of fires were normalised by ship sizes. In shipbuilding, ship size is expressed in many interrelated ways, such as the weight of the ship, its enclosed volume, gross tonnage and the area of all decks. Of these, the gross tonnage (GT) is easiest to obtain for research as it is public. It is also directly related to the volume enclosed by the ship (one GT corresponds to about 3 m^3 of volume, see Definitions). With this input data, a quotient for the number of fire incidents per ship volume (expressed as gross tonnes) was obtained, which made comparisons possible. In practice, the observed number of fire incidents on a ship was divided by its GT and a normalised figure recalculated for a norm vessel of 100,000 GT. For example, one fire incident in a vessel of 80,000 GT would contribute 1.25 normalised fire incidents in the statistics of the shipyard, according to the difference in the gross tonnages. The norm vessel represented a typical medium size for the participating yards at the time (A vessel of about 270 m in length and carrying 2,500 passengers and a crew of 1,000 persons), but the graph can also be interpreted as the number of fire incidents per 100,000 GT in production at the shipyards. During the research, the raw incident graphs similar to Figure 3.6 were also presented to the shipyards, but the normalised versions of the statistics were preferred for comparisons of ignition-related factors. It was also found that, for presenting the magnitudes of the effects of the rare *established* fires and the associated risks for the projects, the statistical data was too scarce, and thus normalisation was not relevant for that part.

An overall view of the normalised fire incident statistics is shown in Figure 3.8. It is based on the European statistics of 221 incidents. At the request of the participants, the published data is slightly altered with regard to ship sizes to prevent direct identification of vessels. This plotting template was used in all the subsequent interactions with the participants. During the interactions, similar plots were produced created for sister ships (similar ships in a series) and each shipyard separately, in addition to the European averages. Later, when the participants were getting comfortable with sharing their performance with their competitors, the graphs for each yard were openly distributed to all shipyards, and used in their internal development work. The system was adopted directly for development work, and is still (2014) in use at the member shipyards of the Safety Interest Group (S.I.G.). The results are discussed at length in Chapter 4.

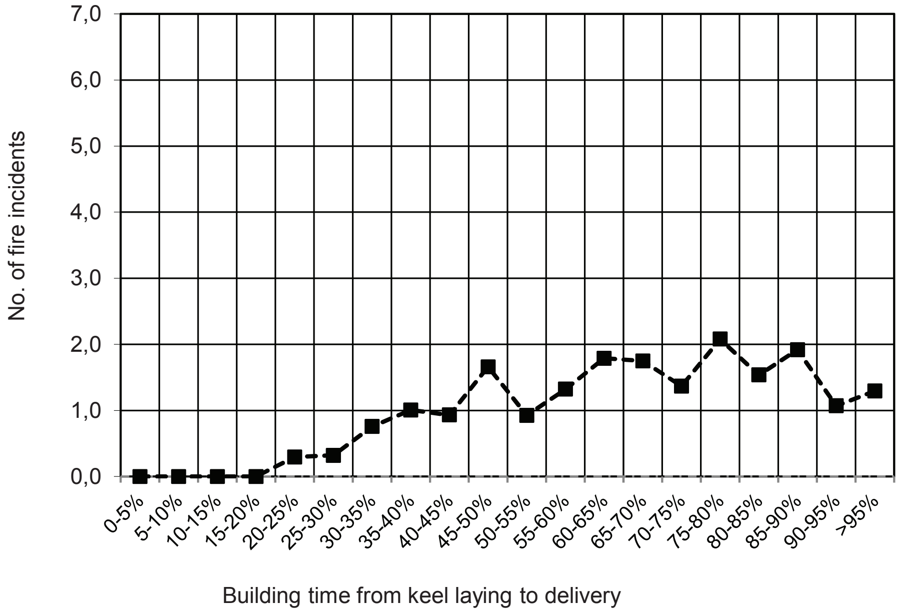

Figure 3.8 Normalised number of fire incidents of European yards, averaged in 5% time intervals for a norm vessel representing 100,000 GT in production (Räisänen 2003e, unpublished) (Duplicated here from Figure 4.2)

3.3.5 Fire safety surveys

Patrolling of ships by fire guards was used at all participating shipyards to prevent fires and their escalation. The guards surveyed the level of fire risk management on-board and produced both qualitative and quantitative information. For this study, two sources of surveys were available: the owner's surveys from three shipbuilding companies, and one shipyard's own fire guards' surveys, which are discussed below.

The RCCL's consultants BSS Ltd. carried out three to five days' safety surveys on-board their ships at three shipbuilding companies at intervals of a few weeks. The inputs to be annotated on deck plans during the inspection rounds were selected by the BSS inspectors and the researcher. Data from 17 surveys was used in the research, which provided an abundant amount of information. After some trial rounds, the final observation data consisted of six inputs related to preventing ignitions on-board, ten inputs related to managing the consequences of established fires and a remark field. An example of an annotated deck plan by an inspector, taken from the user instruction slides (Räisänen 2001a) is shown in Figure 3.9 and the resulting survey findings table is shown in Figure 3.10.

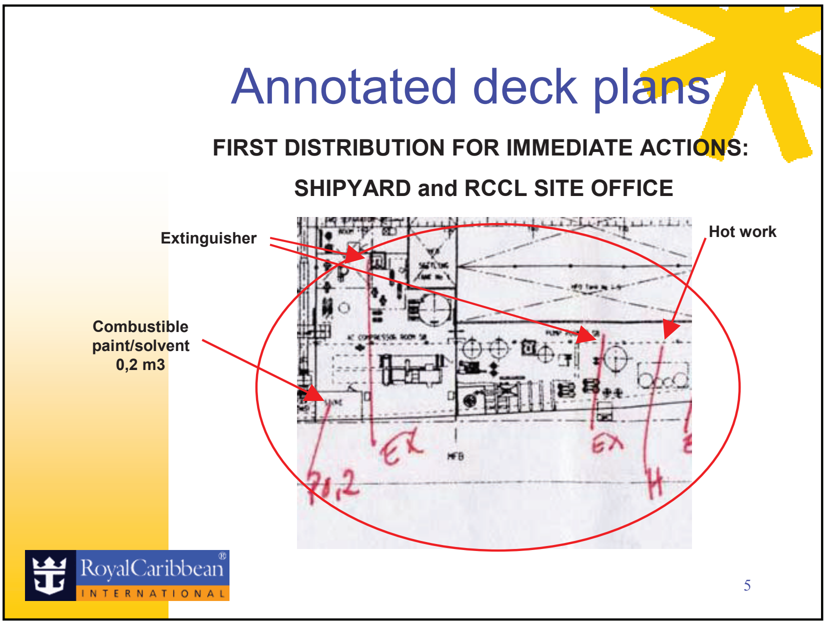

Figure 3.9 Instruction slide for principle of annotated ship's deck plans, (showing remarks added in freehand by the inspectors) (Räisänen 2001a, unpublished)

ROYAL CARIBBEAN CRUISE LINE AS / BALTIC SHIP SAFE OY LTD

FIRE RISK ASSESSMENT

Alue area	Volume of combustible trash m³	Volume of combustible paint/solvents m³	Number of open firedoors	Number of open cabin doors	Number of gas leaks	Number of Hot Work	Number of uncovered /dangerous HW	No of uncovered bulb lights	No of poor extinguisher locations	No of poor evacuation/ information signs	No of obstructed/ dangerous evacuation/ exit routes	Tidiness	No of proper extinguisher locations	Temporary fire alarming system	Fire Detection system	Sprinkler system in working order	Fireguards observed	REMARKS
Name of vessel: Adventure of the Seas							Date of inspection: 12 - 16 February 2001						Inspector (s): Lipponen, Servanto					
	T	P	/	X	G	H	HD	L	PE	PS	OBS	TD	EX	FA	FD	SS	FG	R
TT	5	0,2	2			3						1	13	2				
TW	4		3			3						0	10	1				
D 0	3		4	20		3						1	34	3				
D 1	25		36			10						1	39	4				
D 2	12		15	40		7						1	3	1				
D 3	12		5	15		8						1	19	1			2	
D 4	7		7			6						0	22	1				
D 5	17		6			8						0	24	1				
D 6	12		4	50		5						1	28	2				
D 7	7		11	45		1						0	15	2				
D 8	12		6	76		2						2	12	3				
D 9	9		7	58		2						1	20	3				
D 10	13		6	48		5						2	14	3				
D 11	15		6			10						1	19	1				
D 12	25		8			7						1	10					
D 13	19		2			5						1	8					
D 14	2		2			1						1	5					
D 15	1											0	2					

Fire Safety Inspection Sheet A1 / Ver 4

Figure 3.10 A typical BSS/RCCL survey summary table (Servanto 2001a, unpublished). Rows denote decks of the ship and issues for responses are found in the columns

All the participating shipyards had their own fire guards' survey systems. During the actions, one of the shipyards formalised its approach with the researcher and thereafter provided data from 2001 to May 2003. In the information collected, there were two inputs related mostly to preventing ignition, six inputs related to managing the consequences of fires and a free remark section, as shown in Figure 3.11. Each survey consisted of the findings of fire guards' nightly rounds in all spaces on-board, covering approximately one-fifth of the ship. There were 101 such nightly surveys, which provided comprehensive data for the research.

Ship no. xxx Fire safety inspection						#####				
Inspectors										
Target			Observations							Responsible
Area Number	Excessive fire load / m3	fire doors open	Cabin doors open	Vertical shafts open	Gas hose leaks	Access / escapes	Exit signs	Extinguishers and their markings	Remarks	Responsible persons
Distibution: RCCL, outfitting manager, project manager, accommodation outfitting manger, ship coordinators, area coordinators										

Figure 3.11 Shipyard fireguards' fire safety survey form (translated into English from the shipyard original by the author)

Findings from the both types of surveys were used during the actions as time series mostly to demonstrate the history and status of some key issues for participants. For the research, these provided data on possibilities for managing fire risk. The information was typically presented for the preceding months, and allowed comparisons to be made. The results are discussed in chapters 4 and 5. Typical results of surveys can be seen as graphs in Figure 4.15 to Figure 4.24.

3.3.6 Questionnaire survey of risks and response feasibility

During the interactions, the potential of responses to mitigate the risks and their feasibility in shipyard operations were constantly addressed with the participants, as the purpose was to find practical solutions for risk management. In addition, a special questionnaire survey for fire risks and the feasibility of responses was carried out among the expert managers of three shipyards and one ship-owner during 2011, offering a Delphi-style temporal glimpse of risks and responses. This resulted in the ranking of 13 contributing factors of ignition and three types of consequences in three categories: ‘Low or average’, ‘Elevated’ (i.e. increased risk compared to average risk) and ‘High’, which gave insight into risk frequency and impact, and ranking of the 141 available responses for these, in both potential of mitigation and feasibility for shipyard processes. The choice of scale was based on a 5-step ranking, but the lowest ranks of the scale were combined to make answering as practical as possible. The questionnaire form is shown below.

	Ranking points 1= low or average 2= elevated 3= high	NAME OF RESPONDENT		Ranking points 1= low or average 2= elevated 3= high	Ranking points 1= low or average 2= elevated 3= high
Risk	Expert opinion on importance of the risk (high frequency and/or severe impact= 3)	**Possible responses**	**No.**	Expert opinion on potential of the response to reduce the risk	Expert opinion on suitablility of the response to shipyard process, and of the ease of taking it into use
Risk of arson	Fill your points (1 to 3) on importance	Automatic suppression	1	Example: 3	3
		Good lighting	2	Fill your points (1 to 3) in these columns, please	
		Guarding of premises, control of access to vessel	3		
		Housekeeping to avoid flammable waste	4		
		Restricted access to compartments	5		
Risks due to autoignition	0	Avoiding autoignition of glues and plastic, ignition of incompatible chemicals	6	0	0
		Managing the use of incompatible chemicals used in the plant	7	0	0
Risk of capsize of ships due to extinguishing water	0	Making pump capacity available for draining of suppression water	8	0	0
		Removing obstacles from drainage paths	9		
Risks due to electric phenomena	0	Static electricity: proper grounding of vessel and its temporary and permanent parts, especially pipes	10		
		Use of lightning conductors, earthing in general	11		
Risks due to electric systems	0	Damage control of cabling	12		
		Ensuring overheating protection in electric systems	13		
		Overheating checks with IR equipment	14		
		Prohibiting domestic appliances onboard, e.g. coffee-makers	15		
		Proper installation of temporary electric systems	16		
		Shutting down of electric appliances when not in use	17		
		Systematic maintenance of electric appliances and cabling, e.g. motors, transformers and welding machines	18		
		Use of explosion-proof appliances in hazardous areas	19		
		Use of protected work lights instead of unprotected bulb lights	20		

Figure 3.12 The risks and response feasibility questionnaire input form

The management in charge of safety, the fire chiefs of the participating shipyards and one ship-owner answered the survey. There were 11 respondents: three participants from STX France, five from STX Finland, one from Meyer Werft and two from the ship-owner RCCL. The STX France and RCCL answers, respectively, were provided as joint estimates of the teams. The averages were calculated from the eight survey answers. Most participants had over 10 years' experience of fire safety. Also, the fire incident statistics had grown to more than 1,100 incidents at the participating yards, which gave the participants additional insight. The results were analysed by calculating the averages, and comparing them to each other. The results are discussed in sub-chapters 4.3 and 5.4. The complete data is presented as Appendix H.

3.3.7 Miscellaneous supplementing research material

In addition to the main research materials discussed in the previous sub-chapters, some additional information was used to obtain a richer view. These are discussed briefly below.

3.3.7.1 Participants' graphs on ignition risk during construction

A graphical inquiry method was used to find out about the views of the participants early in the action phases, and to promote discussion. In two of the interviews and at two meetings, the participants present were asked to draw on a blank paper a curve representing their view of distribution of ignitions as a function of building time, with their comments on the form, the location of the maximum (maxima) of the curve, etc. (Figure 4.26). These graphs were later also compared with the actual distribution of fires (Figure 4.2) and used as a dialectical device.

3.3.7.2 Top management estimates on the size of fire risk

At a meeting with the board of top managers of a shipyard, an opportunity was offered for the researcher to gain some insight into the fire risk management views of top shipyard managers. They were a level higher in the hierarchy than the participants of the research. Their estimates on how fire risk should be ranked relative to other risks for the business were asked for. The views added to the pre-understanding of the problem.

3.3.7.3 Test of fire risk index

It would be beneficial if a single quotient could be used to compare the risk levels during a shipbuilding project. The SIA 81 (also called the Gretener method) ((Fontana 1984, Ramachandran 1999, p. 366) fire risk index output was tested, but further development of such indices was discontinued due to lack of interest of the participants. The lack of interest was attributed to the effort required for the collection and filtering of the input data from fire guard survey reports. In future, with automated input from electronic survey records, a new trial could be carried out. For completeness, a typical input and output are presented in Figure 3.13 and Figure 3.14. A description of the index work is added in Appendix I. However, some of the factors used in the calculation risk index were interesting in themselves and were used further in assessments.

Input values:				
			Observed fire load by BSS	
Moveable fire load	q	1.092	228 MJ/m2	Linearized, all fire load collected in one fire compartment
Combustibility	c	1.2		
Smoke formation	r	1		
Danger of corrosion/toxicity	k	1		
Fixed fire load	I	1		
Storey level or clear room height	e	3	Basement 12 m below the quay level	
Large compartment	g	1.8	7000 - 9000 m2, ratio 1:5	
Potential fire danger	**P**	**7.08**	$P = q \cdot c \cdot r \cdot k \cdot I \cdot e \cdot g$	
Protection measure quantification:				
Ordinary measures	N	0.95	$N = n_1 \cdot n_2 \cdot n_3 \cdot n_4 \cdot n_5$	
Special measures	S	1.785	$S = s_1 \cdot s_2 \cdot s_3 \cdot s_4 \cdot s_5 \cdot s_6$	
Protection structural measures	F	1.495	$F = f_1 \cdot f_2 \cdot f_3 \cdot f_4$	
Calculation of risk:				
Exposure to danger of fire:	B	2.792	$B = \frac{P}{N \cdot S \cdot F}$	
Activation danger	A	1.325	Mean of value for mechanical engineering and chemical laboratories from SIA 81	
Effective fire risk	**R**	**3.70**	$R = B \cdot A$	
Accepted fire risk Ru=1.3P$_{H,E}$	**Ru**	**0.78**	$P_{H,E} = 0.6$	from SIA 81
Fire safety quontient	**Ru/R**	**0.210856**	Should be above 1 for ordinary buildings	
Fire risk/ accepted risk	**R/Ru**	**4.743**	Risk is 4.743 times larger than the risk accepted for ordinary buildings by SIA 81	

Figure 3.13 An example of the calculation of the SIA 81 fire risk index for a shipyard (Räisänen 2001b, unpublished)

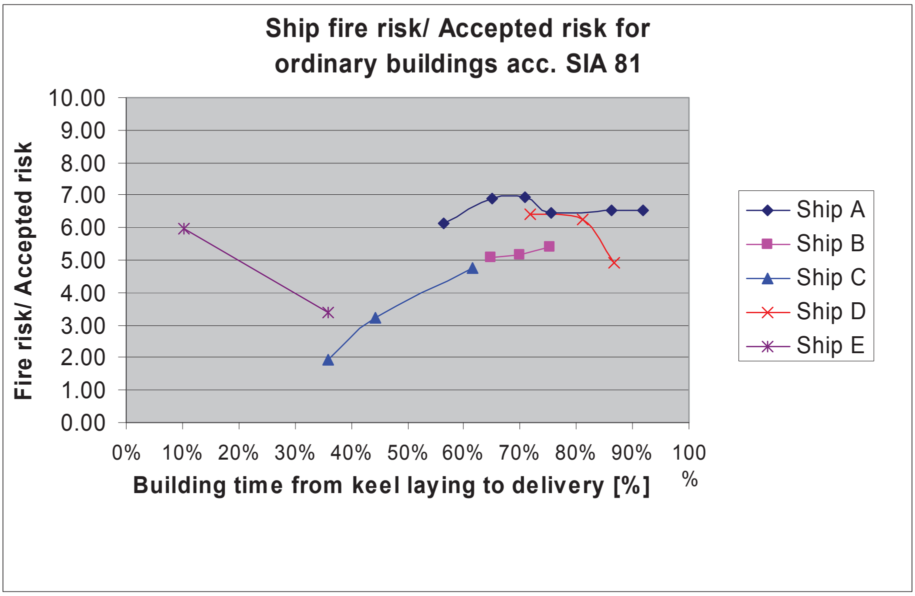

Figure 3.14 Some fire risk index results from BSS surveys on three shipyards (Räisänen 2001b, unpublished)

3.3.7.4 Shipyard benchmarking by the owner's consultants

The experienced owner's consultants were asked to prepare a benchmarking study of the important safety issues of the three shipyards that were building ships for RCCL at the time. The three shipbuilding companies were given a ranking order for some safety issues. This proved to be an effective inducer of discussion when the researcher was starting the first action cycles. The grading was linear: from zero to five, five being the best score (Servanto 2002), as requested by the researcher. In the resulting lively discussions, several suggestions to remedy the weak points of the yard emerged. The success of this benchmarking of the yards was encouraging for the consequent joint development actions at the yards.

Baltic Ship Safe LTD's evaluation of the shipyard fire safety management

	Yard 1	Yard 2	Yard 3
Preventing ignition			
Condition of gas hoses and gas equipment	4	2	3
Condition of tools	4	4	4
Fire load	2	5	3
Fire patrolling	3	2	4
Hot work culture of the work force	3	1	2
Location of protective material	4	3	1
Orderliness	2	4	4
Tidiness	2	4	3
Type and condition of temporary lights	1	3	5
Usage of protective material	3	3	2
Managing fire			
Closability of fire doors	4	3	1
Closability of watertight doors	3	3	1
Extinguishing equipment on the quay	2	3	3
Fire alarm buttons/other alarm systems	2	4	1
Fire compartmentalization	3	2	4
Fire detection system	1	2	5
Fire doors kept closed	4	2	1
No. and location of extinguishers	4	2	3
No. and location of hoses and nozzles	3	1	1
Readiness and co-operation of local fire authorities	3	1	5
Managing exposed			
Emergency lighting	4	1	4
Fire alarms/ sirens, other alarm systems	4	2	1
Lighting	4	3	4
Location and accesssability of escapes	4	3	2
Number of escapes	4	3	3
Safety training of work force	4	1	4
Usage of personal protective gear	2	1	4

Scale 0 to 5, Best=5

Figure 3.15 Evaluation of shipyard performance, based on subjective observations during RCCL ship fire safety surveys by an experienced surveyor of Baltic Ship Safe OY Ltd. (Servanto 2002, unpublished), re-arranged by the researcher

3.3.7.5 Usage statistics of fire-protective cloth at one shipyard

When carrying out hot work in the vicinity of flammable or heat-sensitive materials, the workers are requested to use fire-protective cloth, which is readily available. The record of the amount of cloth used on approximately similar-sized vessels has been obtained from one yard, and used as a quantitative indicator for personnel attitudes towards fire risk management, which added to general knowledge of the matter (see Figure 4.16).

3.3.7.6 Event tree

During the action cycles of this study, the possibilities for early deployment of a ship's own and temporary extinguishing systems were discussed with the participants several times, as it is well-known from public buildings and industrial facilities that an operational sprinkler system is a very effective way of managing the consequences of fires as discussed earlier (e.g. page 32). The ship's systems were typically available for fire protection during the few last weeks of production, if the customary installation procedures were used. Increasing the time span of the protection by ships' own systems during production met some resistance from the production organisations of the yards. Installation and testing of systems that cross borders of building areas on-board were especially seen as problematic, as the areas often have differing degrees of readiness. Also, the use of these systems on-board has its problems. Accidental release and damage to piping and heads (freezing, knocks and misconduct, see page 32) have been mentioned.

To obtain a quantitative view of the capabilities of operational automatic extinguishing on-board, an event tree for an escalated fire was built (Appendix J). The probabilities of various branches were approximated, based on educated guesses, fire incident statistics or literature, and were subjected to participant scrutiny. This produced comparative numbers for the safety managers for their co-operation with the production management, and increased confidence in making the conclusions about the effects of sprinklers, discussed in sub-chapter 5.2.1.

3.3.7.7 Waste volume and calorific value

In the surveys discussed in sub-chapter 3.3.5, volumes of moveable fire loads of waste and flammable liquids on-board were recorded. During first actions with the shipyards, volumes were converted to fire load in megajoules (MJ) by assuming a density of waste, and relative amounts of plastic, wood products and non-flammable waste. Later, this figure was adjusted when yearly volumes and weights of waste types became available from the waste transport records of the yard (Logistics Manager, yard AAA, 2002). In the yard surveys, the fire load data was presented as a floating sum of five consecutive surveys, as one survey covered approximately one-fifth of a ship (see e.g. Figure 4.17).

3.4 Documentation of action cycles

During the twelve action cycles presented in Table 3.1, research progress was continuously documented. The records consist mainly of documents on development targets, Best Practices documents, minutes of the development meetings, the researcher's notes and the two conference articles published by the researcher and the safety managers (Räisänen et al. 2003a), (Räisänen et al. 2003c). For each action, the theoretical and practical status and key results were documented both at the start and end of the cycle, similarly to Eden and Huxham (1997, see Figure 3.1), who refer to "theory explication" and "methodical reflection". The same terms are used in Table 3.5, where the key records of the action progress are presented with its main topics. The column of 'Main topics of actions' is especially interesting, because it illustrates the changes of focus during the research. In the beginning, the research was concentrated in factors that influence fire risk, metrics and statistics. Later, the direct improvement possibilities of work, and systemic relationships of fire risk are more prominent as the work progresses. In addition to listing the key documentation of the action cycles, the case histories of the actions were also recorded. They are described in Appendix F.

During the research, many unpublished, confidential sources have been used. For completeness of the Action Research documentation, they have been included at the end of the study, in References and in List of unpublished references; and denoted with text "unpublished".

Table 3.5 Topics of action cycles and their documentation during the research (continues on the next pages). The action cycle numbers correspond to Table 3.1.

Action cycle no.	Documentation of theory explication before the action	Documentation of methodical reflection after the action	Main topics of actions
1	Fire safety index points (Räisänen 2000)	Fire safety survey principles (Räisänen 2001a), Fire Safety survey graphs (Räisänen 2001b),	First suggestions of contributing factors on fire safety management. Preliminary lists of contributing factors. Metrics on surveys for open fire doors, fire load, hot work practices, proper location of extinguishers. Calculation of SIA 81 fire risk index in shipbuilding context.
2	Safety manager meeting Nov. 2001 slides (Räisänen 2001e). Safety manager meeting Nov. 2001 risk index slides (Räisänen 2001f).	First version of Good practices of passenger vessel shipyard fire risk management (Räisänen 2001c).	Hot work transfer to workshops. Alternatives to hot work. Ignition of incompatible chemicals. Ignition of electrical and gas heaters. Hot pipes during machinery trials. Protection of materials from sparks. Hot work procedures. Trash chutes. Unpacking practices.Temporary fire protection. Temporary sprinklers. Extinguishing capacity. Alarm system. Escape routes. Fire door practices.
3	Analysis of a shipyard fire incident data Jan 2000 - March 2001 (Räisänen 2001g).	Minutes of the meeting (Räisänen 2002c).	Daily and weekly distribution of fire incidents. Fire guard surveys. Flammable waste reduction measures. Negotiations with suppliers for non-flammable packing. Maintenance of gas distribution systems. Practice of training foreign workers. Support of yard management. Training. Hot work culture. Closability of fire and watertight doors.
4	Safety manager meeting Nov. 2001 slides (Räisänen 2001e). Safety manager meeting Nov. 2001 risk index slides (Räisänen 2001f). Revised oral presentation.	Meeting notes (Räisänen 2002d).	Hot work prohibited during holiday times. The safety personnel of yard to give the safety courses. Regular smoke diving exercises for voluntary firefighters of the production departments

Table 3.5 Topics of action cycles and their documentation during the research (continues on the next page). The action cycle numbers correspond to Table 3.1.

Action cycle no.	Documentation of theory explication before the action	Documentation of methodical reflection after the action	Main topics of actions
5	Agenda for the safety managers meeting April 2002 (Räisänen 2002q).	Memo of Fire Safety Meeting at yard CCC (Räisänen 2002e).	Trash management as a logistical question. Temporary fire detection systems. Fire mains capacity. Counting personnel on board after evacuation. Measuring safety attitudes.
6	Shipyard fire safety co-operation (Räisänen 2002f).	Memo of Fire Safety Meeting at yard BBB (Räisänen 2002g).	Subcontractor behavior. Intervention in safety violations. Evacuation testing. Electricity off (blackout) testing. Radio communication on board.
7	Safety Manager meeting slides September 17, 2002 (2002i). Graph of stakeholders perception of fire risk	Memo of Fire Safety Meeting at yard AAA (Räisänen 2002h). Good practices of passenger vessel shipyard fire risk management v.12 (Räisänen, P., Longeroche, J. L., Moisio, P., Wähler, M. 2002). Comparison slide of hot work procedures.	Hot work practices. Differences in area types regarding trash fire load. Subcontractors' role in fire incidents. European standard fire incident reporting and statistics.
8	Slide show for shipyard fire department (Räisänen 2002o).	N/A	Attitudes towards RCCL surveys. Motivation of shipyard survey personnel

Table 3.5 Topics of action cycles and their documentation during the research (continued from the previous pages). The action cycle numbers correspond to Table 3.1.

Action cycle no.	Documentation of theory explication before the action	Documentation of methodical reflection after the action	Main topics of actions
9	Fire safety presentation for the yard line management (Räisänen 2003a).	Memo of four Supervisors Fire Safety Meetings (Räisänen 2003c).	Waste logistics. Unpacking of installation material. Negotiations with further suppliers for non-flammable packing.
10	Safety Manager meeting slides 14. 4. 2003 (Räisänen 2003f). Shipyard safety report all yards v.18 April 2003 2002 data, 100 weeks (Räisänen 2003e).	Publications in Fire in Ships- and Cruise+Ferry-conferences: (Räisänen, P. et al. 2003a) and (Räisänen, P. et al,. 2003c). Good practices of newbuilding fire safety management for RCCL (Räisänen 2003g) and for the Fire Safety Interest Group (Räisänen, P. et al. 2003d).	Prohibiting unnnecessary automatic electric devices on board. Possible problems with non-welded structures. Unauthorized hot work causes most fires. Dangers of temporary storage on board. Closing of temporary openings. Handling of safety violations. Normalized incident reporting.
11	Risk management yard-RCCL brainstorming issues Nov 28 2002 (Räisänen 2002p).	Shipyard process risk management meeting of one yard and RCCL (Räisänen 2002a).	Probability - impact grid for fires in shipbuilding. (Figures I1 and I2)
12	Presentation and memorandum on probability of a large fire onboard cruise vessels under construction and the use of sprinkler systems. (Räisänen 2003i)	Appendix A, Appendix J	Importance of early deployment of sprinklers in avoiding large fires

3.5 Summary

As the researcher was working for a ship-owner with three shipbuilding companies, and was in a position to initiate changes in their fire risk management, the action research method was found suitable for studying fire risk and responses. The work resulted in forming a co-operative Safety Interest Group of the European shipyards, (S.I.G.), which works to improve fire safety at the participating yards. The research work was mostly carried out between 1999 and 2003. After literature reviews in project risk management, general fire risk management and shipbuilding, 12 interaction cycles with the shipyards were carried out between 1999 and 2003. The action cycles consisted of the improvements made by the participants at their respective shipyards, steering actions carried out by the researcher, and explication of theoretical and practical contributions. The action interventions were carried out with shipyard middle management, mostly in safety and project management disciplines.

There were nine main sets of research materials and seven sets of supplementary data from miscellaneous sources. The main sets of materials were obtained with six research methods within the action research: Interaction with key participants; writing of best practices; archival analysis; fire incident statistics review; fire safety surveys; and managers' questionnaire (Figure 3.3). The extent of the coverage varies by method. Qualitative information was obtained from participant estimates, best practices and safety observations at the shipyards, and quantitative information from fire incident statistics, fire safety survey data on-board and a questionnaire survey of expert managers. A unique statistic of 221 fire incidents, two of which had escalated into major fires, was particularly important in forming the conclusions of the research. Such extensive data set was not available before this study, and the initial fire incident statistics developed into the statistics reporting system that is currently (2014) in use at the participating shipyards.

In addition to information related to fire incidents, quantitative information was obtained from the patrolling of ships by the owner's surveyors as well as by one shipyard's own fire guards. Data from 17 on-board fire safety surveys of 3-5 days in duration, and of 101 surveys of overnight duration were used in the research. Furthermore, small studies were made on changes in fire risk during construction, top management estimates, testing of fire risk index, shipyard benchmarking, use of fire protection, sprinkler effectiveness, and waste volume and calorific value.

The flexibility of the action research method required rigorous documentation, which was recorded methodically for each action cycle, and the key issues were also publicised in two conference articles published by the researcher and the safety managers of the participating shipbuilding companies. The co-operative action research with the shipyards produced plenty of qualitative and quantitative research material. The use of several different methods for gathering data widened the scope and reliability of the information. The abundance of qualitative information and the exceptional extent of the fire incident statistics placed great hopes in their interpretation, which is discussed in the following two chapters on empirical findings.

4 Findings on fire risk, its assessment and size

As discussed in Chapter 2, general fire risk literature and shipbuilding literature gave some views of factors that contribute to fire risk, and of available responses for cruise vessel construction. More information became available in the empirical research, which presented an opportunity for a holistic view of the fire risk in cruise vessel shipbuilding. The participating shipyards had a heavy workload at the time, and had fires every few weeks. This made the problem tangible for the stakeholders. As all large fires in shipbuilding affected the insurance payments of the whole industry, there was a sense of common urgency, especially after some notable fires that caused extensive damage. The views on fire risk, yard problems and their developments were gained especially via participant estimates and ignition statistics but also in daily interaction with the shipyards.

Examples of fire incident records from the shipyards are shown in the listing of a page from a typical shipyard database, Figure 4.1, in which hot work and fuels characterise the usual cases. The excerpt shows the extent of information that was typically obtained from the yards: date, time, ship's project number at the yard (Newbuilding-536), location on-board and incident histories.

Time	Location	Incident
11.11.2001 at 18.00	NB-536 Area 120 Spa	Rockwool plastic packaging ignited by flame cutting. Extinguished by dry chemical
18.11.2001 at 10.15	NB-536 Balcony of cabin 5566	In welding a sewer pipe, its rubber seal ignited. Extinguished by suffocation
21.11.2001 at 12.15	NB-536 Area 44 (Pantry)	Can of paint ignited by a welding spark. Extinguished by dry chemical, reason for spark insufficient earthing
9.12.2001 at 18.00	NB-536 818 Quay P-side	Garbage bin was ignited from welding some decks above. extinguished by two 12 kg extinguishers, two 10 kg water extinguihers and water from fire truck
10.12.2001 at 14.40	NB-536 Alue 22 (Laundry)	Papers in a tool container ignited by a grinding spark. Extinguihed by dry chemical
15.12.2001 at 13.35	NB-536 Area 445 (schooner bar)	Floor panel sealing compound was ignited by a welding spark. Extinguished with dry chemical.
16.12.2001 at 16.24	NB-536 Area 57 Boat deck P-side	Protective plastic coverings were ignited from welding deck above. Autoextinguishing
25.12.2001 at 9.20	NB-536 Area 412 Deck 4	Can of paint hardener ignited by a welding spark. Extinguished by dry chemical
28.12.2001 at 8.20	NB-536 Area 711 Deck 7	A leak in a gas centre was ignited by welding or grinding. Extinguished by blowing into fire

Figure 4.1 Typical fire incidents at the shipyards (Räisänen et al. 2003a)

To gain deeper understanding of fire risk, fire incident statistics, incident histories, interviews with key personnel and questionnaire surveys were used. However, the most important source of information on fire risk was the comprehensive fire incident statistics named Main Statistics (described in sub-chapter 3.3.4, see also Table 3.4), where 221 fire incidents on-board were recorded by their causes, fuels and case histories. Access to this data provided a unique possibility for explication of the properties and frequency of fires, allowing for the first time estimation of fire risk for cruise vessels under construction. This required the assumption that the frequency of observed fires in the past was an indicator of the size of fire risk in future. The assumption was deemed good for practical purposes although it was not studied in the strict sense of probabilistic risk analysis, due to limitations of input data and resources. To ensure consistency of the conclusions, the qualitative and quantitative materials were regularly used for triangulation during the research actions. As the material was very extensive, only a part of it is discussed in the following sub-chapters. For completeness, materials and contributions of the methods are summarized as action cycle histories (Appendix F), and in matrix format (Appendix K).

In this chapter, the findings on characteristics of fire risk, its assessment and size (research questions 1, 2 and 3 on page 9) are described in sub-chapters 4.1, 4.2 and 4.3, respectively, and summarised in sub-chapter 4.4.

4.1 Fire risk in cruise vessel projects

In the interactions with the yards, it was found that they treated fire as a controllable threat to people, materials and projects. The shipyards' risk management was focused not only on *preventing ignition* by controlling fuel and heat sources, but also on mitigating the *consequences of established fires*, which also corresponds to the views found in literature. Therefore, the first research question: *1) What is fire risk in cruise vessel construction projects?* was addressed in these two parts. To address the question, we need to describe how often and when the fires break out, why the ignitions occur, and what kind of consequences the established fires have. These were studied mainly from the statistics of 221 fires and some qualitative data.

The findings are described in the following sub-chapters. To focus the analysis, the ignitions and consequences were categorized (discussed in sub-chapter 4.1.1). For an overall view of fire risk relative to project progress, temporal distributions of fires were calculated (sub-chapter 4.1.2). Further, it was found that heat sources and fuels were important factors of fire risk (sub-chapters 4.1.3 and 4.1.4). To complete the view of the main features of fire risk, the consequences were studied (sub-chapter 4.1.5).

4.1.1 Categories of factors that contribute to ignitions and consequences

During the action cycles, it was found that categorization was needed for describing the fire risk with ignitions and consequences, respectively.

Of the factors that contribute to ignitions at the shipyards plentiful information was derived, both qualitative and quantitative. Information from general fire safety and shipbuilding literature (summarized on p. 42 and in Table 2.1) and empirical data suggested 14 categories of factors, which were used to sorting the ignition data. The categories were based on the basic physical factors of ignitions: the fuel and the heat sources. In Table 4.1, the categories, and the percentages of contributing factors to ignition are shown. It is noticeable that the fuel in fires was generally known (98% of the incidents) either by witness reporting or inquiries on-scene. The most common heat source category was hot work (80% of fires). Electric systems were found to be associated with 12% of the 221 fires at the yards. Auto-ignition, heating and ventilation, and the smoking of tobacco were rare in the statistics, but were all found to be significant, as qualitative evidence revealed that delayed or unobserved ignition can increase the chance of fire escalation before alarm. Rapidly expanding fires can also result from explosions of dust, gas and vapors. Fires in other categories were even rarer. Based on general fire safety literature and qualitative data of this research, none of the categories could be ignored. All categories were well represented in the qualitative material such as joint documents on best practices (sub-chapter 3.3.2) and the internal safety material of the shipyards (sub-chapter 3.3.3).

Table 4.1 The final 14 categories of contributing factors to ignition and distribution of the 221 fire incidents at the shipyards in them. Note that the sum of percentages is over 100% as several factors can contribute to a fire.

Factors which contribute to ignition	Percentage of fire incidents in the statistics of 221 fires	Remarks
1) Arson	0 %	Suspected but not proven, categorized as Miscellaneous
2) Autoignition	1 %	
3) Electric phenomena	0 %	
4) Electric systems	12 %	
5) Explosions, dust, gas, and vapors	0 %	One fire
6) Fire load	98 %	In 2 % of fires no reporting of fuels, or fuel not visble
7) Heating and ventilation	1 %	
8) Hot surfaces and open flames	0 %	
9) Hot work (welding, cutting, grinding, torching)	80 %	
10) Machinery	0 %	One fire
11) Painting	0 %	
12) Sea trials	0 %	
13) Smoking of tobacco	1 %	
14) Miscellaneous	8 %	Unknown fire ignition causes

The contributing factors were studied in depth, and the extent of inquiries was based not only on their importance in ignitions but also on their potential consequences. It was found that the risk management efforts at the yards were also based on similar logic. The incident statistics thus played an important part in determining which factors to study closer, but also in the practical improvement actions of the yards.

The other side of fire risk, the consequences, were categorized more simply. The actual damage was found to be small in many of the incidents, as most of the fires were extinguished rapidly by the persons nearby. However, the shipyards were found to be preparing for the worst case scenarios, as the consequences could have been severe in several cases had the extinguishing not been successful. Therefore, the categorising of the empirical information was based on potential consequences more than actual recorded data, as much of the information is broad and circumstantial, and can belong in several categories. Based on literature (summarized on p. 42 and in Table 2.2), qualitative data of the shipyards, and case histories of the 221 incidents, three categories were found useful for the empirical data:

1. Human damage in fire
2. Direct material damage in fire
3. Secondary damage

During the action cycles of the research, the above categories were used continuously in the sorting of the qualitative data, such as methods of limiting the escalation of fires, evacuation as well as protection of people and property. It was observed that the yard managers invariably focused first on avoidance of human losses.

4.1.2 Occurrence of fires at the shipyards as a function of time

One way of characterising the fire risk is the time of occurrence of fires relative to project progress. At the outset of the research, it was known that fires can occur on-board during most of the production time but not much was known about their distribution relative to project milestones. To remedy this, the incident data was summarised and put in generic format (subchapter 3.3.4, p. 68 and 70). A result is plotted as Figure 4.2, where the average number of fires in 22 ship projects is presented. The graph is normalised so that it represents the observed number of fires per 100,000 GT in production in the European shipyards, arranged in five- week (5% of normalised building time) intervals. The normalisation per 100,000 GT was chosen as it represents a typical vessel at the time of actions. Thus the graph can also be interpreted as number of fires per one 'standard ship' in production at a shipyard. As stated earlier (p. 89), it was assumed that the frequencies of observed fires in the past were indicative of the size of fire risk. The graphs are labelled accordingly. From the graph of Figure 4.2, it can be seen that there were no fire incidents on the ships during the first 20% of building time, close to keel laying, indicating a low fire risk. A probable explanation is that steel fabrication dominates at the start of the building process, and bare building blocks have little flammable material. After this period, there would be between one and two fire incidents per five weeks of per 100,000 GT in production, approximately 20 fires during a ship project. This is a high number, considering that a bad fire may destroy the whole ship. Further, it can be implied that significant fire risk is present throughout production time after flammable materials start arriving on-board. The qualitative material, such as the shipyards' internal safety material showed similar trends. The variation in the number of fires between yards was relatively large (Appendix F), which was used a benchmark with the yards to induce their actions.

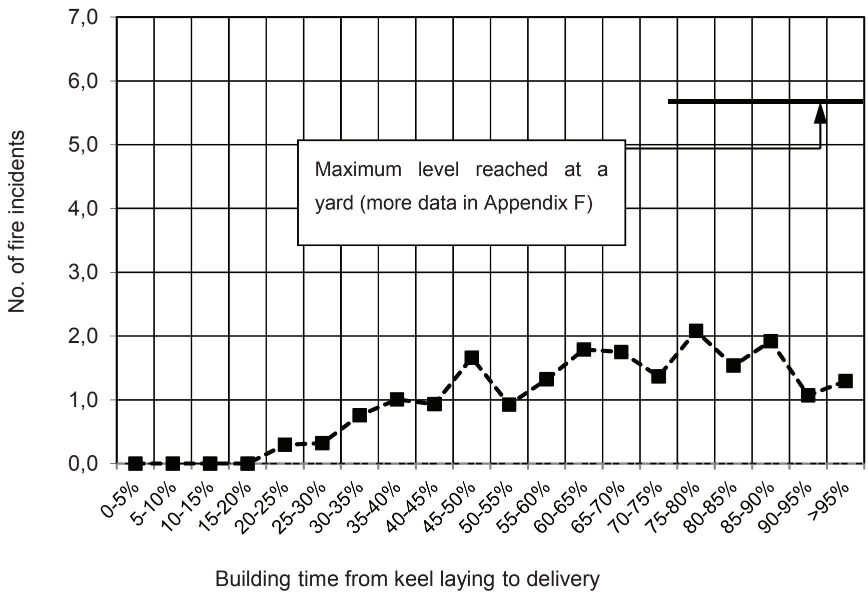

Figure 4.2 Distribution of fire risk during ship projects, as implied by the number of fire incidents at the European cruise vessel yards 2002, total of 221 fire incidents in the Main Statistics. Data is not from complete delivery cycles. Averaged in 5% production time intervals for a standard vessel representing 100,000 GT in production (Räisänen 2003e, unpublished). Data for the seven shipyards is included in Appendix F.

To meet the confidentiality requirements of the yards, the presented data in Appendix F has been made unidentifiable and the yard letters A to F are redistributed.

An important question in risk estimation is how fires on-board grow, but less quantitative evidence was available than for ignitions. The fires that grew beyond local extinguishing were called ‘established fires’ and, further, a definition of ‘large’ fire was used with the yards: a material loss of one million euros or more. There were two such large fires in the 221 incidents, and one large fire among one yard’s 227 incidents (see sub-chapter 3.3.4 for origins of data). From these, it could be estimated that one large established fire occurred per 100 – 200 fire incidents.

Based on the incident data as a whole, no conclusive evidence was found of periods where the frequency of fires would be particularly low. An exception may be the time close to the sea trials, where the ship leaves the yard to test its functionality at sea. This trend is not visible in Figure 4.2 as the position of sea trials in the building schedule varies between the yards (but may be seen in the frequencies of single yards, e.g. in Figure F6 and Figure F10 of Appendix F at 90-95% of building time). The reasons may be presumed to be a reduced amount of fire load when the ship is cleaned for the sea trial. In addition, the times of vacations implied a low frequency of fires at some yards. Upon closer inspection, these yards were found to limit or close off on-board work during vacation periods, which naturally reduced the number of fires.

The statistics were processed for the daily and weekly distribution of fires, which is interesting for analysing the effects of work habits (Räisänen 2001g, unpublished). For illustration, two graphs are given in Figure 4.3 and in Figure 4.4, which represent daily and weekly fire incidents at a shipyard, based on a subset of 29 and 28 fires, respectively, in the Preliminary Statistics (see Table 3.4). The subset is of two sister ships, which were built with same routines, such as lunch hours and cleaning practices. The data provided insight to work process and fire safety. From the daily distribution of incidents, it was observed that there were peak times for increased fire frequency, indicating higher than average risk of fire. This was interpreted in the interactions with the yards to be due to the practice of non-overlapping work shifts. It allowed smouldering fires, which were lit during work time, to go unnoticed during lunch breaks or after the evening shift (see figure below at 10.00, 12.00, 14.00, 16.00, 18.00 and 22.00). Later, this practice was changed so that working times overlap, or that watchkeeping time was extended at the critical locations and the distributions became more even.

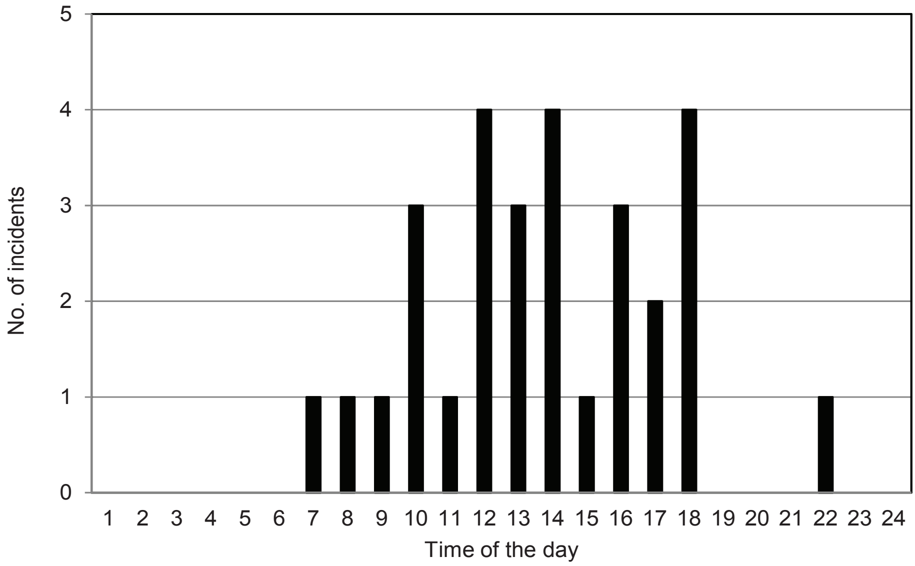

Figure 4.3 Distribution of fire risk based on time of day, as implied by the fire incidents on two sister ships, 29 fire incidents Jan 2000-March 2001, a subset of Preliminary Statistics. Data is not from complete delivery cycles. (Räisänen 2001g, unpublished)

Similarly, the distribution of incidents for the days of the week was studied, and it was found that occurrences are specific to the yard, and related to work arrangements. In the example graph below, the number of fire incidents at a yard is noticeably lower on Fridays. A possible explanation could lie in the practices that lead to accumulating fire load during the week, and extra cleaning on Friday, before routine inspection rounds by the management of the yard in question.

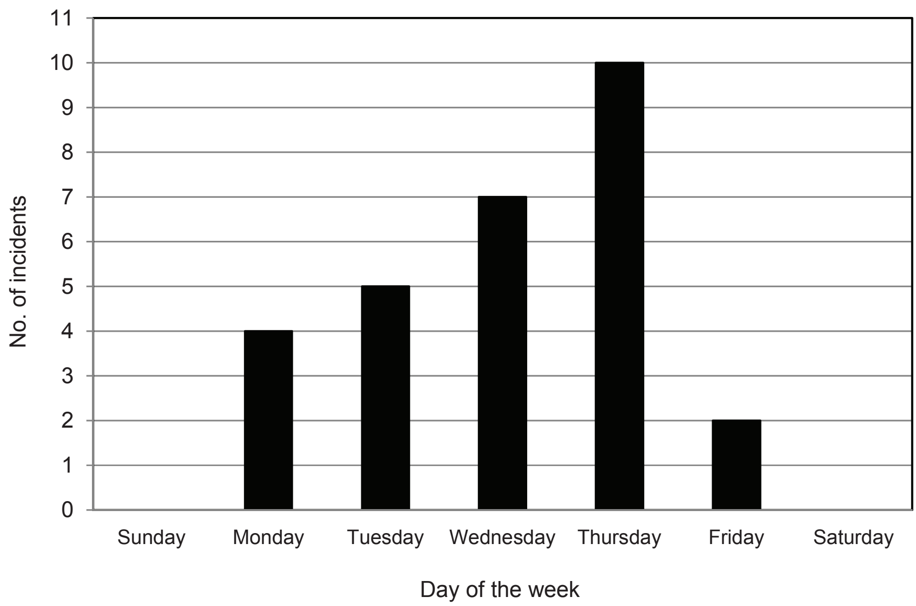

Figure 4.4 Distribution of fire risk on weekdays, as implied by fire incidents on two sister ships, 28 fire incidents Jan 2000-March 2001, a subset of Preliminary Statistics. Data is not from complete delivery cycles. (Räisänen 2001g, unpublished)

Analyses of the temporal characteristics of fires on-board were useful in tracking the factors that contribute to risk. The next step was to analyse the possible causes, which is discussed in the following sub-chapters.

4.1.3 Heat sources in ignitions

The recorded frequencies confirm the fire risk view from literature that hot work (grinding, welding or flame cutting) is a common heat source for ignitions. However, the dominance of hot work in shipbuilding fire risk was unexpectedly strong. As stated earlier, in about 80% of the incidents, the fires were ignited by hot work at the yards (Table 4.1), of which about 36% was flame cutting, 41% welding and 3% grinding, see Figure 4.5. Electrical reasons were involved in about 12% of the cases. In about 8–9% of incidents, the ignition cause remained undetermined, i.e. in most of the incidents in the category 'other'.

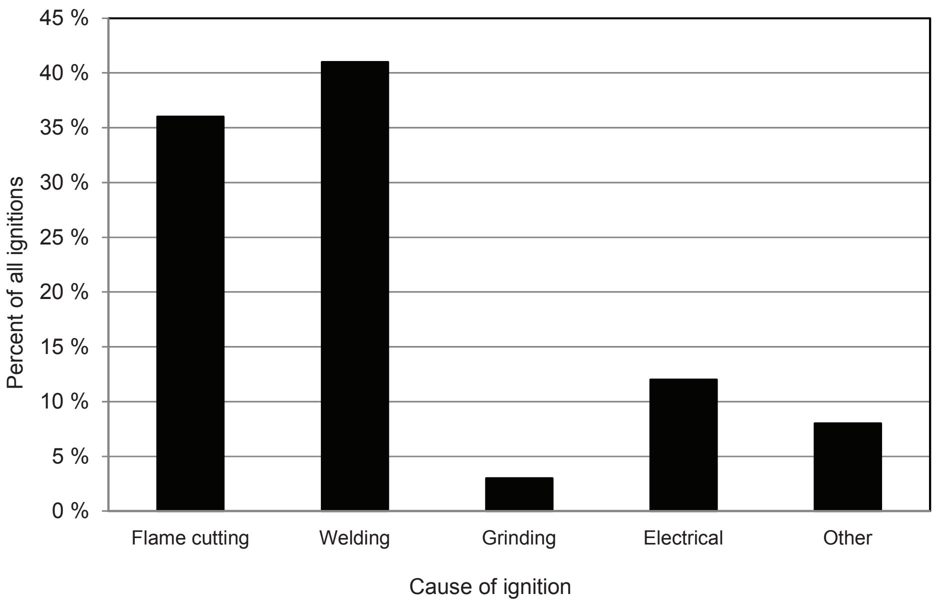

Figure 4.5 Causes of fire ignition at European yards according to their statistics 2002-2003, total of 221 fire incidents.

The differences between shipyards were moderate, if the total percentage of incidents due to hot work was compared (range 70% - 91%) (Figure 4.6).

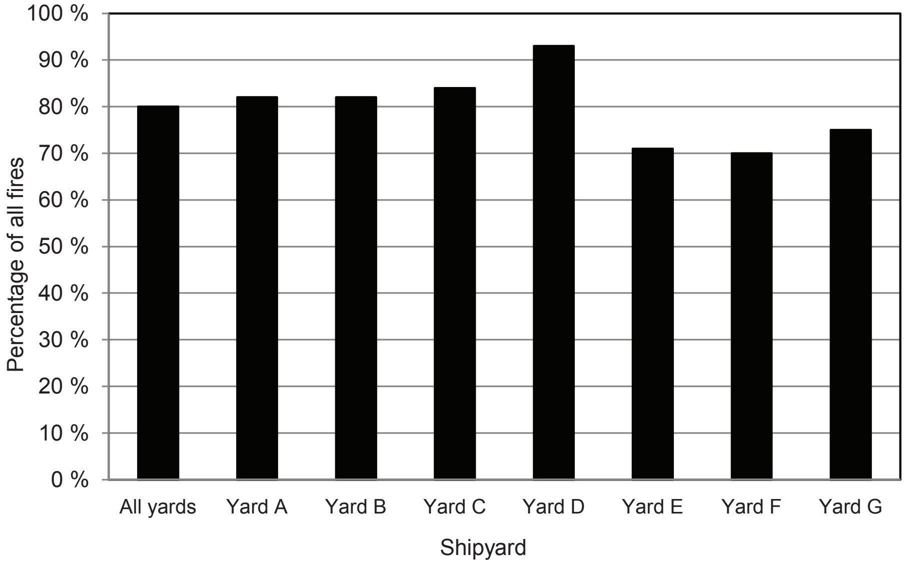

Figure 4.6 Percentages of fire incidents due to hot work of all fires, total of 221 fire incidents (Räisänen 2003e, unpublished)

On the other hand, the differences between yards were remarkably large when hot work was investigated more closely. For example, the numbers of incidents due to flame cutting were found to vary between yards from 7% to 67% of all incidents. Some explanation for the differences may be the use of alternative cutting methods and non-standard incident recording practices.

Based on the above, it can be concluded that fire risk is certainly linked to the amount of hot work on-board, and to the quality of its execution. Also in all qualitative materials, the role of hot work in fire risk at the yards was clear.

The next largest category of heat sources in ignitions was electrical. Unattended electrical machinery such as heaters and blowers were found to be especially dangerous as fires may escalate unnoticed. Again, the differences between shipyards were rather large; the variation was from 0 to 25% (Figure 4.7). From the qualitative data of the interactions it was noted that there were differences in maintenance scheduling and the age of the equipment of the yards, subcontractors and shipyard departments, but the causes of differences remain unexplored for further studies. However, it became apparent that risk is related to the maintenance and positioning of electrical equipment in fire-safe locations.

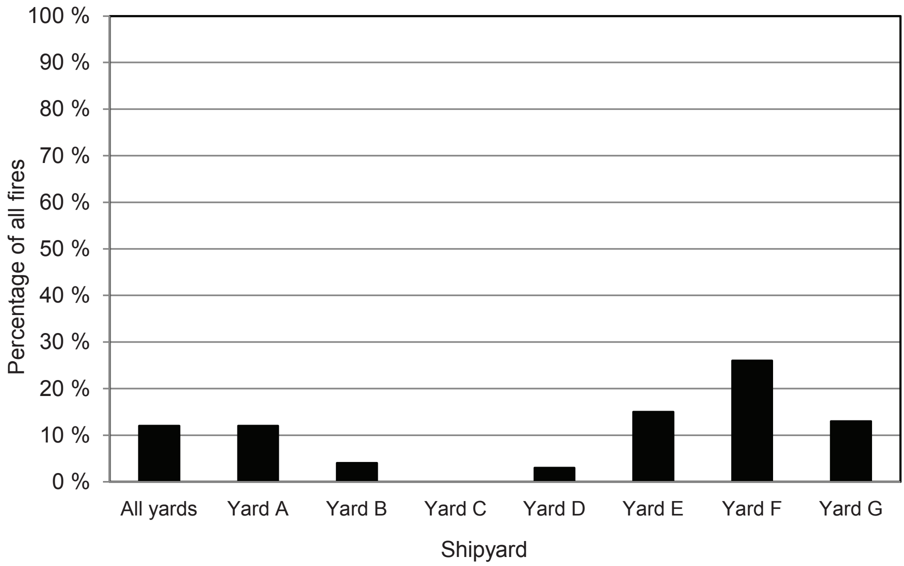

Figure 4.7 Observed fire incidents due to electrical reasons, total of 221 fire incidents (Räisänen 2003e, unpublished)

Other heat sources found in the incident records and qualitative data during the actions were chemical reactions, electric systems, heating and ventilation, hot surfaces during machinery trials, lighting systems and mechanical systems. All these have the potential to generate uncontrollable heat, which is related to fire risk, but is not quantifiable with the current statistics. However, the shipyards clearly acknowledged their contribution to fire risk.

4.1.4 Fuels in fires

Typical fuels in shipyard fire ignitions were found to be combustible liquids, gases and waste that are on-board temporarily. Although their fire load was relatively small compared with the installed structures of the vessels, which conformed to the SOLAS fire safety regulations (see Appendix B, page B2), their flammability was high compared to the installed materials. Some examples: easily flammable packing material, such as plastic bubble wrapping, cardboard and plastic chips were used by the shipyard suppliers. Contact glue brands that can be ignited by a spark were in use. Highly flammable acetylene and fire-enhancing oxygen are needed on-board for flame cutting of steel. On average, combustible liquids, gases and waste amounted to about 65% of the incidents; see Figure 4.8. In addition to the fact that waste is highly flammable, it can be speculated that workers are more cautious when executing hot work near finished structures, which can affect the frequency of the ignitions of installed materials.

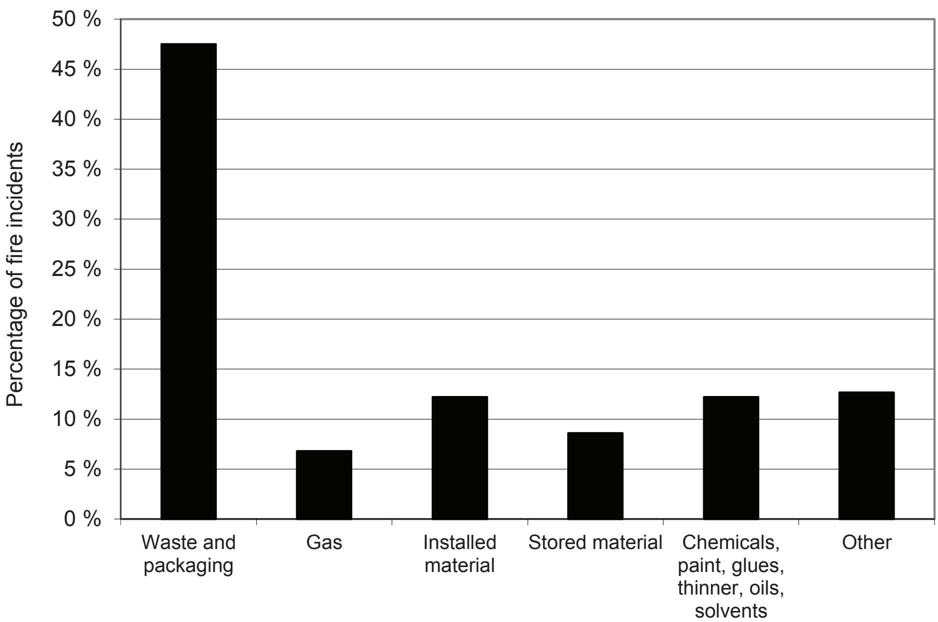

Figure 4.8 Fuels of fire incidents at European yards according to their statistics 2002-2003, total of 221 fire incidents (Räisänen et al. 2003c)

Based on observations and frequencies of fires at the shipyards, waste on-board contributed to many fires, and the fire risk was clearly related to cleanliness. The differences between yards were rather large, from 30% to 79% of the incidents (Figure 4.9). In the joint best practices, which the researcher was writing with the shipyards, control of fuel, and especially wastes, flammable liquids and gases, played a prominent role, similarly in on-board surveys.

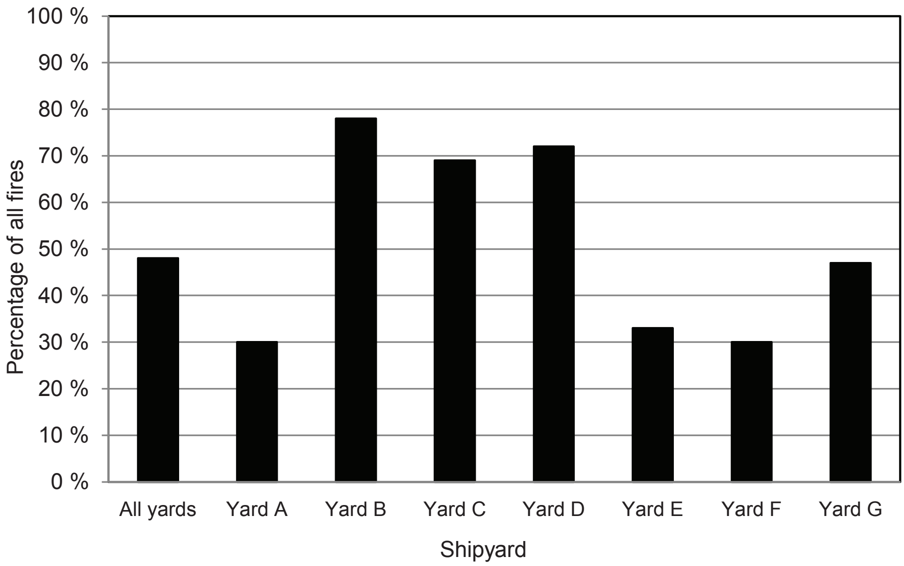

Figure 4.9 Percentage of waste-related incidents of all incidents, total of 221 fire incidents (Räisänen 2003e, unpublished)

The differences between yards were clearly visible in the statistics, but also during shipyard visits. The best yards, A and F, had a logistic system of stripping packaging and removing waste. For the worst yard, B, there were challenges in waste logistics as well as the overall arrangement of work process. Yard B had more than twice the amount of waste-related fires compared to the best ones. Similarly, cleanliness and the quality of hot work of the yards can be illustrated as the observed average time between waste-related fires that were also derived from incident statistics (Figure 4.10). During the period of observation, the differences between the yards were found to be large and, for some of the yards, a good potential for fire risk management development was seen.

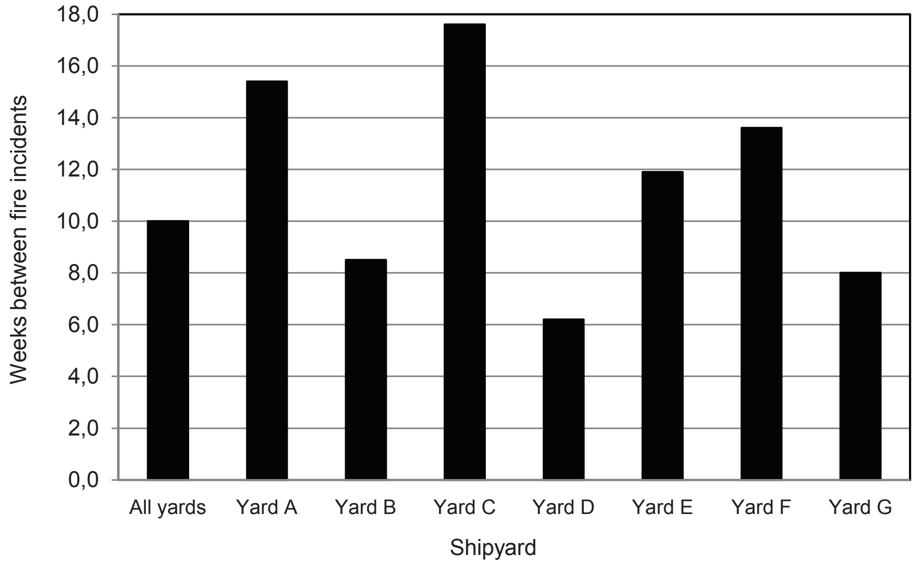

Figure 4.10 Differences between yards, presented as the average times between waste-related fire incidents, total of 221 fire incidents (Räisänen et al. 2003c)

Some of the yards had room for improvement in protecting installation material, i.e. the material awaiting installation or that is already at its final location. Again, fire incidents provided insight into the risk. The variation between the yards was found to be large, from 0 to 55% (Figure 4.11).

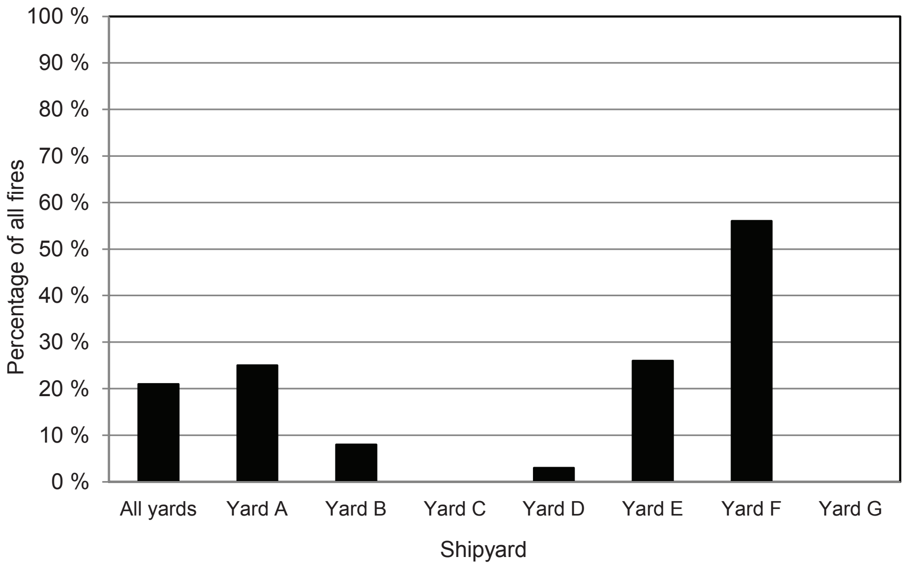

Figure 4.11 Installation material-related fire incidents, total of 221 fire incidents (Räisänen 2003e, unpublished)

Although the observed number of gas-related fires was relatively small, 0 to 15% of all incidents at the yards (Figure 4.12), the potential for explosive ignition and major fire escalation increases the fire risk. Many participants emphasised the danger of gas leaks, and their prevention through proper maintenance, and installation of gas distribution systems was seen as important. Again, the reported fire incidents show differences between yards. This reflects the state of the usage, equipment, maintenance and permanent distribution network set-up, which were later brought up in the qualitative material, particularly interviews and other participant estimates. There were also differences in the closing of valves during breaks and in flow monitoring.

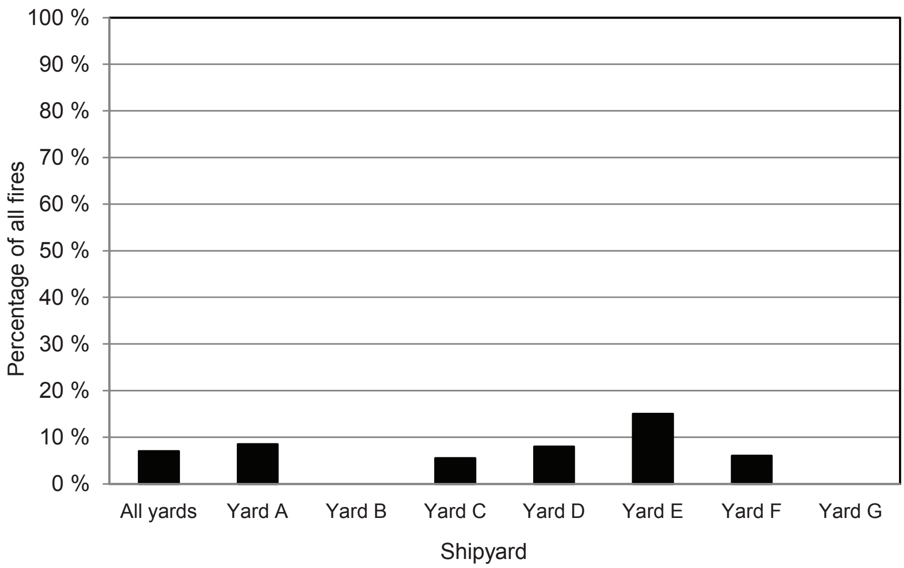

Figure 4.12 Percentage of gas-related fire incidents, total of 221 fire incidents (Räisänen 2003e, unpublished)

The share of other chemical fuels such as paint, glues, thinner, oils, and solvents, of all fire incidents was around 12% (Figure 4.8). In many of the cases, the ignition was caused by a combination of human error in hot work and flammable liquid. Many chemical substances observed on-board had a high calorific value and were easily flammable, increasing the possibility of fire escalation.

Finally, it can be noted that arson and tobacco smoking are typical causes of fire ignition in urban areas and some industries, but were found to be rare at the participating shipyards, which may be attributed to good personnel behaviour and successful safety management.

4.1.5 Consequences of established fires

In addition to factors that relate to ignition of fire, the consequences of fires are important in describing the fire risk. At the yards, the potential consequences were studied mostly qualitatively due to the fact that established fires (i.e. fires that needed more than local suppression with portable extinguishers) were relatively rare. It was found that the possibility of fire growth at the shipyards was dependent on fire load, on heat transfer paths and on the protective measures that were in place at the time of ignition. Typical protective measures were automatic suppression, closing of openings for heat and smoke, as well as establishing fire barriers. This corresponded to the view that had been obtained from the literature surveys, too. All the shipyards were found to be well aware of the possibilities, but the local practices and adherence to protective measures varied from yard to yard. All the shipyards used the ‘injury of persons in fire’ and ‘total loss of vessel’ as bases for their large consequence scenarios and preparation for the risk. In fact, there are routinely thousands of people on board at risk, and economic losses can considerably exceed the cost of the vessel: there are secondary costs in delayed delivery, especially for the ship owner and the insurance companies.

Figure 4.13 The consequences of this large fire on-board a cruise vessel under construction in 2002 were allegedly in the range of USD 300 million (The photo is not from the yards that participated in the research). Source: AP/Lehtikuva

In Figure 4.13, the consequences of a large fire are illustrated. The fire raged for 36 hours and the direct losses were believed to be in range of USD 300 million. The ship superstructure was nearly completely destroyed, and allegedly the fire was started by hot work. This is the realisation of the nightmare vision that all the shipyards' safety managers had, and it was apparent in their attitudes.

In classical risk management, the consequences are assessed and used in decision-making, but the shipyards of this study assumed the fire to be potentially large every time, and instead, preferred to assess their protective systems. The reason was that established fires on-board can lead to the loss of many lives and the whole vessel, and thus studies of potential consequences did not differentiate alternatives. Instead of analysing potential loss magnitudes, the shipyards' risk management philosophies were found to be mostly based on a simple assumption: *for fire risk in cruise vessel shipbuilding, the potential consequences are always assumed large*. This is useful from theoretical point of view as well, as the assumption simplifies the analysis of responses and helps in focusing the research. With the assumption, it was found sufficient to assess the factors of ignition and the measures that were used to mitigate the consequences.

4.2 Fire risk assessment

Already at the outset of the research, it became clear from literature, and from the qualitative materials of the shipyards, that thorough probabilistic analyses in the style of nuclear or chemical industries were not feasible for assessing fire risk in shipbuilding. Instead, the risk was assessed as a mosaic of several independent factors during the action cycles. It was found useful to define the risk size as an unknown function with generic terms

$$Risk\ size = f(observed\ frequencies\ of\ fires, contr.\ factors\ of\ ignition, consequences).$$

where the terms 'risk size', 'observed frequencies', 'contributing factors of ignition', and 'consequences' were chosen deliberately to reflect the mixed quantitative-qualitative nature of the information on the shipbuilding project fire risk. The assessment of fire risk was mostly carried out for each term separately. Of the terms, the observed frequencies were discussed already in sub-chapter 4.1. The others will be discussed in the following sub-chapters, and used to address the research question number *2) How can fire risk be assessed in cruise vessel construction projects?*

It was found in the beginning of the study that that the yards had great variety in availability, types and accuracy of the input data for risk assessments. Therefore, metrics were created separately for each set of comparable input data, such as heat sources on-board. The methods of assessment were studied and developed in interactions with the participants. A practical consideration was that, if possible, the information should be obtainable as a by-product of other activities that were already in place at the yards, such as fire reporting, safety surveys or fire guard rounds. At the participating shipyards, the ease of use, flexibility, suitability for prototype environment, and low cost contributed to which fire risk assessment methods were applied, especially during the early interactions (Interactions with Longeroche 2001 and Moisio 2000). Typically, the department of the shipyard, or sub-contractor, that was responsible for an operation, such as building a restaurant, was also responsible for many of its fire risk management tasks.

Qualitative information (mainly described in sub-chapters 3.3.1, 3.3.2 and 3.3.3) was available on items such as the assessments of fire risk, fire inspections, evaluation of fire risk and management reviews. Assessment of fire risk was found to be used continuously in project risk management at the shipyards. New assessment methods were developed during the actions. In particular, quantitative methods were developed further: fire incident statistics (described in sub-chapter 3.3.4) were formalised and taken into use at all shipyards; fire safety surveys (sub-chapter 3.3.5) were carried out by both shipyard and ship-owner; and a questionnaire survey of expert managers (sub-chapter 3.3.6) was used. In addition, seven smaller sets of supplementing information (sub-chapter 3.3.7) provided further evidence. The contributing factors that were most common and had most potential for large fires were the focus of development during the actions. From the statistics and the incident histories, it was found that most ignitions led only to small fires that were suppressed locally with a portable extinguisher for example, and established fires with large consequences were rare events. Thus it was found that the assessment of consequences of established fires and their management was more indirect than the assessment of ignitions. In the following sub-chapters, the assessment methods are discussed, and some numerical data is given for contributing factors of ignitions and fire consequences and its management.

4.2.1 Assessment of factors that contribute to ignition

As discussed earlier, the most frequent source of heat in on-board ignitions of fires was hot work. The shipyards used a hot work permit system to control and monitor operations in areas deemed to be sensitive to fire. Hot work without a permit was prohibited and sanctioned. The permits were written on standard forms, and specifically for a defined work task, or for some duration of time, at a specific location on-board. Often the persons who wrote permits also reviewed the location of fire risk with the work crews. Attention was focused on correct working methods, cleaning, extinguishing and fire watches. The numbers of permits and their locations on-board were used for assessment of daily fire risk. Usually the permits were plotted on the general arrangement of the vessel, highlighting the increased fire risk for relevant managers.

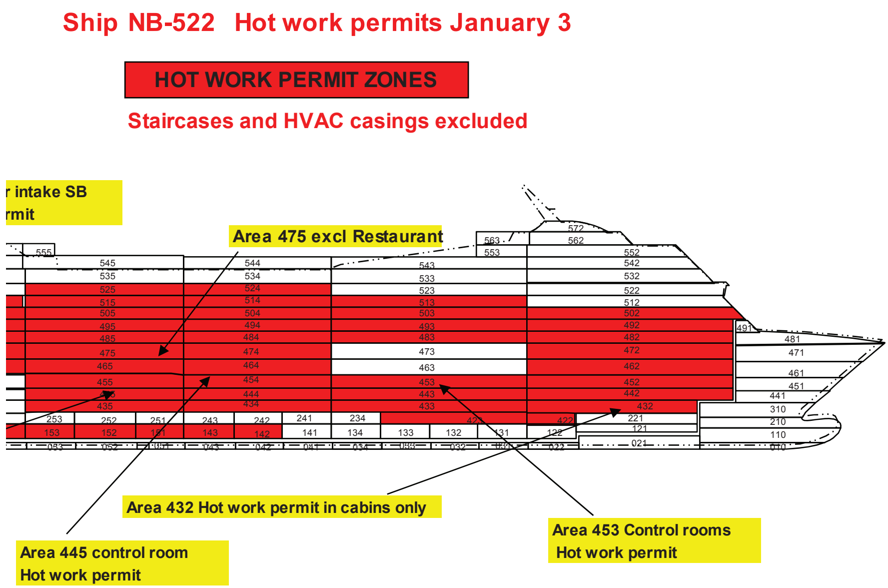

Figure 4.14 Example of a hot work permit display

All the yards had clear rules on how hot work should be carried out. Typical rule deviations were observed in the protection of surroundings, in missing fire watch and in missing extinguishers. During the course of the study, the deviations that fire guards observed during their surveys were used in the assessment of the performance of the yards. This gave insight into the mind-set and training of the people involved in hot work operations. This method was used to measure systematic deficiencies in the hot working habits of the workforce as a whole, as shown in Figure 4.15. For example, it can be seen that, at around 35% of building time, for ship C a serious major lack of discipline in hot work had developed, when the on-board surveys revealed that about 75% of the workers did not follow the safety procedures. The yard immediately started corrective actions, and it can be seen from the graph that the metric reacted accordingly. In a well-run yard, the percentage is close to zero.

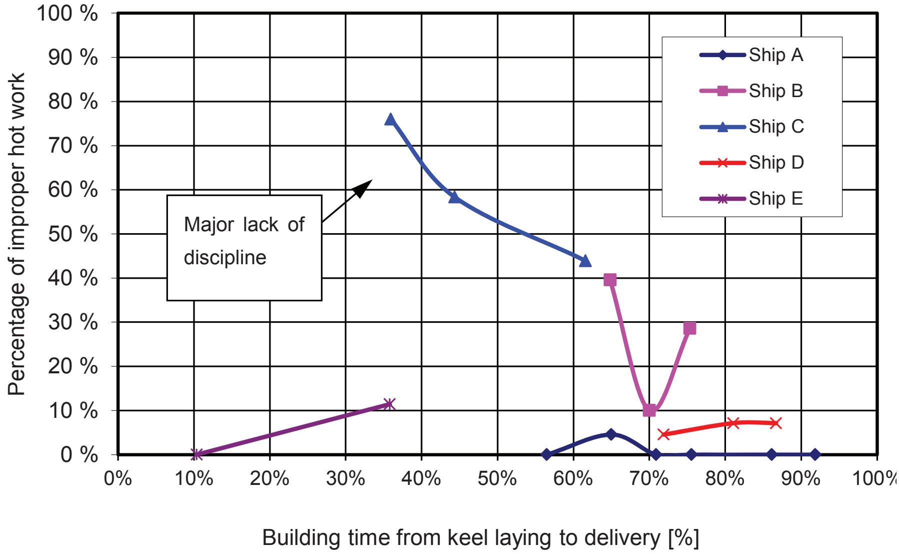

Figure 4.15 Observed amount of instances of deviation from hot work rules (improper hot work) relative to all observed hot work in ship-owner's on-board surveys, results of 17 surveys by ship-owner (subcontractor BSS Ltd) of 3 to 5 days in duration (Räisänen 2001b, unpublished)

The above method was found to be well suited to detecting gaps in general hot work policies and their enforcement in ships and their building areas. However, the bad hot work practices of single individuals (that caused the majority of fire incidents at the participating shipyards during the period of observation) cannot be discerned continuously by an outside observer. Instead, continuous self-assessment and assessment by line management and fellow workers is needed.

The hot work habits are part of the generic personnel safety behaviour on-board, which was found to play a key role in fire risk management in several other aspects too. Some metrics were recorded during on-board surveys or obtained from shipyard data. Examples: data of access to the vessel (relates to such as arson investigations), frequency of ignitions due to electrical and gas heaters, frequency of ignitions due to incompatible chemicals, training feedback of in-house and foreign workers, observed protection of materials from sparks, and observed tobacco smoking on-board. However, these metrics were not all developed further in this study, due to the abundance of possibilities. An example of safety behaviour metrics is shown in Figure 4.16. It illustrates the improvement of workforce behaviour, through records of the use of fire-protective cloth. The data was obtained from one of the yards that built a series of similar ships, and increased safety training and managerial emphasis on fire safety during the series. The improved safety performance was indicated as increased use of protection material in later ships.

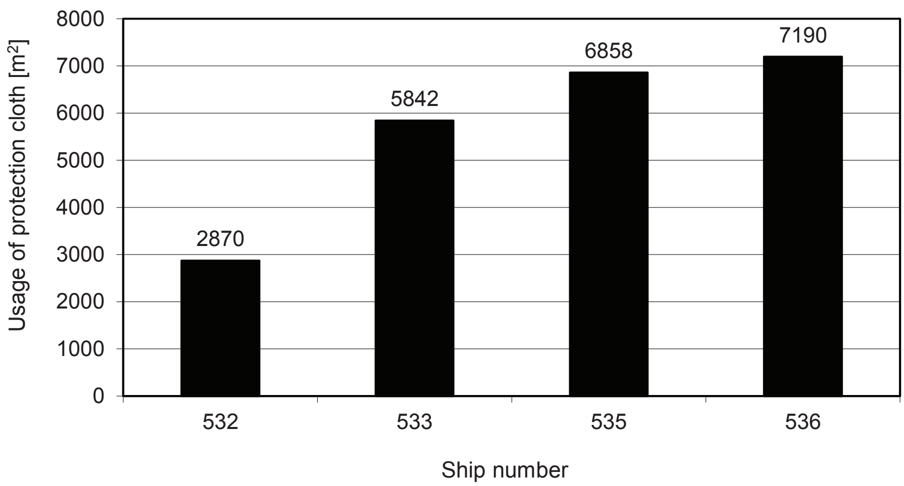

Figure 4.16 Increase in the use of fire-protective cloth in sister ships, used as a metric of fire risk management awareness at the yard. [Increasing ship identification number (changed for anonymity) denotes later keel-laying] (Räisänen 2002b, unpublished)

Human error-related occurrences dominated the quantitative and qualitative evidence on ignitions. It can be concluded that the attitudes and skills of the workforce should be continually assessed. Further, the possibilities of assessing and influencing workforce behaviour are an important topic for future research.

Electrical sources of heat that corresponded to 12% of the fires on-board were more varied than hot work sources. Typical were overheating and short circuits in welding machines, electric motors, fans, heaters and transformers. The risk was assessed by the shipyards by following the number of appliances on-board, their maintenance history and, in some cases, by thermal imaging the equipment.

In addition to heat energy for ignition, fuel is needed for fires. On the shipyards, it was typically assessed by theoretical design calculations (e.g. fixed fire load such as ship interior parts) and on-board surveys (moveable fire load, typically waste or material that is awaiting installation). Especially continuous assessment of moveable fire load on-board was found to be an important management tool for yard area supervisors and other operational management. A fire load metric was obtained for the amounts of observed flammable waste and flammable liquids by weighing the contents of representative samples from different waste bins (as described in sub-chapter 3.3.7.7). In one measurement (Information from Logistics Manager, Yard AAA, 2002), the volume of waste per year for a cruise ship in its final outfitting phase was about 9% of the total volume of the vessel. Similarly, the volume of burnable waste was 4%. The measured average density of waste in the waste bins, including wood, was found to be 0.14 t/m^3. Average calorific values from literature (Babrauskas 2003, p. 943), (Di Nenno et al. 2002, p. A-40) were used for the waste components in the estimation, and the average fire load was found to be 2,700 MJ/m^3.

Waste on decks was also studied. During surveys, the observed fire load of waste remaining on deck areas was found to average below 10 MJ/m^2 (Figure 4.17), naturally with great variations from area to area. For comparison, this is equivalent to the energy content of only one kilogramme of moist wood, or the paper from five evening papers, suprisingly small amount but fires occur nonetheless. The energy content of waste was low compared with the allowed fire load in SOLAS (Appendix B, page B2), but its flammability was high, which explains its role in ignitions.

When the data sets of Figure 4.17 were compared with each other, it was found that fire loads recorded by owner's representatives (Baltic Ship Safe Ltd) were generally larger than those recorded in the yard's own surveys. This led to further examination of data and yard survey practices: variation in the patrolling performance between individuals may have been present. No systematic temporal variation in recorded factors could be found. In a dynamic environment, day-to-day differences in fire load, for example, may be appreciable. When survey material of one ship was compared with the material of a sister ship at the same building stage a year later, the same orders of magnitude were found but results also possibly depended on the survey method and the surveyors. Sister-ship surveys are interesting topics for future research, as is the flammability of the environment, which is known to be important in ignition processes.

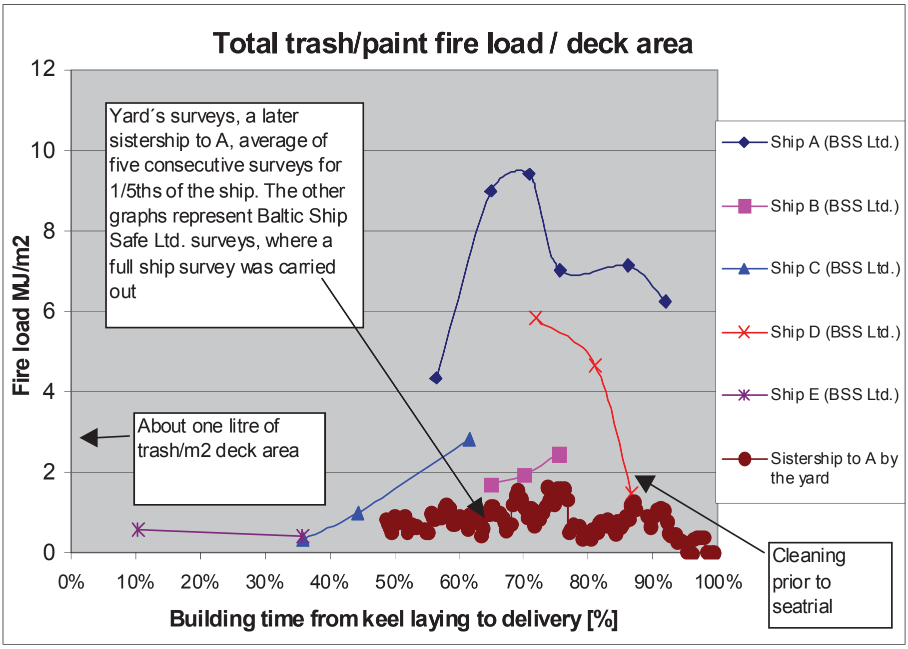

Figure 4.17 Observations of fire load by two different methods, result of 17 on-board 3-5-day surveys by the ship-owner (by subcontractor BSS Ltd) and 101 overnight surveys by the shipyard (Räisänen et al. 2003c)

Fire load surveys on-board gave views on the spatial distribution of burnable matter and allowed assessment of rooms on-board. If the guards saw deviations from shipyard rules during their nightly rounds, they issued negative remarks for the production organisation for next morning. The remarks provide good material for the daily assessment of fire risk. The examples in Figure 4.18 show that most problems were identified in cabin and public areas, which were under intensive building over the period shown. The observations of fire load in the staircases were especially noted. If compared area-wise, the staircase areas were relatively small, but still got a relatively high proportion of remarks. In addition, the consequences of a fire in a vertical room extending to all decks would probably be more severe for fire escalation than for a similar-sized fire in a room bound by decks, such as in cabin areas.

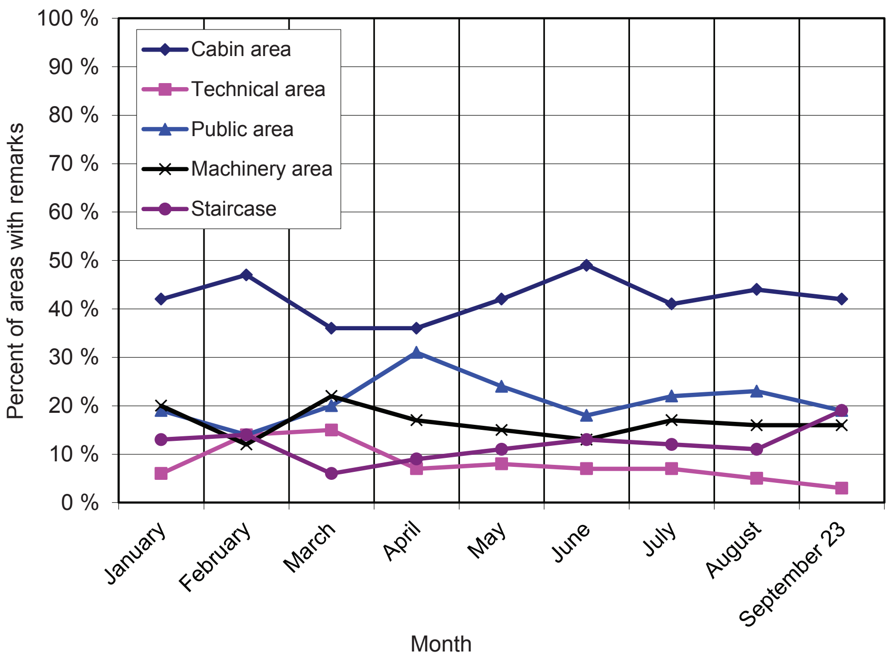

Figure 4.18 Shipyard fire guards' survey - fire load remarks for area types, 101 overnight surveys by the shipyard on one ship (Räisänen 2002k, unpublished)

Fire load problems were also assessed according to area ownership. The general conclusion from Figure 4.19 is that, in this case, the yards' own areas were in general cleaner than the subcontractor areas. It was remarkable, however, that the differences between areas were large. Percentages over 100% were possible if some areas received multiple remarks.

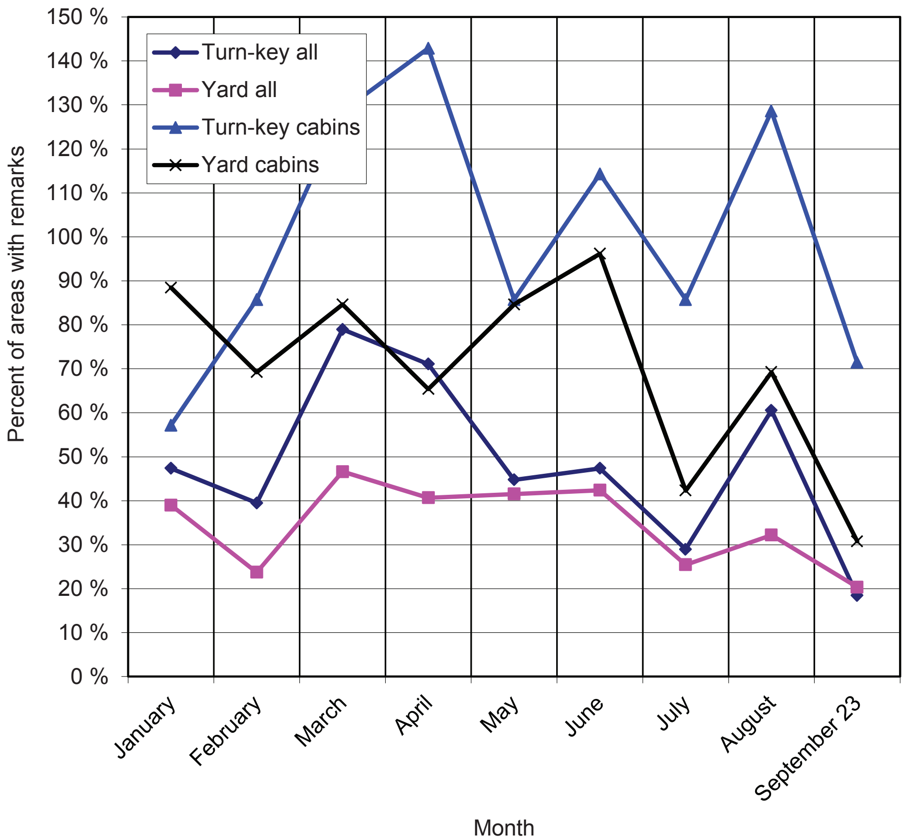

Figure 4.19 Shipyard fire guards' survey - fire load remarks for yard and turnkey contractor areas, 101 overnight surveys by the shipyard on one ship (Räisänen 2002k, unpublished)

An interesting possibility for future development could be the combining of displays of existing hot work permit systems and daily fire load survey results, which would provide continuous assessment tools for co-existing flammable material and heat sources.

4.2.2 Assessment of consequences of fires and its management

As noted earlier (p. 107), the shipyards of this study assumed the consequences of ignitions (human damages, material damages and secondary damages) to be potentially large every time, and instead of estimating the possible losses, they preferred to assess their protective systems. In the study, metrics for fire suppression, fire barriers and evacuation were developed for the shipyards. These correspond to the generic response of "managing the consequences of fires" in general fire safety literature, specifically the branches of "managing fire" and in "managing exposed" (people and property) in Figure 2.1 on p. 24.

Fire suppression capacity on-board was assessed at all of the shipyards for both permanent and temporary fire-fighting arrangements. According to the statistics and incident histories, most of the fires on-board were suppressed early by persons on-board. Thus metrics based on the number and distribution of portable extinguishers were developed for assessing early fire-fighting readiness. Data was recorded in the BSS surveys, and the number of available extinguishers was related to 1,000 m^2 of deck area, which was a suitable round number representing a public area on-board. A typical, good amount is five extinguishers per 1,000 m^2. The number and availability of portable extinguishers were recorded during the building time and compared between ships. In Figure 4.20, the curves are not level, reflecting the fact that temporary extinguishers were moved between several vessels and placed on-board the vessels with highest perceived risks. The extinguishers were transferred to newer projects from previous ships as their final extinguishers arrived on-board and permanent suppression systems advanced, as reflected in the drop of the curve of ship A after 70% of building time.

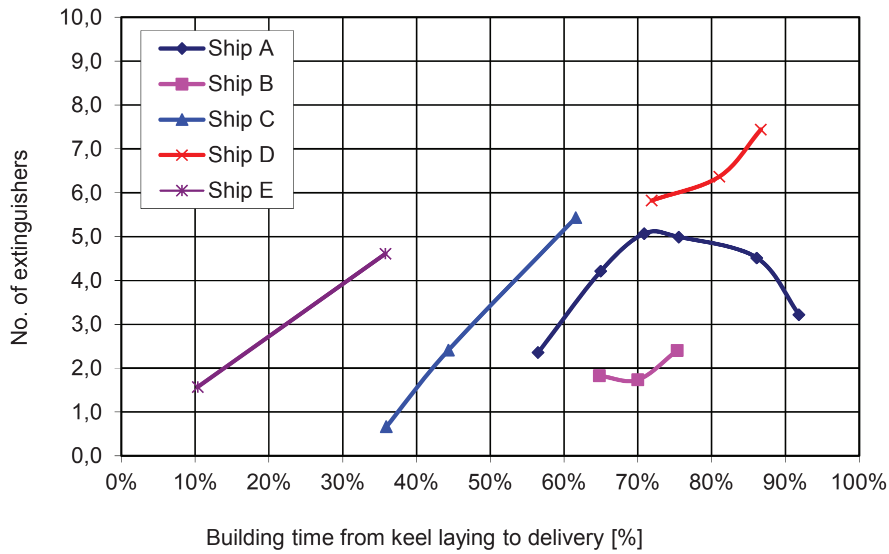

Figure 4.20 Number of available portable extinguishers per 1,000 m² of deck area, results of 17 surveys of 3-5 days in duration (Räisänen 2001b, unpublished)

Another way that was used to assess early suppression capability was developed based on U.S. OSHA requirement on average maximum fetch distance to an extinguisher (OSHA 2003d). For averages in shipbuilding, the fetch distance was calculated from the average of deck area per extinguisher as the radius of a circle having the same area. For example, 1,000 m^2 represented an average maximum extinguisher fetch distance of about 18 metres in an open deck area like a restaurant. A summary of observations is shown in Figure 4.21. The information is essentially the same as in Figure 4.20. The true distance to an extinguisher is underestimated in the graph, if partitions on decks have been erected, as the run of the corridors does not follow the shortest distance. Later, the International Maritime Organization (2008) provided guidance on suitable numbers for operation vessels: one extinguisher per 250 m^2 (= four per 1,000 m^2) for public spaces and a maximum fetch distance of 25 metres in corridors per each deck and vertical fire zone. This is comparable to the survey results.

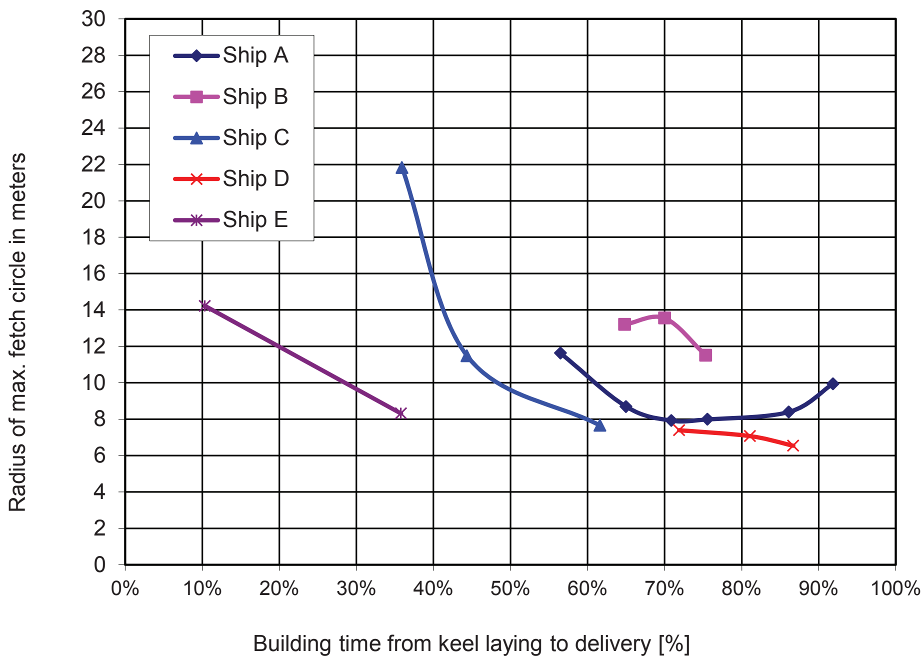

Figure 4.21 Average maximum fetch distance of a portable extinguisher on-board, results of 17 surveys of 3-5 days in duration

In addition to the number of extinguishers, their usability is important. For example, extinguishers hidden from view behind a door, or inaccessible due to stockpiles of installation materials, are not readily available for suppression. This was monitored by surveys on-board, and expressed as the ratio of number of poorly located extinguishers to the total number of extinguishers (Figure 4.22) and used in feedback for the production organisation. From the graph it can be seen that, in the worst case, up to 30% of the extinguishers were poorly located. In future, the number of portable fire extinguishers could also be compared to the number that is used in the same vessel in operation, as per the SOLAS (Ch. II-2, Part A, Reg. 6) regulations.

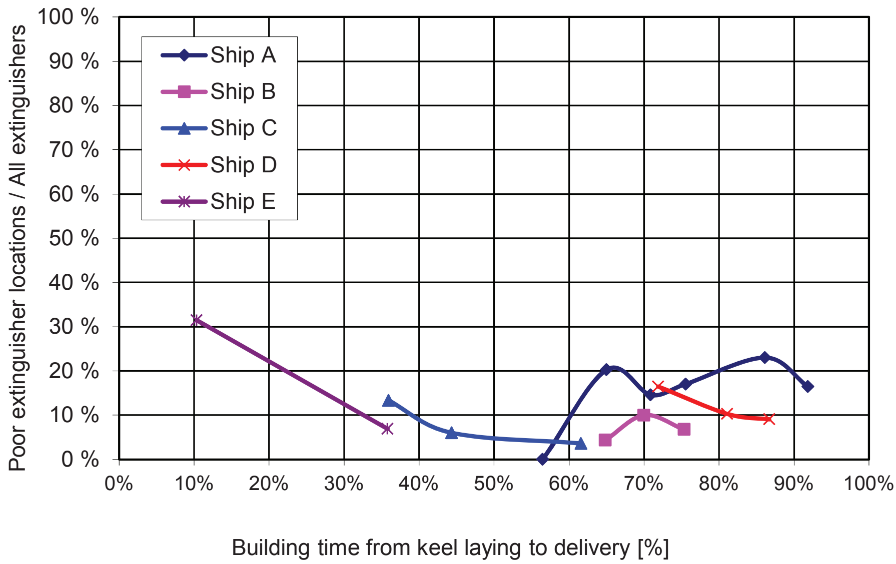

Figure 4.22 Poor extinguisher locations of all extinguisher locations, 17 surveys of 3-5 days in duration (Räisänen 2001b, unpublished)

A temporary fire-fighting water piping system is erected on ships early in the process for use before their own systems are operable. This was assessed regarding the extinguishing water capacity and pressure on the uppermost decks of the vessel, which can also be compared to SOLAS requirements for operational cruise vessels.

As the effectiveness of the fire brigade of the yard and their municipal counterparts is crucial in escalated fires, the usual metrics such as the number of available fire-fighters during ship construction and time from alarm to start of extinguishing were used for benchmarking. In general, yards which are located near large cities benefited from the availability of municipal fire services.

For the ships' sprinkler systems, a very useful metric was found to be the percentage of availability of the system per area, and the display of availability similar to hot work permit display, which allows real-time monitoring of risk reduction. Further assessment of the efficiency of automatic extinguishing systems could be carried out by event tree analyses (a simple example is shown in Appendix J) and dynamic fire simulations, which allow the variation of fuel, oxygen and combustion product flows as well as suppression. This is especially useful for the risks of building large public spaces, such as atriums, high passageways and restaurants several decks in height.

To protect against fire escalation, and to provide safe escape routes, ships have fire barriers in the form of bulkheads, doors and hatches. A common problem in the ships under construction was that some of these barriers were finished late, were inoperable or left in an open position. During the actions, the yards were developing their building processes to allow early installation of fire doors and to promote the closing of openings in fire bulkheads. These success efforts can be assessed by comparing the date of installation to the date of delivery, the earlier the better.

A further challenge was found to be keeping the installed doors closed: all yards had rules, which stated that in general all fire doors should be shut, and active closing of doors was enforced. The risk of non-compliance with the rules was again assessed through the results of on-board surveys. A ratio of open doors to all doors was calculated to obtain a metric. An example of the use of fire doors is shown in Figure 4.23. It is noteworthy that the doors do hinder work and the large spread of results from 5% open to 80% open doors reflects the efforts in installation as well as active closing, education and enforcement that were needed. From the survey results, the chances of fire damage to neighbouring fire compartments can be assessed, as an open door almost certainly leads to at least smoke damage in an established fire. Similar metrics could be developed for all relevant openings such as vertical casings, which were also recorded in the BSS on-board surveys.

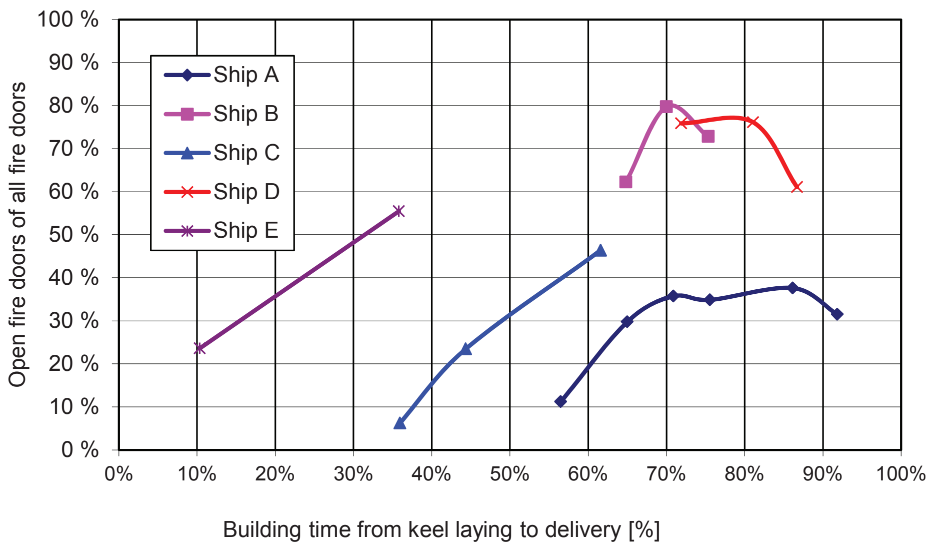

Figure 4.23 Percentage of open fire doors of all fire doors, 17 surveys of 3-5 days in duration (Räisänen 2001b, unpublished)

The closing of cabin doors was also found important for limiting fire, protecting flammable cabin contents and limiting the area of search for survivors in fires. Consequently, it was used as a metric. In the surveys (Figure 4.24), it was notable that variations were large (0%– 30% of doors were open) and that the active efforts of management had effects. In addition to increased fire risk management, the closing of cabin doors also contributes to the protection of cabins from damage and theft that may sometimes be an issue.

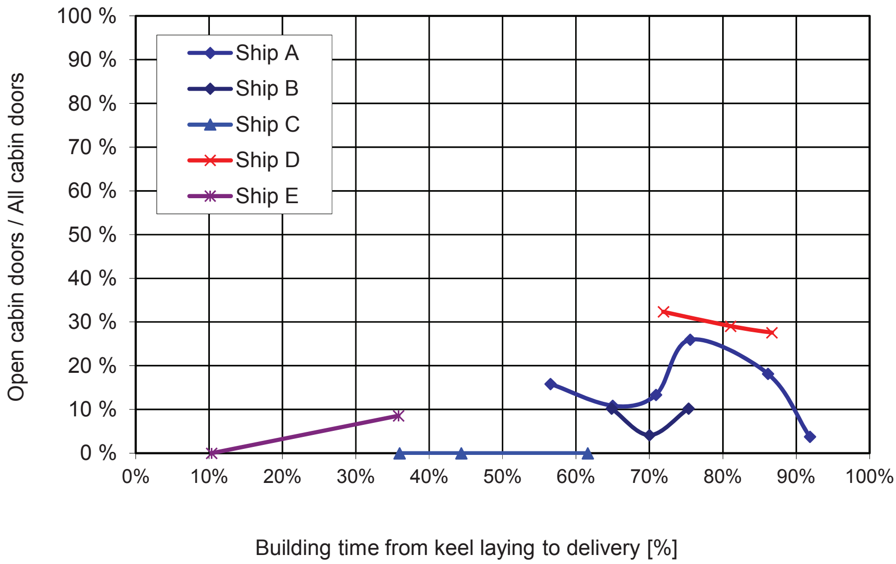

Figure 4.24 Percentage of open cabin doors of all cabin doors in 17 surveys of 3-5 days in duration (Räisänen 2001b, unpublished)

Evacuation of personnel was an important issue at all shipyards, and metrics were developed accordingly. In evacuation, the alarm is sounded, people on-board leave the vessel and report to predetermined assembly points, which was rehearsed by some of the yards at some suitable time during the building process. They recorded the time needed for evacuation, from alarm to confirmation of arrival of personnel at assembly points, which was found to be an excellent metric for evacuation capacity. The observed variations between yards were found to be large during the research actions. The best evacuation times for a whole vessel were in the range of a couple of minutes.

Further, emergency lighting, evacuation routes, signage and alarm systems that all contribute to evacuation can be assessed with on-board surveys. It may be interesting to note that the yards, which had suffered a major fire, were the most prepared at the beginning of the action cycles.

The safety behaviour of the personnel is a key factor in avoiding ignitions and also in mitigating the effects of established fires. It was assessed in several ways. The number of unknown fire initiators (the graph below) was used as a metric of the willingness of the organisation to learn from mistakes. Fire incidents due to yard/subcontractor personnel gave the yard management a view on which organisations the development efforts should be directed at. An extract of fire incident statistics, selected on the basis of fire initiators at four yards (Figure 4.25), shows that differences between organisations are considerable, and development efforts needed vary considerably from yard to yard.

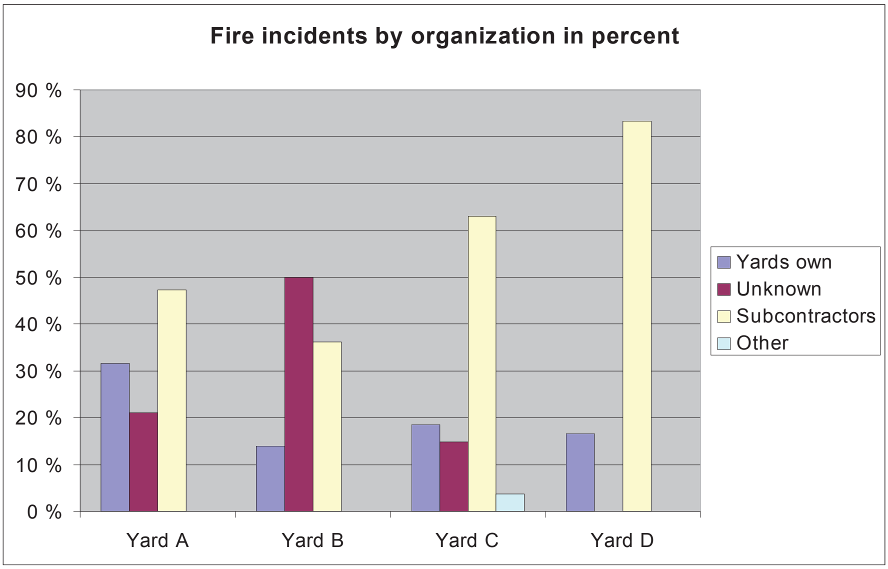

Figure 4.25 Fire incident initiators by organisation (Räisänen et al. 2003c)

4.2.3 Key metrics of ignitions and consequences and typical values

The assessments that were developed with the yards during the research were discussed in the previous pages. As a summary, the key metrics are listed below, with typical observed values and some comments in parenthesis.

Observed frequencies:

1. Frequencies of fire incidents in general *(1-2 fires every five weeks of production for an average-sized ship, large fires: one per 100-200 fires. Case histories provide additional information if focus is needed)*
2. Frequencies of fires related to key features such as causes and fuels *(Hot work 80% of the incidents. Waste, combustible liquids and gases 65%. These can be used in combination with other metrics such as hot work permits)*

Contributing factors of ignition:

3. Numbers of hot work permits and their locations on-board (*A real-time display of ship decks with locations and numbers of permits provides an overview of the risk for project managers and area supervisors)*
4. Hot work rule deviations and observed hot working habits by the workforce *(10% deviation. Can be collected during daily fire-guard rounds, provides daily feedback for management, subcontractors and supervisors)*
5. Electrical sources of heat in fires on-board *(12% of incidents, can be used for improvements such as an input for device maintenance)*
6. Observed flammable waste, gases and flammable liquids *(Very little needed for fires, sufficient amount for fires observed always in the on-board surveys. Cleanliness is a good indicator for waste-related fires, and the data can be collected daily for feedback to each area supervisor)*

Of the three main categories of the consequences (human, material and secondary damages, p. 92) the secondary damages were found to be least prominent at the shipyards. Four direct metrics were found altogether:

Assessment of consequences of established fires – Human and material damages

7. Loss of life *(Not observed during research period but hundreds possible)*
8. Human injuries, for example Lost Time Injuries *(A possible metric, more frequent than deaths, rare occurrences, however)*
9. Direct material damage costs *(Hundreds of millions of dollars, up to the value of the whole vessel, paid by the shipyard and insurance companies)*

10. Secondary costs such as delays and insurance costs *(Tens of millions of dollars, paid by the shipyard, ship- owner and insurance companies)*

It was found that not only the consequences needed measuring, but also the available responses for limiting them. Their number was rather large, due to the complexity of the problems but also due to large number of available protection alternatives. Based on the empirical material and the generic fire safety literature (see p. 26) the metrics were divided in three groups: fire suppression, limitation of fire and evacuation.

Assessment of limitation of consequences- fire suppression:

11. Number and distribution of portable extinguishers *(Four per 1,000 m^2 of deck area. Can be observed in daily rounds of fire guards, provides daily feedback for area supervisors and project managers)*
12. Extinguishing water capacity and pressure on the uppermost decks *(Sufficient pressure and water volume so that fire-fighting can be carried out with several hoses on the uppermost deck. Needs a specific test occasion.)*
13. Number of available fire-fighters *(Some tens with city brigades. In the largest of fires, many parts of the ship will burn until the fuel is finished, irrespective of manual fire-fighting capacity)*
14. Observed time from alarm to start of extinguishing *(A couple of minutes. An important metric as fires can increase very rapidly)*
15. Percentage of availability of the sprinkler systems *(20% during last 20 weeks of production. Automatic sprinklers are an effective method available for limiting an established fire, therefore a key metric also.)*

Assessment of limitation of consequences - limitation of fire:

16. Installation readiness of fire doors related to building time *(Fire doors can limit fires only if they are installed, the earlier the better)*
17. Metrics related to closing of temporary openings in fire bulkheads and decks *(Fires typically escalate through unclosed openings. This metric focuses on keeping openings such as cable routes closed during production, although their final closing may not come until near delivery)*
18. Closing of fire doors *(Fire doors can limit fires only if they are kept closed, can be observed daily by fire guards and reported to area supervisors)*
19. Ratio of open fire doors to all doors *(40%. A non- dimensional metric, typically collected daily by fire guards for safety and project managers for trends)*
20. Ratio of closed cabin doors to all cabin doors *(15%. A non- dimensional metric, typically collected by fire guards for safety and project managers for trends. Locking of cabins reduces smoke damage, ignition positions and also thefts)*

Assessment of limitation of consequences - metrics related to evacuation:

21. Time needed for evacuation of workforce to land *(10 minutes to two hours. Depends on, for example, alarm strategy, cleanliness and escape training, tested rather rarely as exercises are expensive)*
22. Numbers of obstructed escape routes *(Can be reported daily by fire guards for area supervisors)*
23. Coverage of emergency lighting *(Can be reported by fire guards for area supervisors)*
24. Operability of evacuation routes, signage and alarm systems *(Tested and reported regularly to safety and project managers)*

The behaviour of the people on-board is a paramount factor in fire risk management as they both ignite and suppress most of the fires. Some metrics were tested and found feasible, listed below. It should be noted that it is relatively easy to find further metrics, and this remains a good topic for future research.

Assessment of safety behaviour of the workforce

25. The usage statistics of fire-protective cloth *(Gives indications of safety mindedness in general and hot work procedures in particular)*
26. The number of unknown fire initiators *(Indications of safety culture and surveillance)*
27. Fire incidents due to yard/subcontractor personnel *(Indications on performance of the organisations for project and safety managers)*

4.3 Size of fire risk

For addressing the research question 3) *What is the size of fire risk in cruise vessel construction projects?*, its parts, the frequencies of fires, the contributing factors of ignitions and the consequences were assessed directly as described in the previous sub-chapters. The results were summarized in subchapter 4.2.3. It was found that the size of risk can be amply described by using the combination of metrics but no exact single outcome could be derived of them as the 'risk size'.

A general conclusion was drawn from the assessment of recorded incidents at the yards and the potential consequences of fires: at the outset of the research actions the risk was high. All of the participant shipyards had one or two fire incidents in a few weeks' intervals per ship project, i.e. order of magnitude of 20 fires per project. As summarized earlier (Table 4.1), in four incidents out of five, hot work and waste contributed to the ignition. Further, the potential consequences of each fire incident were loss of several lives and material losses larger than the value of the ship. This conclusion was supported in the historical records of the shipyards, which showed that they all had experienced large fires of well over million euros in damages. Fortunately, no lives had been lost in the fires.

The discussions on reducing the risk size were focused on the contributing factors of fires, and on the measures that were in place for managing the consequences. The yards assumed that the amount and quality of hot work, and the amount of waste on-board were linearly linked with risk size, and they strove to minimise both to reduce the risk. Further, fire suppression readiness, limitation of fire by barriers and evacuation were linked qualitatively with it. For practical purposes, the yards assumed only that improvements would reduce the risk of a large fire, which was sufficient for initiating improvement measures, but did not allow comparisons of alternatives in mitigation of risk. Also the safety behaviour of the workforce was found to affect the risk size, but no direct appraisal of it was attempted at the yards, as improvement needs were obvious.

In addition to the direct metrics, three methods were used to study the perceived risk size of some shipyard experts: distribution of ignitions (method described in sub-chapter 3.3.7.1), size of fire risk (sub-chapter 3.3.6), and benchmarking by the owner's consultants (sub-chapter 3.3.7.4). In addition, an event tree (sub-chapter 3.3.7.6) simulation was used to test the possibility of calculating the risk size directly.

Some shipyard and ship-owner's experts (Table 3.1) played a special part in the action cycles of the research: they were in charge of putting the improvement measures into practice. Their perceptions of fire risk affected the topics of the research and their improvement actions on the yards, and conversely, the research affected their views and actions. This interaction provided fertile ground for developing views of fire risk, its assessment and responses, for example, the participants' views were collected during the action cycles of the research and they took part in writing best practices to minimise the risk for the shipyards. But, in addition to indirect inquiries, their knowledge about the distribution of ignitions and size of fire risk was also surveyed directly. The results are discussed in the following.

In Figure 4.26, some experts' estimates of distribution of ignition risk are presented. The differences between experts were found to be rather large, which stressed the importance of obtaining comparable data from shipyards. Some differences may also have stemmed from differences in production arrangements between yards, such as variation in time of launching and sea trials. However, when the estimates of the eleven participants were averaged, the resulting curve (thick black line) was found to resemble the quantitative data from observed frequencies (Figure 4.2). When the estimate of the experts was asked about the consequences of established fires, they again described them as "potentially so large that maximum consequences should be assumed in developing the responses". They reflected on the fact that even a small fire can escalate on board any time after the first weeks of production. During the first weeks, relatively bare steel structures are assembled in the dry-dock and no significant amounts of fire load are yet on-board, but later in the building process there is enough installed and temporary fire load in the ship for a large fire. This means that, according to experts' views, possibility of having an established fire was rather linearly related to number of ignitions on-board, assuming that normal protection of established fires, such as suppression, was in place.

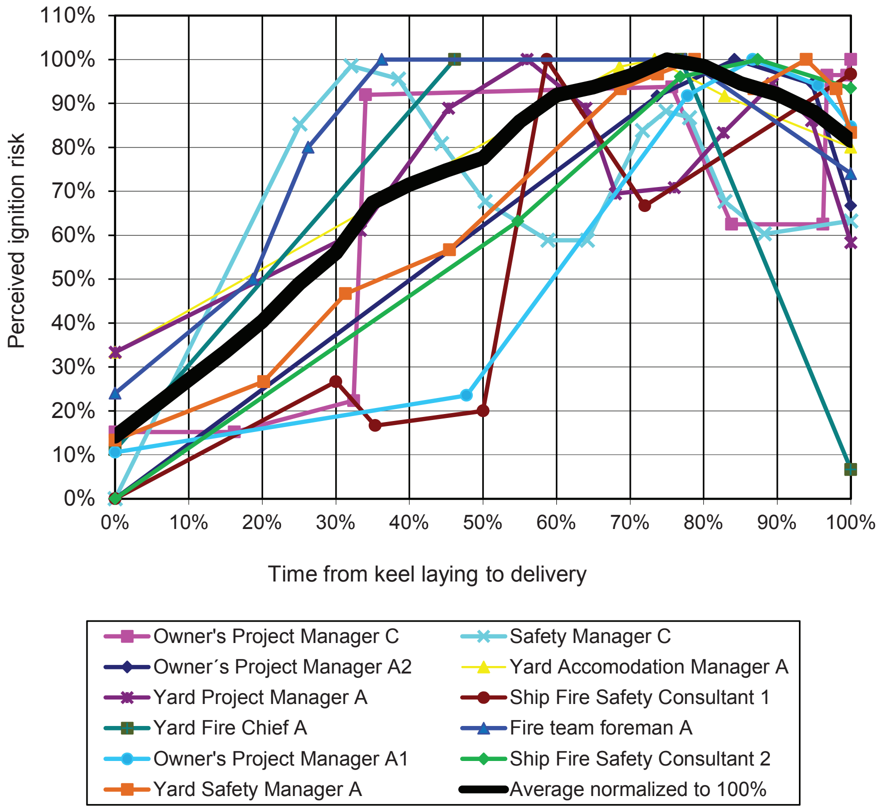

Figure 4.26 Participants' perception of distribution of risk of fire ignition as a percentage of its maximum. Average of 11 participants (Räisänen 2002j, unpublished)

Later, several years after the research actions, eleven key experts (not same as those of Figure 4.26, see p. 76 for details) again volunteered to evaluate the size of fire risk, taking into account the frequency and potential consequences of fires. During the action cycles, fire risk was described with contributing factors to ignition and main types of consequences. Each of these factors and consequences were evaluated by experts relative to the size of risk, and averages calculated to provide ranking. The results were consistent with other qualitative and quantitative data: the contributing factors that were associated with the largest risk were fire load and hot work. The experts also considered the ignitions of dust, gas or vapours to have high risks, probably due to the escalation potential of explosively growing fires. Further, the experts associated highest risk with the consequences of human damage in fires. The complete results are shown in Table 4.2 and Table 4.3. Their estimates about relevant responses are discussed in sub-chapter 5.4.

Table 4.2 Averages of eleven experts' estimates on contributing factors of ignition and size of fire risk (low or average, elevated=higher than average, and high) in the 14 categories of ignition in Table 4.1.

Contributing factor to ignition	Expert estimate on importance of the risk (frequency and consequences) Ranking points 1= low or average 2= elevated 3= high	
1) Arson	2,1	Elevated
2) Autoignition	2,0	Elevated
3) Electric phenomena	1,5	Low or average
4) Electric systems	1,9	Elevated
5) Explosions, dust, gas, and vapors	2,5	High
6) Fire load	**3,0**	**High**
7) Heating and ventilation	1,6	Elevated
8) Hot surfaces and open flames	2,0	Elevated
9) Hot work (welding, cutting, grinding, torching)	**2,9**	**High**
10) Machinery	1,6	Elevated
11) Painting	2,0	Elevated
12) Sea trials	1,8	Elevated
13) Smoking of tobacco	1,9	Elevated
14) Miscellaneous	N/A	N/A

Table 4.3 Averages of eleven experts' estimates on consequences of established fires and size of fire risk (low or average, elevated=higher than average, and high) in the three categories of consequences

Consequences of established fires	Expert estimate on importance of the risk (frequency and consequences) Ranking points 1= low or average 2= elevated 3= high	
1) Human damages in fire	2,6	High
2) Risk of direct material damages in fire	2,5	High
3) Risk of secondary damages	2,0	Elevated

In general, it can be said that the expert managers saw fire risk similarly compared to other research material. This is consistent with the fact that all the related, extensive evidence has been available for managers in their shipyards over the years, and the general features of fire risk did not differ greatly between yards.

Another view on risk size was obtained from shipyard benchmarking by the owner's consultants (sub-chapter 3.3.7.4), which provided views on fire risk, on responses in particular. Also in their view, the size of risk was characterised by ignitions and the consequences of established fires. From the benchmarking material, a set of contributing factors for ignition was found: the condition of gas hoses and gas equipment and tools, fire load, fire guarding, hot work culture of the work force, protection issues, housekeeping, and lighting systems. The evidence from benchmarking on the consequences of fires, related to suppression, confinement of fires and evacuation, supported the findings from other data.

With some simplifying assumptions, the probability of an escalated fire from an ignition was studied briefly during the actions. With an event tree (sub-chapter 3.3.7.6) simulation, a realistic on-board fire scenario was analysed for getting an overview of sprinkler effectiveness. Although not all the probabilities of the events in the tree were available from the shipyards, the principles of escalation could be studied well. In conclusion, prevention of ignitions, availability of automatic and manual suppression, as well as confinement of fires was found to be crucial. The result was well in line with the generic fire safety literature. The information was used to provide motivation for improving responses, and it led to the invention of new procedures for the assembly of automatic extinguishing systems on-board. The responses are discussed in Chapter 5.

4.4 Summary of the findings

As described in previous sub-chapters, evidence from literature and empirical actions were gathered for addressing the research questions. Quantitative information of fire incidents and their histories in particular gave a good view of the problem. In the following, the first three research questions are addressed.

The first research question refers to the definitions and nature of fire risk; *1) What is fire risk in cruise vessel construction projects?*. The shipyards were found to treat fire risk in line with a traditional definition of risk, such as '"potential for realisation of unwanted, adverse consequences to human life, health, property and environment'. Fire risk was seen at the yards as a combined threat of ignition and the adverse consequences of established fires, respectively. For arranging the research evidence, this division was also found to be practical. Factors that contributed to ignition and consequences were studied separately, which simplified inquiries on assessment and responses.

Many findings were based on records of fire incidents on-board, but also on vessel surveys by the ship-owner and the shipyards. The main source was a large collection of records of 221 fire incidents, which included fire causes, incident histories, extinguishing histories and shipyard conclusions. From the observed frequencies, it was found that on average one to two fires ignited every five weeks of production per 100,000 GT in production during the last 80 weeks before delivery (Figure 4.2), on average about 20 fires per ship project, which is high. Daily and weekly distributions of fires (Figure 4.3 and Figure 4.4) were calculated and used in mitigation actions. In about 80% of the incidents, hot work (grinding, welding or flame cutting) was a reason for ignition (Figure 4.5). Electrical reasons were the cause in about 12% of the cases. The amount of installation material and the on-board flow of flammable materials were found to affect fire risk. Typical fuels in fires were combustible liquids, gases and waste, which have relatively small fire load compared with the materials installed on the vessel. However, their flammability is high compared to installed materials, such as the thin burnable liners of wall panels. On average, combustible liquids, gases and waste amounted to about 65% of the incidents (Figure 4.8). The observed number of dust-, liquid-, and gas-related fires was relatively low at the yards (Figure 4.12), but the potential for explosive ignition and major fire escalation make them important for risk management.

Evidence of the causes of ignitions consisted of shipyard practices, participant estimates, observed frequencies of fires, incident histories and qualitative information about contributing factors. They were categorised into 14 contributing factors, which were found to be important for ignitions at the yards:

1. Arson
2. Auto-ignition
3. Electric phenomena
4. Electric systems
5. Explosions, dust, gas and vapours
6. Fire load
7. Heating and ventilation
8. Hot surfaces and open flames
9. Hot work (welding, cutting, grinding, torching)
10. Machinery
11. Painting
12. Sea trials
13. Smoking of tobacco
14. Miscellaneous

The probability and mechanisms of escalation of fires from ignition to established fires at the yards was also studied. Escalation was found difficult to predict from circumstances on-board but, based on statistics, it can be estimated that one of 100 - 200 fire incidents led to a large established fire. The qualitative information of the study revealed that loss of hundreds of lives and hundreds of millions of dollars in damages are possible consequences of a fire incident on-board. In this respect, it was logical that the shipyards based their fire risk management on the practical paradigm that fires must always be assumed to have large consequences when planning mitigation. Escape arrangements, closing of openings and suppression arrangements were important in dialogues about consequences at the yards. For prioritising risk management, the consequences of established fires were divided into three categories at the yards:

1. Human damage in fire
2. Direct material damage in fire
3. Secondary damage

The division was also useful for focusing the research. For consequences of fires, less quantitative evidence was available than for contributing factors to ignitions. However, empirical qualitative information correlated well with generic fire safety literature. During the action cycles, it was observed that the yard managers consistently focused on avoiding human damage.

In summary, it was found from research material that, commonly, fires at the yards were ignited due to co-existing hot work and waste, and that the consequences were increased when products of the initial fire spread through openings in structures. Consequences may be particularly large for fires that can escalate suddenly or unnoticed. For example, gas fires can grow explosively and fires started by unattended machinery may escalate unobserved.

For addressing the research question, *2) How can fire risk be assessed in cruise vessel construction projects?,* it was found that not enough knowledge about ignition, fire escalation and impacts was available for rigorous probabilistic analysis. Instead, it was found that fire risk could be assessed by studying the contributing factors and mitigation of consequences. 27 key metrics for fire risk were developed with the yards (subchapter 4.2.3, starting on p. 124), focusing on factors that were common in fires, or factors that can cause fire escalation on-board.

It was found that both qualitative and quantitative assessment of fire risk on-board is needed, especially assessment that relates to hot work practices and fire load. In particular, the constant surveying of hot work habits and flammable waste on-board was found useful. As gas leaks have a potential for large and explosively expanding fires, the number of observed gas leaks is an important metric, although the number of fire incidents related to gas was relatively low. Similarly, the malfunctioning of unattended electrical equipment can produce fires that have escalated before they are detected.

Assessments of the safety-related behaviour of people on-board were carried out by observing their conformance to work rules and use of protection. It provided information for responses, such as directing safety training and management effectiveness in preventing ignition, as well as protecting people. Hot work habits, tidiness and fire door closing practices were practical metrics. Similarly, for management of the consequences of fires, the closure of openings, extinguishing arrangements and availability of escape routes were easy to assess. Regarding the risks for managing the consequences of established fires, the evidence from fire incident histories of the statistics, on-board surveys and qualitative information showed firmly that risks to humans and property ranked highest among managers.

For a ship's sprinkler system, a useful metric is the percentage of availability of the systems per area. In view of innovative architectural designs in cruise vessels, such as atriums, further assessment of the efficiency of automatic extinguishing systems can be carried out by event tree analysis and dynamic fire simulations, which allow the variation of fuel, oxygen and combustion product flows as well as suppression.

The broad quantitative and qualitative material that became available from the shipyards during the research actions allowed a fairly clear empirical view to be obtained of the nature and relative importance of factors that describe the size of fire risk on-board. This was used further in studying and developing responses for the risks of ignition and established fires, discussed in the following chapter. As the number of fires per ship keeps decreasing with safety improvements at the yards, the statistical value of the fire occurrences of the diminishing sample is reduced. In future, more emphasis can be directed to analyses of fire incident histories instead.

For addressing the third research question *3) What is the size of fire risk in cruise vessel construction projects?*, quantitative and qualitative information became available during the action cycles of the research. Observed frequencies, contributing factors of ignition, consequences, and their limitation were studied.

A generic, unknown function with three terms was formulated for risk size:

$$Risk\ size = f(observed\ frequencies\ of\ fires, contr.\ factors\ of\ ignition, consequences)$$

The terms ‘risk size’, ‘observed frequencies’, ‘contributing factors of ignition’, and ‘consequences’ reflect the mixed quantitative-qualitative information that can be used for assessing project fire risk at the shipyards, instead of the rigorous probability-impact approach that is applicable in some other industries. As discussed earlier, the assessments revealed that fire risks at the yards were large at the outset of the actions.

For the size of established fires, there was not much quantitative evidence. Three larger, established fires with material loss of more than one million euros were included in research data and further large fires were found in the historical records of the shipyards. It was found qualitatively that openings in fire barriers, which may allow escalation of fires, are one of the key factors for evacuation, spread of fires, as well as smoke and heat damage. Further, extinguishing effectiveness is a key issue regarding the size of the damage. Further research on risk size is recommended.

In addition to the direct metrics, the perceptions of the expert managers were inquired about, and compared to views of the risk that were obtained from the other research materials. This was particularly interesting as the managers were in a position to initiate improvements at the yards. Three methods were used to study their views. No major differences to the other evidence were found. This was not unexpected, as the managers were very familiar with the circumstances at the yard. One further view was obtained by an event tree calculation where one fire scenario with realistic initial values was tested. The test revealed no discrepancies but rather emphasised the importance of automatic suppression in avoidance of large fires.

In summary, fire risk and its size in cruise vessel shipbuilding were described with information about frequencies of occurrence, factors that contribute to ignitions and the consequences of fires. The evidence from all six main sources of information (sub-chapter 3.3) gave surprisingly homogenous views on the fire risk, and triangulations with other sources supported the conclusions well. Multiple types of metrics were made available for the participating shipyards. Consequently, they were used in focusing risk mitigation, which is discussed in the following chapter.

5 Findings on responses to fire risk at the shipyards

In this Chapter, the discussion of Chapter 4 on the characteristics of fire risk is widened to the responses that were found to be applicable at the shipyards, by addressing the fourth research question *4) What are available responses to fire risk in cruise vessel construction projects?*.

During the first action cycles, the responses were obtained from literature (p. 41). Next, these were combined with the empirical information of the shipyards, and finally developed further with the participating shipyards during the later research action cycles (p. 53, p. 58). Responses were sought for both parts of the fire risk: for preventing ignition and for limiting the consequences of established fires. In addition, some generic responses were found that related to such as project processes and safety behaviour of the workforce. The responses ranged from detailed controls to broad polices at the yards. They are discussed generally in the following three sub-chapters. A further interesting issue from practical point of view was how each of the responses would suit the processes of the shipyards. This was assessed with the stakeholders, and is discussed in sub-chapter 5.4.

In total, 141 responses were found during the action cycles. All are summarized and listed in Table 5.5 to Table 5.7 at the end of this chapter, and the numbers *[nn]* in the discussions of following sub-chapters refer to them.

5.1 Responses to ignition

As discussed in sub-chapter 4.1, 14 main categories of contributing factors for ignitions (Table 4.1) were derived during the actions. When the frequencies of occurrences of fires were studied, the most important factors were flammable waste, gases and liquids, which were typical fuels in fire incidents, and hot work, electrics or unattended machinery that provided ignition energy. Obviously these were the focus of improvement at the shipyards. In the following two sub-chapters, findings on responses to heat sources and fuels in fires are discussed.

5.1.1 Heat sources

As stated earlier, a key heat source was hot work. An efficient way of responding to fires due to hot work is to reduce their number on-board, in which the information of the hot work permit system (p. 109) was useful. If the work on-board is moved to workshops *[Response number 52 in Table 5.5 to Table 5.7]*, fire risk in the ship is eliminated for this part. The respective increase of fire risk in workshops may be engineered to be smaller due to more freedom in arrangement, compartmentalisation and protective measures. From the shipyard point of view, it also offers a chance to change risk ownership and reduce the amount of capital at risk, if the work is transferred to a subcontractor. For reducing the number of ignitions by changing hot work to non-hot work *[64]*, changes in design and work procedures are needed. Typically, these could include replacing flame cutting with mechanical cutting, and welding with mechanical fastening methods. An example was using nailing instead of welding in fastening the cabins to the decks. Operational trials of such solutions are needed before they can be introduced en masse (e.g. attention must be paid to the durability of alternative fastening methods through the lifetime of the vessel. Should an alternative fastening later fail through fatigue or ageing, it may have to be welded in a vessel in operation, causing costs and fire risk). Using less heat by changing the welding method to laser and plasma welding and cutting could also be investigated. Further, it was found that reducing the possibility of human error in hot work by training and management support of the personnel is important. In addition to planned welding, several fires were caused by improvised welding for holding parts temporarily in position. Response to this risk is the availability of mechanical clamping. Carbon-arc cutting was not as prominent a cause of fires as other hot work, but entails high energy. This method is effective and fast and not easily replaced by a heatless response, thus extra vigilance is needed.

It was also found that the chance of ignition is greatly reduced if hot work can be carried out early *[58]* in the building process. The reason is the bare metal structure of the ship, which reduces the amount of fuel. The fire load on-board increases in the outfitting phase, when interior details and equipment are brought on-board. Typical outfitting hot work was the welding of the supports of pipes and cable trays to the ship structure as well as flame cutting and welding penetration of decks and bulkheads. If the construction drawings are ready at an early stage, much of this work can be carried out at the block-building stage of the building process. Then the risk of catastrophic fire is lower than at the outfitting stage, as blocks are separated from each other at the workshops and yard lots, and thus less fuel for the fire is at one location. The work process of the yard may have to be revised to make this possible. The trend in yard process development had been towards increased pre-outfitting and concurrent engineering, to reduce the time between contract and delivery. This development had increased the possibility of design changes, which increased the amount of hot work during the later outfitting stages. In prototype ships or the first ships in a series, design changes are especially frequent. Reasons may be attributed to design errors (which in many cases can be traced back to lack of design time from contract to construction), the owner's own design changes and open issues in the building specification of the contract documentation.

In increasing pre-outfitting type of construction *[58]*, the work can be distributed to several locations, which may offer a possibility to reduce fire risk. At fixed workshop locations, a permanent, operational fire extinguishing system and better tidiness can be achieved. Another way of controlling heat source-fuel interaction is protective covering when hot work in the vicinity of potential fuel is to be carried out (Kvaerner Masa-Yards 1999), (Chantiers de l'Atlantique 2001). This has the added benefit of protecting the surface finish of the surroundings. This relates to the general response of reducing human errors *[46, 47, 50, 53, 59, 61, 78, 80, 133, 135, 136]*, attributed to bringing the ignition source together with fuel. It was found that differences in companies, subcontractors and individuals may be large, especially with worldwide subcontracting and crewing. All yards had a formal system for people entering the yard for the first time, and those doing hot work were required to have formal training at 6-month- to 2-year intervals. The typical duration for a hot work and safety course was 4-8 hours, with some hands-on training of extinguishing. Multilingual signs and instructional videos were used. Human errors are controlled by safety procedures, such as hot work permit systems *[50]*. In Table 5.1, a comparison of hot work permits procedures at the yards is presented as an example. The term 'area' in the table refers to a logical room on-board, such as a restaurant.

Table 5.1 Hot work permit procedures of the yards. Yards are named H, I, J, K to emphasize that they are not linked to other yard- related data, for ensuring anonymity.

	Area covered	Duration	Place where written	Written by	When hot work permit system is started	Number of people who can write a permit	Average number of hot work permits written per day	Average number of firemen on board
Yard H	One area	Work duration,max 1 day	On site, the actual hot work location	Fireman	Depends on progress, Fire chief decides together with area foreman, based on the risk assessment and firemen´s opinion. Fire chief has the final word.	8	50	6
Yard I	Whole ship	Max. one week	Central office outboard	Hot work coordinator	Collaboration of safety manager, firechief	6	40	12
Yard J	One area	Work duration,max 1 day	On site, the actual hot work location	Area production coordinator	Depends on progress, Production coordinator decides	about 20	200	5 -6 fire guards , 1 fireman
Yard K	One area	Work duration,max 3 days	Central office outboard	Safety manager, Fire chief and safety team	Collaboration of safety manager, firechief and production coord.	4- 5	25	Before drydock, 4 fire guards on the ship, 2 firemen outboard. After drydock: 1fire guard per deck max., 4- 5 firemen onboard ship

The location of writing the hot work permit and its duration were the most significant differences in procedures between the yards. Optimally, an experienced person should write a permit for each hot work task at the actual location and thus have a chance to view the surroundings and rectify safety problems that otherwise might go unnoticed. Vigilance is needed during hot work but also after it: work should be stopped 1-2 hours before employees leave the vessel so that they can detect smouldering fires.

Further response details that were found to help in separating heat source and fuel can be listed as follows:

- Protected workshops inside the vessel
- Fibreglass shields
- Spark scoops for collecting sparks on the opposite side of a bulkhead or deck
- Hot work permit and protection blanket go together

Many fires that hot work caused were started unnoticed by the person performing the work as heat was conducted through steel members to flammable materials in neighbouring compartments. There are few practical ways to prevent this except housekeeping and guarding the adjacent spaces. However, fire guarding *[138]* can be used not only to detect fire outbreaks, but also to educate people on-board on hot work practices, other heat sources and fuels. For example, at one of the yards, the insurance company required that each part of the ship be patrolled every 2 hours, and in special areas every 30 minutes during evening hours. This resulted in the employment of about 20 fire guards per vessel, working in shifts with about five men aboard at a time.

In addition to hot work, the study revealed important responses for other heat sources as well. Malfunctions in electrical equipment can cause hidden fires, which are particularly dangerous. When the reasons for electrical fires in the statistics were investigated in more detail, it became evident that many of them could have been avoided by systematic maintenance *[11, 17, 41, 66, 67, 68],* similarly to practices in other industries (e.g. Petersen & Paulsen 1991). To reduce the chance of equipment malfunctioning, prohibiting automatic electric devices *[14]* that are not necessary on-board, such as coffeemakers, was usual at the yards. Vigilance in monitoring was recommended for recently commissioned electrical components, such as transformators as untested equipment may have increased the incidence of fires. Regarding reactions of incompatible chemicals or mixing ratios, available responses are to prohibit reactive chemicals on-board *[7, 23]* as far as practicable, and maintain a comprehensive database of incompatible materials.

Further, heating of the vessel is necessary in northern climates: electrical and gas heaters can cause excess heat. Safety devices *[42]*, central heating outside the vessel and covered docks were available responses. Heat from hot pipes during dock trials have similar qualities, and can be monitored by infrared cameras *[13]*, and the risk reduced through insulation *[44]*. Further, arson and tobacco smoking are significant causes of fires in the world, but in the past have not been major contributors to fires at shipyards. Further, the current requirements on cigarettes state that they should be self-extinguishing, which also reduces the ignition risk. Thus the responses by shipyards to security and smoking prohibition seem to suffice. However, arson is a potential source of escalated fires, and responses through guarding *[138]* and personnel screening are particularly important.

5.1.2 Fuel

The other ingredient of fires, the fuel, also offers possibilities for responses. In general, ships must be built of approved non-flammable materials, governed by the rules and regulations of International Maritime Organization, classification societies and flag states (International Maritime Organization 2001a). The rules are a result of the extensive experience of the industry with fire-fighting on-board, and give relatively good protection against ignition. As stated earlier (sub-chapter 4.1.4), the fire incident records of the participant shipyards showed that the most frequent items of fuel were temporary packaging materials and flammable liquids. In this view, the amount of unpacked installation material stored on-board, the efficiency of waste removal *[Response numbers 4, 25, 27, 35, 40, 72 in Table 5.5 to Table 5.7]*, the flammability qualities of the materials used for packaging and temporary protection *[31]*, and the handling procedures for paint, glues and solvents *[26, 34]* are important. The temporary fire load was found to consist of building- time material such as protective plastic, packaging, scaffolding, tools and waste on-board, and was dependent on the actions of the people working in the building process, as well as of the ship type. Vessels with a small amount of outfitting are less vulnerable. The maintaining of cleanliness *[27]*, purchasing of goods in non-flammable packaging *[31]* (Moisio 2003a), yard quality systems and workflow issues such as reducing the amount of storage of installation material *[32]* on-board determine the general conditions of work on-board. The yards used contractual pressure on sub-contractors *[31]* on safety cultural issues, especially work procedures and cleanliness. An extraordinary risk of rapidly spreading fire stems from gas leaks on-board. Responses of gas monitoring and shut-down procedures and devices *[20, 30]* can be used.

The control of the amount and distribution of fire load on-board a ship under construction may be seen mainly as a project management, work process design, ship design, purchasing, logistics and human behaviour issue. In broad terms, the first five items seem to determine the minimum possible amount of fire load at a given time, and the behaviour of individual employees any excesses to the minimum fire load. The project management of the ship construction, both on the owner and yard side, had a fundamental effect on the amount of fuel on-board. Local and timely fire load management is needed. An example is shown in Figure 5.1. Note that the yard is not the same as in Figure 4.3 and in Figure 4.4. The fire load was found to vary considerably during the week. The low amount of fire load at this yard on Thursdays coincided with their weekly area teams' cleanliness surveys. The large amount of fire load on weekends was probably due to the practice of loading a lot of installation material on Friday so that work could start promptly on Monday.

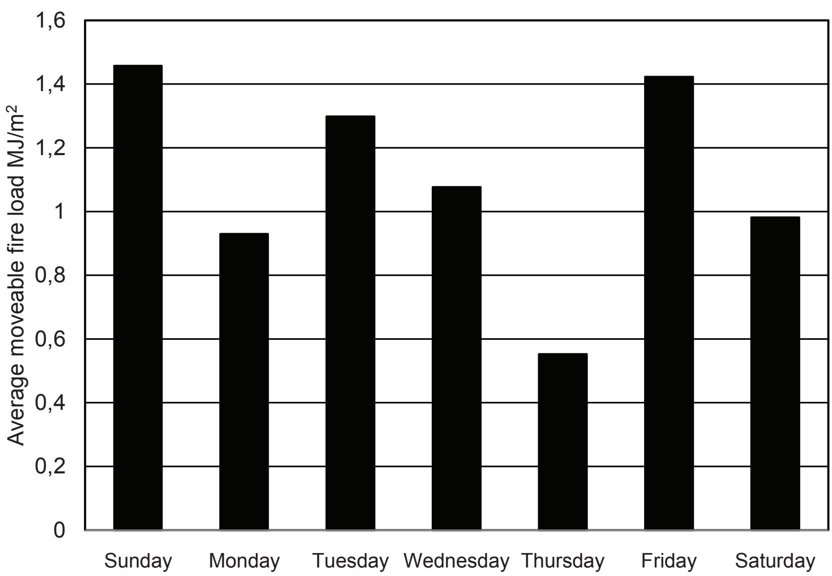

Figure 5.1 Average moveable fire load on days of the week in the fire guard surveys of one of the yards (Räisänen 2003d, unpublished)

This kind of knowledge in the temporal variation of fire load helps the yards in planning the responses. The incident statistics of each yard and the actual fire load *[40]* could be studied in more detail in future.

Of the fuels, packaging of inner ceiling panels was found to be a particular problem, because often all the packages had to be opened simultaneously to find all the parts, and much of the packaging was flammable. If the packages were properly filled and marked, they could be opened one at a time resulting in less waste exposed to heat. The size of parts and storage facilities on quays also plays a part. For example, in restaurant construction, larger modules may require sturdier packaging, and open quays and bad weather affect the amount of weatherproofing (typically shrink-wrap or similar) needed for the packages. In waste removal, a goal of one-day turnaround was found to be a suitable target. This kind of response could be achieved, for example, by organising cleaning during the night so that unused crane capacity could be used, or arranging sufficient lift-off- or roll-off points on each deck. If there are waste collection areas on-board, they should receive special attention in ignition protection. Some possibilities for reducing the amount of waste on-board were found: 5-10 waste chutes per side of vessel, and removal of packing material before the goods arrive on-board *[36]*. Flammable gases are typically distributed on-board via temporary pipes and hoses. Flammable liquids are transported on-board in containers (paint, glue, solvents) or filled directly into the ship's tanks. Hazardous situations on-board often involve leaks during outfitting work and sparks from static electricity or electrical equipment. Temporary flame cutting gas distribution systems as a source of fuel and oxygen should also be scrutinised. Preventive maintenance was found to be important. Gas leaks of acetylene and oxygen may produce explosive fire starts. Finding leaks during the nights may be challenging as lines are typically closed down for the night and during the day observation is difficult. Leakages of inert gases (Argon, CO_2) and air should also be attended to, as hissing could mask the more dangerous leaks. In addition, inert gas leaks may cause suffocation by filling closed spaces. Controlling the amount and handling of hazardous gases and liquids is the first step; and alternative joining (e.g. less hazardous glues) and cutting methods (e.g. using sawing instead acetylene cutting) are an important research topic. For flammable liquids in containers, a ventilated, preferably removable storage with a fire alarm and a CO_2 extinguishing system is a good solution.

When the ship is nearing completion, new sources of ignition may emerge. During launching and sea trials, the form of the vessel may change and cause stresses in pipelines, for example, causing leakage of flammable liquids. Consequently, extraordinary preparations for fire risk should be in place when machinery and sea trials begin. The owner's own equipment deliveries and their installation work provide additional fuels and hot work. This typically occurs late in the building process, and increases the fire risk in critical time near delivery.

5.2 Responses to established fires

As summarised in sub-chapter 4.4, the shipyards prepared mainly for three types of consequences of established fires: human damage in fire, direct material damage in fire and secondary damage. For established fires, the focus at the yards was on human damage, the spread of fires and smoke and heat damage. Their main responses to these related to fire detection, alarming and suppression, closing of openings in fire barriers and evacuation. Also, the size of an escalated fire is related to total fire load, and fuel control, which was discussed earlier in relation to ignition, was thus found to be equally important for the later stages of fire, but the discussion is not repeated here.

5.2.1 Alarm, detection and extinguishing

For fire detection and alarming, cruise ships that were studied were equipped with temporary systems most of the building time. Importantly, the people working on-board provided important detection and first extinguishing *[Response numbers 89, 105, 113 in Table 5.5 to Table 5.7]* attack capacity (but, on the other hand, many ignitions were due to human error). For the hours when the workforce is not on-board, fire guarding and detection and alarm systems *[93, 101, 104, 124, 138]* were found necessary, especially for fires that may have been left smouldering by the previous shift or initiated by faulty unattended machinery. A good fire detection system has several hundred automatic sensors and a push-button alarm system with location information, connected to a quayside office. The detectors should be programmable, so that they can be turned off during periods when there is smoke due to work. It was found that temporary systems should be replaced as early as possible with the ship's own systems, which typically have a better coverage. The automatic detectors were connected to a central alarm on the quay or on the bridge of the vessel. The problem of the automatic system is false alarms due to smoke and dust from legitimate hot work. This can be overcome by switching the relevant detectors off during hot work.

For fire extinguishing, all yards had portable extinguishers *[109, 113]* on-board. As the personnel on-board extinguish the majority of fire incidents before any further escalation, the training in extinguishing are important. In addition, backpack-type water mist equipment can be used. This may be faster to deploy than hoses but, on the other hand, lacks the cooling capacity of large water volumes. The fire brigades of the shipyard and local municipality *[114, 117, 123]* play a major role if a fire escalates. There is a need for regular training for special circumstances on-board, as the ship corridors can be obstructed by a lot of temporary materials, hoses and cabling. All yards had a tested system of operation with outside rescuer services. As fast response is needed to prevent the escalation of fire, all yards had their own first response teams in constant readiness. For suppression of escalated fires, temporary fire main lines *[121, 122]* were built in each vessel. The pressure and volume capacity needed to extinguish water flow was dependent on vessel size and the height of the uppermost deck. The yards had tested capacity for providing 10-12 intervention teams with water. Similar requirements for operating vessels can be used for comparison. For example, to fulfil the SOLAS regulations, the Voyager-class ships built in Turku have three pumps of 260 m^3/h capacity at 11 bars (1100 kN/m^2) (Kvaerner Masa-Yards 2000), which allow the water to be delivered at a minimum pressure of 4 bars at all hydrants (SOLAS Chapter II-2, Part A, Reg. 4, paragraphs 2.2.1 and 4.2.1). As water volumes can be large, the yards had teams capable of operating ship systems, such as watertight doors and ballasting, as well as for monitoring ship stability during fire-fighting. However, with the small number of large fires observed, the yards' true effectiveness in suppression remains open for further studies.

In public buildings and industrial facilities, automatic extinguishing systems *[1, 108, 115, 116, 119, 120]* are widely used for protection, and are undoubtedly a valuable method to limit fire losses. Taking into account the possible great speed of escalation of fires in ships due to readily flammable waste, it was found that these systems could be very valuable. For practical reasons such as cost and scheduling, temporary systems were not in widespread use at the shipyards. Some yards used automatic suppression for special purposes, such as temporary CO_2 systems for paint stores *[108]*. Using the ships' permanent CO_2 extinguishing systems in the engine rooms also during construction could be considered *[115, 119]*. The systems suppress the fire by suffocation, and cannot be released before all people have been evacuated. Accidents to people have occurred due to accidental releases and therefore use was avoided at the yards. The ship's main protection system, the automatic water sprinkler equipment became operational rather late, typically close to sea trials. The difficulties in early commissioning of the ships' own systems were found to be mainly related to building process arrangements. Also, building-time damage, such as freezing of piping or malicious releases might occur.

However, from the research material it was concluded that active automatic extinguishing systems would be very effective for the shipyards against their typical fires. For this, some redesign was needed for the building process of many of the participating yards: the practicality of early commissioning of suppression systems depended on the building method. As an example, if the ships were built according to fire zones, the systems could be partially commissioned and the switch from manual to automatic done at the alarm centre at the yard. As ignitions on-board are difficult to eliminate completely, reducing the probability of escalation by suppression is very important. During the research interactions, the shipyards acknowledged that sprinkler systems have the capability to reduce the risk of large fire losses dramatically, and that they should be available in cruise vessel construction as early as possible in the building process, typically 6-8 months earlier than before. *According to preliminary calculations (subchapter 3.3.7.6), this can be expected to reduce the probability of a large fire loss by an order of magnitude in the protected compartments.*

5.2.2 Confinement of fire

Confinement of fire on-board was important for the shipyards, in particular for providing safe escape routes for personnel and for preventing fire escalation, but also for preventing material damages. Often the actual damage by the flames in fires on-board was small compared to the harm done by the smoke that spread to adjacent fire compartments: even a small amount of smoke in a room causes discoloration of surfaces, smell and soot. Often this leads to excessive cleaning operations or replacement of affected material. For example, polished stainless steel structures in galleys may need to be replaced on account of minor surface defects due to soot or suppression effects. To confine fires in ships, fire-insulated steel decks and bulkheads are commonly used. These barriers have openings such as fire doors, hatches and fireproof penetrations of ducts, pipes and cables. Their construction differs depending on the degree of protection, see Appendix B.

Many of the seemingly minor details in structures and personnel behaviour determine their effectiveness.

Many fire barriers were not fireproof in the early phases of the building process due to openings, and responding to fire risk by using temporary closing arrangements *[Response numbers 85, 88, 90, 91, 92, 95, 96, 106 in Table 5.5 to Table 5.7]* was found to be important. Vertical shafts and openings in decks are especially dangerous as they may provide chimney-like effects, increasing fires. Further, unfinished cable penetrations may provide routes for fire to spread along burning cable insulation, unless openings are closed temporarily. Typical problems that were observed at the yards were that the sealing of the penetrations was not finished or closing devices were not installed. Also, it happened that protection was taken out of operation by people on-board, because they were perceived to hinder installation work. Fire doors are important in confinement, and early installation of fire doors *[88]* could be arranged by adjusting the building process. One of the yards especially strove to install them simultaneously with structural steel. The other yards tended to install them later in the outfitting stage and meanwhile used less efficient temporary draught stop doors. The actual closing of fire doors *[95]* and closable opening covers was found to be difficult in practice and required both design process refinements and supervisory efforts. The doors should be closable by design, even when hoses and cables are drawn through door openings (a ‘cat flap’ in the corner). Otherwise the doors may end up being wedged open, even though correct use of fire doors is known to be important. For effective compartmentalisation of the vessel, the personnel attitude towards the closing of doors was found to be important. Locking of cabin doors *[96]* is beneficial, for example for limiting ignition positions, minimising fire load and smoke damages and for clear escape routes.

From past experience, the shipyards were aware that fires can spread very rapidly vertically, not only through openings, but also by conduction of heat to upper decks if fire insulation of steel deck is not finished. Early installation of the fire insulation *[44, 107, 129]* can reduce the risk. This also reduces the danger of collapses of structures in fires, although this was not considered to be problematic. A fire that has increased to a magnitude where the collapsing of structures occurs has already caused such large damage that the structures must be replaced anyway. Also from a personnel evacuation point of view, this is rarely significant: for survival, people must remove themselves from the heat long before structural collapses start to occur. For limiting the spread of a fire during fire-fighting operations, the cooling of steel structures that may conduct heat to adjacent spaces is probably necessary for large fires. For this, fire fighters need to gain sufficient access to allow water spraying. Good housekeeping *[4, 25, 27, 35, 40, 72]* in the vessel is essential at all times, as in the reduced visibility of smoke-diving, even small obstructions may hinder the operation. In extinguishing, excess water can capsize the vessel. All the yards had arrangements for the stability calculations to be carried out: the amount of suppression water may have to be limited to prevent capsize *[130, 131]*.

Temporary smoke ventilation systems were not used by the yards during the study, and their feasibility as responses could not be judged. Assessment by simulations could be a possibility for evaluation but effects of sprinkler extinguishing, flows of gases and temporary escape routes complicate the matter, which remains an interesting research topic for future.

5.2.3 Evacuation

It was observed that the shipyards' priorities in preparations for established fires were in protecting people, not property, and their strategy was to move the people off the ship and then to guard as large a part of the ship as possible from smoke and extinguishing water damage. This may seem straightforward but in practice is not so easy to accomplish, as the environment is challenging. Escape routes may be dark, long, and have obstructions. Visibility may also be poor due to smoke. Especially plastics, such as refrigeration insulation of pipes, cause a lot of black smoke, which makes evacuation particularly difficult. For evacuation, people first have to be alerted about the emergency, and then be provided with safe routes with enough capacity to a safe destination. These are discussed below.

For alerting the people on-board *[89, 93]*, fire alarm push buttons, fire telephones, sirens, VHF radio systems and mobile phones were used at the yards. Warning lights were also used in some spaces. The private mobile phones of people working on-board are not however, operable throughout the vessel, due to interference by the ship's steel structures. Also, multiple alarms and communication jamming at the public alarm centre may result, as several people report the same incident. The ordinary local push-button or field telephone alarm went to yard fire brigade quarters or the main gate alarm centre, which alerted fire guards, intervention teams or the yards' and public fire brigades, depending on the situation. The systems were not all-inclusive: there were areas on-board where an alarm may be overlooked, for example because personal protection was used in plate-fitting operations. Making all persons on-board a vessel under construction aware of a fire alarm was a challenge. Tested alarm systems, colleagues and supervisors were the most important safeguards. Warning the personnel in the bow and stern of the vessel may be more difficult than in other parts of it: the vessel's own alarm and detection systems may not yet be completed, and fewer escaping colleagues pass by than nearer to the exits. There were differences in the alerting and evacuation philosophies of the yards, which seemed to be related to the number of false alarms. Evacuation was started either directly at alarm or, if there were a lot of false alarms, after confirmation by fire guards on-board. The fastest evacuation times were obtained when the workforce was instructed to start evacuation as soon as the alarm signals reached them. When the vessel is nearing completion, the ship's own access control, public addressing and alarm systems *[93]* become operational, which reduced risk.

The size and positioning of the permanent escape routes in an operating vessel are determined by SOLAS regulations (International Maritime Organization 2001, Ch. II-2, Reg. 28, for the ships, which were studied). All fire compartments must have at least two possibilities for exit, and their dimensioning is based on the amount of people expected to be passing through. These escape routes are also used in the vessel under construction. In addition, some temporary doors in the side shell are usually available. Often, the theoretical escape route capacity *[90]* for ship operation is sufficient for people working on-board. However, it was found that the maximum capacity of escape routes was too often severely limited by obstructions such as waste, cabling, hoses and stored installation material. The actual operability of the fire doors *[90, 95]* is critical and all details need attention. For example, fire door handles may have needed temporary removal due to protection of their final finish, and temporary handles were missing, or heavy items may have been piled nearby so that the full opening of the doors was hindered. Signage and temporary emergency lighting *[84]* of the escape routes are also important for safe exit. During fire, shore power may be lost and visibility diminished by smoke, so installing and maintaining lighting and signs are important. The supervisors' duty is to account for their personnel, and gather them in a safe area outside the vessel for a head count. Typically at the yards, the safe destination was a designated collection area on the quay outside the vessel or a building hall.

A practical possibility for a shipyard for limiting the number of people onboard is moving work to workshops, which provides research topics for future. In workshops, in general, permanent fire risk management measures can be accomplished better and escape routes can be made shorter than on-board. This has also been the trend for production effectiveness reasons. From the viewpoint of limiting the number of people on-board at a time, shift-work is effective.

5.3 Production process arrangements as responses to fire risk

As discussed in earlier sub-chapters, practical responses to ignition and established fires were found to be simple in theory but difficult to accomplish in the turbulent environment of cruise vessel construction. Some responses were found that relate to project management and shipyard processes. For project processes, including fire safety in contracts *[134]* (analogously to practices of offshore business), revising production process to minimise design changes and early adoption of ships safety systems *[111, 112, 126, 135]* were found to be useful. Ships can be designed according to advanced alternative design criteria for fire safety, which promotes spectacular designs such as atriums, but also provides room for alternative responses such as smoke control through glass roof panels. These are good topics of further project management and safety research.

It also became clear that shipyard management plays an important role in general response arrangements for safety: the fire safety training of personnel, organising the yard's risk management, organising safety personnel, promoting safety attitudes, and safety communication for the yard and its suppliers *[133, 135, 136]*. The shipyard departmental and project managers also have responsibility for the practical response arrangements on-board, such as arrangement of fire guard systems, fire safety audits, constantly manned central control stations and surveillance of hazardous behaviour *[137, 138, 139, 140, 141]*. Many of the above topics fall in the category of constant improvement topics at the yards, and great improvements became obvious already during the action cycles.

5.4 Experts' assessments of responses and their feasibility for the shipyards

It was fortunate for the research and for the improvements at the shipyards that many of the managers stayed at the yards throughout the period from the first actions to the writing of this study, and were willing to offer their time on the subject. Of them, the researcher formed an expert panel of eleven key stakeholders that provided ranking of the size of fire risk (subchapters 3.3.6 and 4.3). In addition, they ranked the available responses. The survey was carried out in 2011, and at that time the fire incident statistics had grown to more than 1,100 incidents at the participating yards. Naturally, this access added perspective to the experts' estimates. They rated the responses on a scale of 1 - 3 (3 = high effectiveness, and 3 = easy to implement) both on effectiveness in mitigation and on feasibility of responses for use at the shipyards, taking into account things such as suitability for the shipyard's process, budget constraints and the behaviour of the available workforce. The complete list of ranked responses is presented in Appendix H. These provide insight into selecting responses at a shipyard that supported the other findings of this study. It is noticeable that feasibility at the yards varied considerably, as can be seen in the third column of the tables.

From the ranking of all responses, two interesting subsets were derived, which are discussed in the following. The first one is a subset of 21 responses, which according to experts had high potential to mitigate the risk (Table 5.2 and Table 5.3). The findings were in line with the evidence from other sources. Firstly, the focus of ignition prevention was in fuel control through good house-keeping, management of gas distribution, flammable chemicals and installation materials, as well as through protection. For ignition energy, the reduction of the amount of hot work by design and work methods was seen as important. Secondly, for established fires, the focus of the experts was in the traditional responses of alarming, detection, public announcement and extinguishing, keeping fire doors closed and evacuation procedures. The findings supported the other evidence on the importance of hot work and fuel control, extinguishing, confinement of fire and evacuation.

Table 5.2 Eleven experts' estimate on the responses with the highest potential on scale 1 - 3 (3 = high) to mitigate the risks. The numbers of responses [27, 29, 32, etc.] refer to Table 5.5 to Table 5.7. The complete survey results are shown in Appendix H.

Factors which contribute to ignition	No.	Available responses	Expert estimate on potential of the response to mitigate the risk	Expert estimate on suitablility of the response to shipyard process and ease of implementation
Fire load	27	Good house-keeping, especially waste logistics, and near heat sources	3,0	2,4
	29	Maintenance of gas distribution systems	3,0	2,5
	32	Restricted storage of installation materials onboard	3,0	2,4
	39	Use of temporary flameproofed coverings over materials	3,0	2,6
Hot work (welding, cutting, grinding, torching)	58	Reduction of amount of hot work by design	3,0	1,9
	60	Systematic maintenance of gas systems	3,0	2,6
	62	Use of non-sparking tools near flammable materials	3,0	2,0
	63	Use of protective coverings	3,0	2,4
	64	Using alternative methods instead of hot work	3,0	1,9
Painting	72	Good housekeeping with solvents and waste	3,0	2,4
	73	Precautions for hot work, cleanliness, ventilation and chemical reactions	3,0	2,4
Sea trials	77	Tested fire alarm, detection, public announcement and extinguishing systems	3,0	2,8

Table 5.3 Eleven experts' estimate on the responses with the highest potential on scale 1 - 3 (3 = high) to mitigate the risks. The numbers of responses [89, 93, 95, etc.] refer to Table 5.5 to Table 5.7. The complete survey results are shown in Appendix H.

Consequences of established fires	No.	Available responses	Expert estimate on potential of the response to mitigate the risk	Expert estimate on suitablility of the response to shipyard process and ease of implementation
Human damages in fire	89	Early manual detection, alarming and suppression	3,0	2,4
	93	Functional temporary and permanent fire detection, alarming and public announcing systems	3,0	2,3
	95	Keeping fire doors always closed	3,0	2,3
	98	Practiced evacuation procedures	3,0	2,7
	102	Sufficient extinguishing capacity	3,0	2,4
	104	Use of automatic detection and extinguishing systems	3,0	2,1
Direct material damages in fire	113	Fast responses with portable extinguishers	3,0	2,6
	115	Fixed suppression systems in machinery spaces	3,0	2,0
	116	Functional fire suppression, both temporary and ship's own system, preferably automatic	3,0	2,4

A second interesting subset of experts' ranking was formed of those responses that according to experts would be efficient but difficult to implement (Table 5.4). The responses relate to fire load, hot work, closing of vertical ducts and protection of cabins. The other empirical evidence of this study supports their views. From the fire escalation point of view, preventing chimney-like flows of combustion gases would be especially important in preventing fire escalation and damage from the spreading of smoke.

Table 5.4 Eleven experts' estimate on the responses with a relatively high potential to mitigate the risks but most difficulty in implementation, on scale 1 - 3 (3 = high, and easy to implement) The numbers of responses [26, 58, 64, etc.] refer to Table 5.5 to Table 5.7. The complete survey results are shown in Appendix H.

Factors which contribute to ignition/ Consequences of established fires	No.	Available responses	Expert estimate on potential of the response to mitigate the risk	Expert estimate on suitablility of the response to shipyard process and ease of implementation
Fire load	26	Avoiding highly flammable solvents for cleaning and gluing	2,6	1,9
Hot work (welding, cutting, grinding, torching)	58	Reduction of amount of hot work by design	3,0	1,9
	64	Using alternative methods instead of hot work	3,0	1,9
Human damages in fire	106	Temporary closing of vertical ducts during building process, especially cable ducts	2,9	1,7
Direct material damages in fire	120	Sufficient fire detection, alarming and suppression capability in cabins immediately after installation	2,9	1,6

5.5 Summary of the findings

General fire safety and shipbuilding literature provided a view of the contributing factors of ignition, the consequences of fires, and responses, which were summarised in Table 2.1 of Chapter 2. Many similar factors were found in the development actions with the shipyards, and the key responses were discussed in earlier sub-chapters. The categories of 14 main contributing factors for ignitions and three main consequences of fires that were observed for fire risk were found to be applicable for their responses as well. All the 141 responses that were found and developed with the yards were added to the end of this chapter as Table 5.5 to Table 5.7. The tables form a support palette for the managers, from which they can search for response alternatives that are compatible with their local circumstances and budgets. It is noticeable that the extent and details of available responses overlap and vary considerably, which reflects the broadness and complexity of the risk. Anyhow, the set of responses was found to be relevant for cruise vessel shipbuilding. The responses in varied levels of detail were shared and developed at the yards through the research actions. Many of the responses were directly implemented at the yards. The related research question was:

4) What are available responses to fire risk in cruise vessel construction projects?

The most important responses were found to relate to fuel and heat sources of ignition; alarming, detection, extinguishing, confinement and evacuation in established fires, as well as production process arrangements. Hot work (welding, flame cutting and grinding) was found to be the most important contributor to fires in fire incident statistics that were built with the shipyards, and several responses are available for project managers. Reducing the amount of hot work by moving work to workshops and changing to non-hot work were found to be feasible. Alternatively, hot work could be carried out before fire load accumulates on board, or the amount of pre-outfitting type of construction, where the parts are prepared outside the vessel, could be increased. The fires due to hot work can be traced back to employees on-board, and reducing human errors by safety procedures, such as hot work permit systems and fire guarding were used. Heat from machinery on board was also found to cause fires, and systematic maintenance and prohibiting automatic electric devices were used as responses at the shipyards. Analyses of all usual ignition sources were carried out and responses recorded for them.

Similar analysis was carried out for fuels in the fire incident statistics, and waste removal, reducing the amount and flammability of packing materials, and handling procedures for gases, paint, glues and solvents were found to be suitable responses. Reducing the amount of stored installation material was found practical. Further, it was concluded that rapidly expanding fires are especially dangerous, and responses to gas leaks and flammable liquids were found to be crucial.

The people working on-board were important in detection and first extinguishing actions, but also fire guarding, as well as detection and alarm systems were found necessary. For extinguishing, the yards had portable extinguishers, temporary water mains, fire brigades and automatic sprinkler systems available, depending on the readiness of ships' own systems. It was found in the research that *commissioning of ships' own sprinklers very early in the building process could reduce the possibility of a large fire loss by an order of magnitude in the protected compartments,* which was a revolutionary finding, resulting in revised building processes at the yards.

Confinement of fire on-board was important for the shipyards to provide safe escape routes, for preventing fire escalation and for limiting material damage. Temporary closing arrangements for openings in fire barriers, as well as early installation of fire doors and fire insulation were found to be key responses. Again, the actions of personnel on-board in the actual closing of doors play a central role in safety. Keeping escape routes clear is crucial as visibility in fires is generally bad. An important finding was that evacuation times varied considerably, and that the fastest times were obtained when the workforce was instructed to start evacuation immediately at alarm.

Responses were also observed and developed for project management processes related to contracting, design changes and early adoption of ships safety systems. The shipyard management was observed to have an important role in organising the yard's fire safety and promoting safety culture. Departmental and project managers typically carried out response arrangements such as guarding, auditing and surveillance of hazardous behaviour. The detailed 141 responses are presented in Table 5.5, Table 5.6 and Table 5.7 on the following pages.

Table 5.5 Responses to cruise vessel construction fire risk (ignition- part), which emerged during the research (continued on the following pages). For clarity, some responses are mentioned only once, though they were applicable in several ways.

Factors which contribute to ignition	No.	Available responses
1) Arson	1	Automatic suppression
	2	Good lighting
	3	Guarding of premises, control of access to vessel
	4	Housekeeping to avoid flammable waste
	5	Restricted access to compartments
2) Autoignition	6	Avoiding autoignition of glues and plastic, ignition of incompatible chemicals
	7	Managing the use of incompatible chemicals used in the plant
3) Electric phenomena	8	Static electricity: proper grounding of vessel and its temporary and permanent parts, especially pipes
	9	Use of lightning conductors, earthing in general
4) Electric systems	10	Careful electricity off (blackout) testing
	11	Damage control of cabling
	12	Ensuring overheating protection in electric systems
	13	Overheating checks with IR equipment
	14	Prohibiting domestic appliances onboard, e.g. coffee-makers
	15	Proper installation of temporary electric systems
	16	Shutting down of electric appliances when not in use
	17	Systematic maintenance of electric appliances and cabling, e.g. motors, transformers and welding machines
	18	Use of explosion-proof appliances in hazardous areas
	19	Use of protected work lights instead of unprotected bulb lights

Table 5.5 Responses to cruise vessel construction fire risk (ignition- part), which emerged during the research (continued on the following pages). For clarity, some responses are mentioned only once, though they were applicable in several ways.

Factors which contribute to ignition	No.	Available responses
5) Explosions, dust, gas, and vapors	20	Avoiding gas leaks and dust accumulations
	21	Explosion-proof machinery
	22	Pressure relief structures
	23	Restricted storage on board for highly flammable materials
	24	Special cautions for explosives
6) Fire load	25	Avoiding accumulation of dust
	26	Avoiding highly flammable solvents for cleaning and gluing
	27	Good house-keeping, especially waste logistics, and near heat sources
	28	Installing emergency shutoff systems for liquids and gases in piping
	29	Maintenance of gas distribution systems
	30	Odorizing of gases to help in leak detection
	31	Requesting non-flammable packaging from suppliers
	32	Restricted storage of installation materials onboard
	33	Restricted use of flammable temporary materials onboard, e.g. scaffolding
	34	Storage of flammable liquids on outer decks in a protected container
	35	Use of trash chutes at sides of the ship
	36	Unpacking flammable packaging before materials are taken aboard
	37	Use of non-combustible construction materials, furniture and decorations
	38	Use of safety precautions with fuel oil or lubrication oil in connection with hot machinery
	39	Use of temporary flameproofed coverings over materials
	40	Utilizing statistics of yearly volumes, materials and densities of flammable waste in a shipyard

Table 5.5 Responses to cruise vessel construction fire risk (ignition- part), which emerged during the research (continued on the following pages). For clarity, some responses are mentioned only once, though they were applicable in several ways.

Factors which contribute to ignition	No.	Available responses
7) Heating and ventilation	41	Maintenance of blowers and heating systems
	42	Functional overheating protection in equipment
	43	Special caution for unattended heating systems
8) Hot surfaces and open flames	44	Thermal isolation of hot surfaces from fuels
	45	Avoiding work with open flames, protective procedures
9) Hot work (welding, cutting, grinding, torching)	46	Disconnecting gas and electricity of hot work tools when not in use
	47	Effective hot work procedures
	48	Fire watch system
	49	Gas leak detection by listening hissing at night, or before hot work
	50	Hot work permit system
	51	Hot work prohibited during holiday times
	52	Hot work transfer to workshops
	53	Hot work safety exam and personal hot work card
	54	Hot work supervision plan
	55	Measuring gas content in room before hot work
	56	Precautions during fuelling of ship systems
	57	Precautions for hot work in special circumstances, e.g. in tanks
	58	Reduction of amount of hot work by design
	59	Strict policy to unauthorized hot work
	60	Systematic maintenance of gas systems
	61	Training, own personnel and subcontractors, special courses for foreign workforce
	62	Use of non-sparking tools near flammable materials
	63	Use of protective coverings
	64	Using alternative methods instead of hot work

Table 5.5 Responses to cruise vessel construction fire risk (ignition- part), which emerged during the research (continued on the following pages). For clarity, some responses are mentioned only once, though they were applicable in several ways.

Factors which contribute to ignition	No.	Available responses
10) Machinery	65	Jacketing of high pressure oil lines
	66	Maintenance of flame or spark producing equipment
	67	Maintenance of rotating machinery
	68	Maintenance of sliding surfaces in machinery
	69	Risk management of combustion engines and compressors
	70	Safe location of compressors
	71	Systematic procedures for using motor vehicles on board
11) Painting	72	Good housekeeping with solvents and waste
	73	Precautions for hot work, cleanliness, ventilation and chemical reactions
	74	Proper earthing of substances
12) Sea trials	75	Proper engine operation
	76	Seaworthiness checks before sea trials
	77	Tested fire alarm, detection, public announcement and extinguishing systems
13) Smoking of tobacco	78	Education of fire safety
	79	Inspections
	80	Smoking restricted with designated smoking places
14) Miscellaneous	81	Avoiding ignition by shock and impact with material and tool choices
	82	Avoiding light energy (e.g. halogen) ignitions by education
	83	Avoiding sparks in lifting and moving operations

Table 5.6 Responses to cruise vessel construction fire risk (consequences-part), which emerged during the research (continued on the following page). For clarity, some responses are mentioned only once, though they were applicable in several ways.

Consequences of established fires	No.	Available responses
Human damages in fire	84	Adequate emergency lighting and signage
	85	Closing of temporary and permanent openings
	86	Counting systems for the personnel left on board after evacuation
	87	Control of access to vessel
	88	Early division of the ship into functional main vertical fire zones, and separation of rooms by structural and fire bulkheads and decks
	89	Early manual detection, alarming and suppression
	90	Escape and fire-fighting routes built early and kept functional
	91	Fire compartmentation
	92	Fire integrity of vertical casings, staircases and ventilation ducts built early
	93	Functional temporary and permanent fire detection, alarming and public announcing systems
	94	Installation of windows early in the production process
	95	Keeping fire doors always closed
	96	Locking of cabin and storage doors
	97	Possibly smoke and heat ventilation
	98	Practiced evacuation procedures
	99	Reviews of personnel risks and safety culture
	100	Safety training (general , other than fire safety)
	101	Smouldering fires left behind a workshift mitigated with fire watches or overlapping shifts
	102	Sufficient extinguishing capacity
	103	Sufficient safety personnel capacity
	104	Use of automatic detection and extinguishing systems
	105	Use of portable extinguishers by all employees
	106	Temporary closing of vertical ducts during building process, especially cable ducts
	107	Thermal isolation for structural stability in fires

Table 5.6 Responses to cruise vessel construction fire risk (consequences-part), which emerged during the research. For clarity, some responses are mentioned only once, though they were applicable in several ways.

Consequences of established fires	No.	Available responses
Direct material damages in fire	108	Automatic suppression in storage containers of flammable liquids and gases
	109	Availability of portable extinguishing systems close to work locations
	110	Avoiding smoke and water damages by fast suppression
	111	Avoiding structural collapse with material choices
	112	Early commissioning of onboard suppression systems
	113	Fast responses with portable extinguishers
	114	Fire brigades
	115	Fixed suppression systems in machinery spaces
	116	Functional fire suppression, both temporary and ship's own system, preferably automatic
	117	Good liaison with local fire brigade
	118	Isolation of conductive surfaces for structural stability built early
	119	Prevention of accidental CO_2-release in engine rooms
	120	Sufficient fire detection, alarming and suppression capability in cabins immediately after installation
	121	Sufficient fire pumps, hose connections, pressure and water supply for uppermost decks of the vessel
	122	Sufficient supply of pressurized water to premises
	123	Trained shipyard fire brigade available fast
	124	Use of temporary detection and alarming near waste bins
Secondary damages	125	Avoiding damages to environment by containment
	126	Avoiding delayed deliveries to customers by reserves in schedule
	127	Avoiding loss of information by backup
	128	Avoiding lost production by rapid suppression
	129	Isolation of conductive surfaces for structural stability and to prevent fire conduction to adjacent compartments
	130	Making pump capacity available for draining of suppression water to prevent vessel capsize
	131	Removing obstacles from drainage paths for extinguishing water to prevent capsize of vessel

Table 5.7 Responses to cruise vessel construction fire risk, which emerged during the research (shipyard arrangements). For clarity, some responses are mentioned only once, though they were applicable in several ways.

Shipyard arrangements for managing fire risk	No.	Available responses
General shipbuilding fire risk mitigation	132	Alternative ship design criteria for fire safety
	133	Fire safety training of personnel
	134	Including fire safety in contracts
	135	Organized risk management and safety personnel
	136	Safety attitude PR and communication for the yard and suppliers
	137	Systematic fire risk management program and safety plans
Arrangements onboard	138	Arrangement of fire guard systems and inspections
	139	Audits, surveys and inspections
	140	Constantly manned central control station
	141	Surveillance of hazardous behaviour onboard

6 Conclusion: Fire risk, its size and available responses for cruise vessel construction

When a cruise vessel is being built, most fires occur in the outfitting phase of the process. Typical length of this period is about 80 weeks, which ends when the ship is delivered to the customer. During this time, the ship is transformed from a collection of steel blocks to a magnificent floating palace. This requires a well-defined shipbuilding process, which links the massive amount of materials with the armies of workers needed for their installation. The fires can ignite when the materials, their packaging and the heat sources of the work processes meet suitably. Erroneous human actions are often involved. Most ignitions are suppressed locally with little damage, but occasionally they result in established fires, where large-scale suppression with fire-fighters is needed, and damage can be considerable. The typical flow of events is utterly simple, as sketched in Figure 6.1.

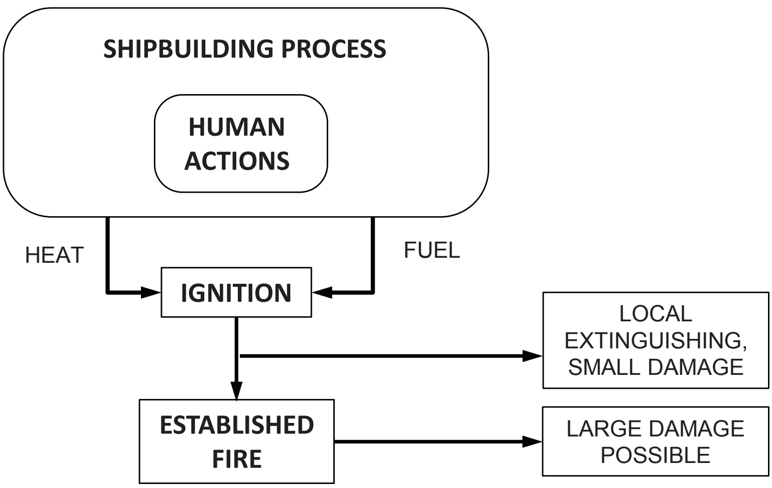

Figure 6.1 Typical flow of events in a cruise vessel fire incident

Beneath the simple flow of events lies a complicated problem of risk management in cruise vessel building industry which needed clarification. The purpose of the research was to identify and describe the project fire risk, to assess its size, and to explicate responses. The research setting reflected the traditional risk management process, and specifically the operational management point of view. The conclusions are summarized in the following.

The first research question

1) What is fire risk in cruise vessel construction projects?

relates to identification of the risk. It was studied during three years in close co-operation with four shipbuilding companies, which not only provided the research material but also many of the results. The view of risk that was obtained was rather uniform and independent of the research methods used, and the multiple sets of information. The risk was addressed as a threat, in two parts: ignition and established fires, which require different types of risk management. For ignition, risk management results mostly in removing the causes, and for established fires, it is directed to limiting consequences.

The fire risk can thus partially be described with factors that contribute to ignitions. These were observed in particular with the extensive statistics of 221 on-board fires and their incident histories. The factors were triangulated with participant estimates, joint best practices, internal materials of the yards, risk management surveys, questionnaires and seven miscellaneous methods. Based on the research, it can be said with confidence that most of the ignitions at the cruise vessel shipyards occurred because of operator errors in performing hot work in the vicinity of flammable materials (about 80% of the ignitions in the statistics). The causes of operator errors are similar to any human errors. However, in many cases shipyard work arrangements contributed. For example, in ship design, architectural changes may result in changes in steel structures or piping routes that are already built on-board, increasing the amount of hot work near flammable materials. Organisational features that affect operator errors such as training, motivation and supervision were also found to be important for the ignitions.

Another significant heat source in the statistics was electricity (12% of the incidents). Electric devices that run unobserved particularly increase the risk of large fires as an ignition may lead to an established fire until noticed. There were large differences between shipyards, 0% to 25% of the incidents, which indicated that the best shipyard's procedures could be used for improvements. Such findings during the research actions often further spurred the development at the yards.

The fuels for ignitions at the shipyards varied more than the heat sources. Most common was flammable waste, such as plastic wrapping and wood, which contributed in about half of the cases. The percentages of the yards varied from 30% to 79% of the ignitions. The data correlated clearly with observed on-board cleanliness, providing good benchmarking possibilities. Gases (average 7%) as well as chemicals and paints (12%) were found to be particularly dangerous as their high calorific value and possibility of explosive fire starts can easily lead to established fires. Further, the installed and stored ship materials were found to be important. They amounted on average to 20% of the incidents.

The contributing factors of ignition that were found from statistics were found to match well with the qualitative sets of information and also with fire risk management literature. Further, it was found that they could be divided into 14 categories, also consistent with findings from literature:

1. Arson
2. Auto-ignition
3. Electric phenomena
4. Electric systems
5. Explosions, dust, gas and vapours
6. Fire load
7. Heating and ventilation
8. Hot surfaces and open flames
9. Hot work (welding, cutting, grinding, torching)
10. Machinery
11. Painting
12. Sea trials
13. Smoking of tobacco
14. Miscellaneous

The categories were particularly useful for classifying the quantitative and qualitative data but also in the development of the responses later during the action cycles. Among the 221 fire incidents, not all categories were represented. For example, arson, which can cause large fires, was only suspected in one incident, but is more common in other industries. However, in qualitative data, all categories were well represented, and responses were prepared for all.

The other part of fire risk is the consequences of established fires. They were studied mostly qualitatively. According to the literature and empirical information obtained at the yards, the consequences were divided in three categories:

1. Human damage in fire
2. Direct material damage in fire
3. Secondary damage

All the shipyards focused on preventing injury of persons and material damages, and used the same simple strategy: they assumed that all fires can escalate and need to be addressed, and did no further analyses on possible extent of damages. The research findings support this strategy, as the amount of fire load needed to get a large fire started is very small in suitable circumstances, and sufficient amounts of fire load were observed during the last 80 weeks of production in all fire guard surveys. For ignitions, the initial flammability of the material, rather than its calorific value was found to be important. But regarding the consequences total fire load dominates. If a fire escalates out of control, everything burnable will ultimately ignite: also many fire-classified materials, including aluminium, will burn at sufficient temperatures. Further, many shipbuilding materials emit toxic and acid smoke, which again increases the consequences. In summary, it was found reasonable to state that the possible consequence of an on-board fire is hundreds of casualties on-board, and the value of the vessel, or more. During the research actions, no deaths were reported in fires. The largest material losses during the actions occurred in a fire at a yard that did not participate in the research. There, alleged losses of over USD 300 million were reported, as the whole superstructure of a 290 m-long (about 120,000 GT), half-completed cruise vessel was destroyed (Figure 4.13 on p. 106).

For selecting the suitable response alternatives, the frequency of occurrence, causes and consequences can be used to assess the size of the risk. In this study, it was approached with two research questions:

2) How can fire risk be assessed in cruise vessel construction projects?

and further

3) What is the size of fire risk in cruise vessel construction projects?

Large shipbuilding projects provide a multitude of options for assessing fire risk, and in this study the focus was set on the issues that were found to be important in the statistics, the case histories and the participant estimates. The unusual setting of competing companies in co-operation, a large amount of data and the possibility of having whole organisations making improvements during the action cycles enabled rapid development of assessment methods. It was mostly based on finding metrics that could be obtained as a by-product of normal shipyard operation, rather than generating new risk measurement tasks. This pragmatic approach was one of the reasons why they could be introduced so promptly, tested in practice and modified if necessary. Further, the metrics were used to initiate new responses and corrective actions in shipyards processes. For example, when the hot work metrics showed a lot of improper work execution on-board, instant improvement campaigns and changes in permit procedures resulted, and the situation improved in a month. Naturally, there were differences between the shipyards and not all methods were adopted by all yards. The adoption of a certain metric seemed to depend much on managers' skills in selling them to the line and project organisations, but also in the ease of obtaining and processing the data.

For assessment of fire risk, it was found that full probabilistic analyses, such as those used in the chemical and nuclear industries, were not feasible in shipbuilding due to a changeable project environment and high cost. A flexible generic expression was developed instead. It describes risk size as an unknown function of observed frequencies, contributing factors of ignition and consequences:

$$Risk\ size = f(observed\ frequencies\ of\ fires, contr.\ factors\ of\ ignition, consequences).$$

The terms in the above relation reflect the mixed quantitative-qualitative nature of the input. Each term was assessed separately of each other, with several sets of metrics. This produced a palette of metrics for key factors of ignition, and for managing the consequences of fires. Some of its features are discussed below.

For observed frequencies, a standardised method of normalising the frequencies of occurrences of fires was developed by the researcher, and taken into use by the participant yards. The statistics and case histories gave an unusually exact view of a risk in an industry, as the industry coverage was very good.

For contributing factors, heat sources and flammable materials were found to be the key issues, and metrics were selected accordingly. It was found that the most varied assessment was needed for consequences and their limitation because there were many alternatives. In summary, 27 metrics were developed. They were listed in sub-chapter 4.2.3., starting on p. 124.

Naturally, the list of metrics is not exhaustive, but was found to be compatible with the needs of the shipyards at the time, and addressed most of the key issues. With such metrics, many of the factors that contribute to fire risk in a project at a given moment can be evaluated by the area (such as a restaurant) building supervisors, the shipyard safety managers and the ship project managers, and the necessary responses can be carried out. Further, all of the shipyards have continuously manned safety command centres, which could monitor the relevant metrics (for example heat sources, waste, fire doors and evacuation, i.e. nos. 3, 4, 5, 6, 15, 18 and 24 in the summary list starting on p. 124) in real time.

As a summary, it can be said that at the time of the actions, the size of fire risk in cruise vessels construction was significant. It was observed that, in a typical cruise vessel project of approximately 100,000 GT in size, 1-2 fire incidents occurred on average every five weeks of building time, during the last 80 weeks before delivery. A typical fire incident at the shipyards was related to the interaction of human error, the need for hot work and the presence of flammable waste (often packaging or protective covering material) or flammable liquids. It was found that, in roughly four fire incidents out of five, at least one of these factors was involved. The statistics and the fire incident histories showed that most of the fires were suppressed early by the people on-board with portable extinguishers, and that roughly one large fire occurred for each 100-200 fire incidents on-board. The size of risk of established fires generally increases if a fire starts explosively or can grow unobserved.

All the shipyards had experienced large fires in the past, and they were conscious that serious injury and death for a large number of persons on-board and loss of the whole vessel were possible. When reviewing the consequences, the shipyard safety managers were found always to consider the people on-board first and material damages only after them.

The assessment was needed in particular for comparing and improving of the responses, which relate to the final research question*: 4) What are available responses to fire risk in cruise vessel construction projects?*

The responses at the shipyards were studied with multiple research methods and with several sets of data. It was fortunate that there was such a great interest at the shipyards in the topic so that many responses were tried during the actions. Altogether 141 responses (Table 5.5 to Table 5.7) were observed and developed at the shipyards. 83 were related primarily to ignitions. Of these, 35 were targeted at hot work and fire load, as they were the main contributors to fires. The study of responses revealed that improved fire risk management required changes at many levels of the organisations, from attitudes and skills of single workers to shipyard and subcontractor work processes.

The second largest group of heat sources in fire incidents was electrical. Evidence was found that the heat generated through the malfunction of unattended electrical equipment, such as short circuits and seized bearings in blowers and heating systems have special importance. Enclosed fires have a high chance of escalation before detection, and thus the use of *unattended* machinery in particular should be minimised. Again, systematic maintenance and installation procedures are potential responses.

Of the fuels, waste, gas leaks, stored installation material, flammable liquids and chemicals were the most important. The control of the amount and distribution of the fire load during construction was found to be an issue of project management, work process design, ship design, purchasing, logistics and human behaviour. In broad terms, the first five items seem to determine the minimum possible amount of fire load at a given time, and the last one, the behaviour of individual employees, determines if the fire load is handled safely.

During the actions, the most important source of detection and alarm for fires during normal working hours was found to be the persons on-board, and their training is important. In addition, all the yards used some kind of temporary system for fire detection and alarms. The ship's permanent systems should be technically operational and competently manned as early in the project as possible, as their coverage is good. Manual suppression with portable extinguishers and later water suppression by the yard's fire fighters and public fire brigades were found important.

The importance of closing openings in metal structures and other partitions were found to be crucial for preventing the escalation of fire, for providing safe paths of escape for persons on-board, and for limiting fire and smoke damages. Fire doors and temporary closing devices should be in place and major openings should be closable as early in the production as possible. Further, for evacuation, the lead time from fire detection to the start of evacuation is important, and good results can be expected if detection of an established fire results in the immediate evacuation of the whole vessel. This was not done by all yards, but it would be important for reducing the possibility of injury for the workforce.

Many of the responses for the ignition risk relate to a large part of the workforce instead of few specialists only. For example, waste management applies to all persons on-board. Thus the implementation of responses demands special efforts from management, and the safety attitudes and skills of the workforce were found to play a special part. Also project management processes that concern contracting, design changes and early adoption of ships' safety systems were found important as they provide the practical limits of flows of materials, energy and personnel on-board at a given time.

The 141 responses for ignition and established fires form a compendium of mitigation tools for use at shipyards, for ship-owners, shipbuilders and insurers, which can be very useful in the practical reduction of the fire risk. This is an important outcome of the research and an answer to the research question no. 4) by itself.

Of all the responses, the sprinkler systems were found to be much more important than previously thought. As there were few large fires, quantitative evidence was limited, but based on event tree calculations (sub-chapter 3.3.7.6), and experience in other industries, a reduction in consequences by a factor of ten or more could be possible. As established fires on-board are very difficult to prevent altogether, it was concluded that the ship's own extinguishing system should be used as early in the project as possible. Thus one of the most important findings of the research was that *sprinkler systems can be made available for suppression 6-8 months earlier than was thought possible previously. This has the potential to reduce the consequences of an escalated fire by an order of magnitude.*

For many of the yards, fire risk management improved remarkably during actions, and the improvement has continued. The average number of fire incidents per 100.000 GT in production has been reduced by more than 50 % when the periods of 2002-2003 and 2004-2013 are compared for the current S.I.G. shipyards (Information provided by kind permission of the S.I.G.). Both fast and longer-term feedback was developed at the yards. For example, fire guard surveys provided daily feedback for rapid changes, but also long-term information on the effects of safety campaigns. The research provided the yards with a benchmark for their actions, which the managers used as a dialectical device to promote changes in their own organisations. For example, providing automatic suppression early was deemed impossible in an organisation, but was introduced when it became known that the competition had implemented it.

Although human error is ever present at the yards and is known to be hard to eliminate, it was the work processes that seemed to be the most difficult to change. This was observed during the actions, and a decade later, in 2011, when the expert managers were asked again about management of fire risk. The changes that could possibly slow down the work on-board were especially difficult to implement. For example: changing to non-hot work in pipe installations was tedious as it was seen slower than flame cutting and welding. In spite of such hindrances, remarkable successes have been achieved by the seven shipyards. Their safety organisations co-operated, and research evidence was continuously tested and risk management approaches revised in real life during the research. Their combined efforts resulted in implementation of new responses that have reduced the risk considerably in the industry.

In conclusion, it was found that the fire risk in cruise vessel construction can be described, assessed and mitigated in two parts: the factors that contribute fire ignition and the consequences of established fires. Further, it was found that direct assessment of many contributing factors, such as amount of flammable waste was possible. However, the organizational and human behaviour, which bring the fuel and heat sources together on-board needed more flexible metrics. Their combination, a mosaic- type assessment of size of fire risk with several different types of metrics was found to produce a rich and descriptive view of the risk, suitable for generating useful responses. During the research process, a fire risk management system and some possible improvements have been described, and implemented both theoretically and practically, which is a very satisfying outcome of the work. This information provides a glimpse of a complete fire risk management system of future, where the risk level can be continuously monitored by several types of metrics and controlled with multiple methods.

7 Discussion

In the following, the main theoretical and practical contributions of the research are evaluated. Furthermore, the reliability and validity of the study are examined, and some key issues for further research summarised.

The background of the study is in the improvement needs of the fire risk management of the cruise vessel building process. The aim of the research was to explicate the risks and the available responses of fire risk management in cruise vessel shipbuilding, but it also contributed to significant improvements in shipyard fire safety. The study covered the large European shipyards, which built most of the cruise vessels in the world at the time of the action cycles.

No explicit theory for fire risk management in the cruise ship building process was found from literature or observed to be in use by practitioners, which could have been used in addressing the research questions. Instead, the frameworks of project and fire risk management were used to construct a theoretical framework for the shipyards' operations. The available theoretical background from literature, the role of the researcher as a key participant in the development process, and a naturally cyclic interaction process with the shipyards led to the selection of the action research method. In other fields of research, action research has been effectively used for theory generation, and for spawning questions for further beneficial research, which was one of the aims of the study.

The research started with three sets of literature: project risk management, general fire safety and shipbuilding. It was found that all were necessary in describing the initial problem. Common features were identified in the sets, such as in descriptions of the risk management process and in nature of fire risk. During the action cycles, the findings of the study were continuously reviewed against the above sets of generic literature. It was found that the compatibility between the observed reality and conceptualization from the literature was good. In this sense, the study in its small part also serves as a further evidence of the usability of the existing theories. In particular, the utility of seemingly simple risk management process concepts in projects was demonstrated. Further, findings on generic and shipbuilding fire safety theory during the research matched the body of knowledge well.

In the pre-understanding phase of the research, a preliminary assessment of fire risk management from the participants' experience of earlier fires was made, and a fire risk management auditing and improvement programme was started by the researcher. During the action cycles, a safety interest group was formed of the participants at the four shipbuilding companies. The group provided research material and much of the participant input. There were twelve action cycles altogether. In the interactions, the findings were cyclically explicated according to action research practice. The research setting was unique: competitors co-operated and benchmarked with each other. An extraordinary asset of the co-operation was that practical development of risk identification, assessment and responses could be tested continuously in real life, and adapted for use by each shipyard according to their needs.

Many of the conclusions were based on the unique fire incident statistics and case histories, which covered seven shipyards of the four shipbuilding companies and 221 fire incidents on 22 vessels. The amount of qualitative research material was also very large. There were nine main sets of research materials, which were obtained with six research methods within the action research, and seven sets of supplementary data.

7.1 Contribution of the research

The research has presented a view on the status of fire risk, its size, and its management in cruise vessel building projects. It has provided new information on issues such as average times between fires, causes for ignitions, typical fuels, daily and weekly distribution of fire incidents and contributing organisations. A large palette of available responses has been uncovered. Very little has been published previously on the topic, although the risk is significant. Therefore, the study has fulfilled a definite need. The contribution of the study may be divided into seven categories:

> Firstly, the theoretical work combines general project and fire risk management concepts from literature in a specific problem in the shipyards' production environment.

Secondly, fire risk has been identified regarding the contributing factors of ignitions, such as hot work and fuels, and consequences, which can be hundreds of lives lost and hundreds of millions of dollars in damages.

Thirdly, theoretical and practical framework and metrics for presenting fire incident statistics and case histories have been developed by the researcher, and consequently adopted in the European cruise vessel building industry. In addition, methods and metrics for assessing the fire risk have been formed, for key factors such as moveable fire load, closing of openings, hot work habits and portable extinguishers.

Fourth, 14 categories of contributing factors for ignition, three types of consequences, 27 key metrics for risk assessment and 141 responses to fire risk have been elaborated on, and used in development projects at the participating shipyards. It is estimated that the fire risk has been reduced significantly during the actions and after them. Successes have been achieved in particular in the control of hot work, the control of waste, in fire guarding, in closing of fire doors and in the use of ships' own safety systems.

Fifth, commissioning the ship's own sprinkler systems unconventionally, very early in the building process was estimated to have reduced the risk of large loss by an order of magnitude, since it became a key development target at the yards after the research actions (Interactions with Furic 2007, Lebaron 2010, Moisio 2010 and Wähler 2010).

Sixth, the unique research setting of action research and mutual safety benchmarking of competitors has been used as a very useful approach for deriving extensive amounts of research information and simultaneously greatly accelerating development of risk management in the participant organisations.

Seventh, a fire risk management process with practical data has been described and tested in an industry, covering most

> of the world capacity. The fire risk was identified, a complete set of metrics for the identified key issues was developed and, finally, a set of available responses was formulated and ranked in feasibility. Many of the key findings, such as normalised incident statistics and early automatic suppression, have been adopted at the participant shipyards.

As summarised above, an important contribution of the study has been in providing a theoretical and methodological framework for academia and the cruise vessel industry for their research and improvement projects. A venue and methodology for cyclic safety benchmarking have also been created in co-operation with the competing industry partners: the Safety Interest Group of the shipyards. This has enabled the distribution of research findings and other best practices among rival participants. Benchmarking and development of shipyards' processes have been provided in, for example, hot work, portable extinguishers, fire load removal, storage on-board, flammable material logistics, fire risk management during sea trials, temporary fire-fighting arrangements, shipyard fire brigades, cooperation with municipal fire brigades, the safety training of yard employees and subcontractors.

Finally, the research has provided a theoretical backbone for shipyards' fire risk management development during 1999-2014, who have had a significant reduction (see p. 171) in their number of fire incidents at many of the participating yards. Later, the thesis work formed the basis for the EU-funded joint 'best practices' document on some fire risk management matters of European cruise vessel shipbuilders.

Based on the above, it is the researcher's opinion that the work has described a fire risk management system in a suitable theoretical context, generated new theoretical data, has provided new fire risk management practices for the industry, and has also contributed practically to risk management by summarising a broad response toolkit for the use of practitioners.

7.2 Evaluation of the research

The extent of actions of the research, its coverage of the industry, number of different research methods and the amount of data in this study were exceptionally large, which has provided a solid background for the reliability of the conclusions. Practical and theoretical validity and the reliability of the research conclusions are reviewed below, in the general context of management research, where the view may be positivistic, detached and prescriptive. In management research, it is customary to formally address the methods, which are discussed in the following sub-chapter 7.2.1. Further, in some management research contexts, the relevance and contribution of an industrial engineering and management study are used to evaluate its appropriateness. “Market tests” can be used to get a view of the success of a research project. These test how useful the product of the research is in practice. The practicality of the outcome has been the prime target of this work, and it is summarised in sub-chapter 7.2.2.

7.2.1 Evaluation of methods and theoretical contributions

The focus of the research has been on operative fire risk management. The chosen focus provided good access to the control processes of the yards. Naturally, this focus also affected the usability of the results. For example, options for top management actions or issues that concern singular welders have not been covered, and remain topics for further research.

A set of cyclic development projects in a turbulent business such as cruise vessel construction is not the easiest research environment for obtaining strict and controlled repeatability, validity and reliability for the results. Emery & Trist (1978, p. 26) use the term “disturbed-reactive environment”. However, in qualitative case research in management science or social science, this kind of temporally changing scene is common. Further, in connection with case studies, Yin (1994, p. 90) discusses three principles of data collection: multiple sources of evidence, creating a case study database and maintaining a chain of evidence. These principles have been followed in this study.

Another way of elaborating on the validity and reliability is to study it in parts as construct validity, internal validity, external validity and reliability (Yin 1994, p. 33). The term “construct validity” refers to “establishing correct operational measures for the concepts being studied”. In this study, for describing the fire risk, assessing its size and finding the responses, both qualitative and quantitative evidence have been used. Yin discusses the tactics of using multiple sources of evidence, establishing a chain of evidence, and having the key informants to review reports. All of these have been used in this study. The varying of types of research material and the use of multiple research methods (triangulation) was carried out during the action cycles of the study, and was evaluated after the available responses had been selected. During the action cycles, nine main sets of research materials and seven sets of supplementary data from miscellaneous sources were used. The main sets of materials were obtained with six research methods within the action research cycles: Interaction with key participants; writing of best practices; archival analysis; fire incident statistics review; fire safety surveys; and managers' questionnaire. The extent of the coverage varied with methods. This variety in research methods and materials provided for unusually comprehensive triangulation. Based on the above, it is deemed by the researcher that variation in methods and materials has been sufficient. With "internal validity", Yin (1994, p. 35) refers to establishing a causal relationship where "certain conditions are shown to lead to other conditions" for explanatory or causal studies. In this study, the causal relation of all of the factors studied could not be confirmed rigorously. For example, it may be deduced, that the work arrangement of the yard (e.g. timing and location of unpacking) and late design changes in the design process (uninstalled old material, unpacking new parts) affect the amount of burnable waste onboard, but no further work has been done on establishing the cause and effects. Rather, many of these causal relationships were seen to provide important research subjects for the future.

The term "external validity" (Yin 1994, p. 35) refers to the generality of the result in other fields. This is possible with the framework and methods presented in this research. It would mean widening the context further to the rest of the cruise vessel building industry, and onwards to the shipbuilding industry in general and, finally, to prototype-building industries with concurrent outfitting and hot work, such as industrial systems construction. As discussed earlier, the coverage of the participant shipyards in the cruise vessel building industry was exceptionally good. They represented four European shipbuilding companies, Finnish, French, German and Italian. The remainder of world production capacity had traditionally been mostly in Japan and Europe. It is expected that the basic building process would be approximately similar throughout the industry. The building materials are also essentially the same, and thus extension of the results to all cruise vessel building is feasible. An indication of similarity may also be a large fire in an unrelated shipyard (CNN 2002), where hot work, flammable material and open fire compartments are believed to have contributed to the loss. An interesting area of further study might be the effect of differences of work cultures and safety attitudes on the risks of the shipbuilding industry. The generalisation of the results against other branches of world shipbuilding may be induced according to the above, and the conclusions are believed to be valid for almost all branches of shipbuilding. Most ships do have accommodation and outfitting-intensive areas, and the safety issues in building are believed be similar: for example, concurrent hot work in the presence of flammable materials, maintenance of electric and gas distribution equipment, attitudes of the workforce; only the scale is smaller in other ship types. For other prototype industries, such as offshore and plant building, there are similarities that can be characterised with hot work- and maintenance-related heat sources and temporary building-time flammable materials, which are not regulated by authorities, and safety cultural issues. The attention and investments to safety may, however, be rather different.

"Reliability" refers to the repeatability of the research (Yin 1994, p. 35). In connection with development projects and action research, this is most often not feasible. Only one check was done in one of the owner's surveys, in which the researcher followed the safety surveyors (see sub-chapter 3.3.5) on-board, and was able to repeat the results. However, even a delay of one day changed the results at many locations, as situations are variable on-board. Due to the problems of repeatability mentioned above, the data collection and documentation methods have been designed so that the results obtained from the seven shipyards are comparable with each other, and the general pattern is discerned through comparison rather than repeating. In the future, using multiple researchers with the same input could reduce the bias. Unfortunately, in this study this test was not possible for practical reasons.

A popular view in qualitative research is that the validity and reliability of research may be assessed through examination of its relation to theory, the correctness of its methods, and its contribution and connections to the real world (Argyris 1980, p. 181), (Gummesson 1991, p. 160): some potential limitations of this research and its validity are discussed below.

In addition to the dynamic environment of prototype ships, a potential limitation of the study is also the fact that the researcher has been employed partially by the ship-owner, and has had the position of client's representative for many of the participants. Can this have led to whitewashing of the problems, omitting incidents from statistics, etc.? Naturally, this is a possibility. However, no evidence of such phenomena has been observed. This may be attributed to the fact that, at three of the four shipbuilding companies, the owner's supervisors were continually present on-board, and reported their findings via the inspection offices to the researcher. This allowed crosschecking. Minor discrepancies that were sometimes detected were deemed insignificant in forming the conclusions. A minor complication for the triangulation of this study has been the question of fire risks that are well under control at the yards but are known to cause problems in other industries. Two examples are tobacco smoking and arson. Although there were few fire incidents that they have caused on-board, and the participants regarded them as relatively small problems, should these have been studied more closely? On the basis of maximising the impact on the relevant questions, they have received less attention.

The term 'fire incident statistics' has been used liberally in the study, but the quantitative evidence of fires on-board has not been treated with rigorous statistical accuracy. This was not deemed useful, as the shipyards were making leaps in safety development throughout the project, and had several prototype vessels under construction. The variation caused by the changing environment was deemed to endanger the predictive power of a rigorous statistical model and this approach was not used. Instead, the incident numbers and case histories were used to augment the evidence that emerged in the actions, and used as a dialectical device in benchmarking. The number of large fires in particular was small. In addition, the data was not from the complete delivery projects of all ships. However, in the main set it was large with 221 fire incidents, as explained earlier, and each of the seven yards had more than one vessel under construction. Fortunately, the yards provided data of different parts of the delivery cycles of similar vessels, so that the bias due to incomplete projects is somewhat compensated. The quantitative evidence was used especially in forming the conclusions about contributing factors of ignition.

In addition to generic case-study-related reliability and validity criteria discussed earlier, there are specific, though somewhat controversial, criteria for evaluating specifically action research. For completeness, the research was evaluated against two sets of these criteria as summarised in Appendix L and the research was found to fulfil them as well. The action research method has been criticised for lack of chain of evidence between observations and conclusions. The method implies less rigour than, say, a statistical survey. Due to this possibility, the chain of evidence in this study was kept short and the amount of evidence was large. For example, by studying the histories of fires, conclusions about reasons for ignition and fuels could be drawn. From these, recommendations for responses were induced and evaluated. The views of informants of the study have played a major part in the research, and their reviews have received considerable attention. All minutes of meetings, Best Practices documents, meeting presentations, fire incident statistics and some versions of this study have been subject to the informants' own reviews. In addition, two conference publications have been produced with some of the participants, and formal interviews with some of the key participants have been recorded and reviewed. Most of the responses were subjected to practitioners' scrutiny and approval during the research actions. Therefore, it is believed that the evidence provides a sufficiently broad view of the problem, and that the answers were realistic and applicable to a shipyard environment. With this kind of hard reality ‘filtering’ by the practitioners, some new and unconventional solutions might receive less attention than the conventional ones.

7.2.2 Evaluation of the practical outcome

A key characteristic of the study was the co-operative participation of the shipyards’ safety organisations, which provided the data, participated in the development of the risk management processes and shared the outcome. As risk identification, assessment methods and developed responses were applied at the yards, the research results evolved continuously throughout the twelve action cycles. It was exceptional that the research outcomes were subjected to such extensive real-time testing. In the end, this produced very practical results, which could be also applied immediately, as the safety managers were influential members in their organisations. Thus many results of this study, such as incident statistics, and early automatic suppression, were directly adopted in 85-90% of the industry capacity worldwide, which reduced the risk of major fire loss considerably. To the author of this study, this kind of acceptance by the industry meant that the “market testing” was very successful.

In summary, it may be stated that based on the extensive qualitative and quantitative empirical evidence, the conclusions of the study are believed to be valid, and explicated clearly enough for practical use. Generally, the seven shipyards showed remarkable similarity in their fire risk and responses, and the reliability of the conclusions is believed to be good. The answers seem logical and practical, also when triangulated with general fire safety literature (sub-chapter 2.2) and shipbuilding literature (sub-chapter 2.3). The conclusions have been produced with several research methods and multiple types of research materials as described in Chapter 3. This has enabled triangulation in methods, data acquisition, participants and temporal changes: no major contradictions in the research findings have been noted. It is believed that the conclusions are representative of the cruise vessel building industry as a whole.

7.3 Recommendations and issues for further research

The study offers a view of the fire risk management of large cruise vessels under construction, and obvious risk management development areas were found in hot work, the control of moveable fire load and the maintenance of electric and gas systems. Also the evacuation of personnel, alarm systems and accounting for persons on-board provided room for further studies. Co-operation with further shipyards could produce new information, and inclusion of the rest of the world's cruise vessel shipyards would be interesting.

The combination of the action research method and the mutual safety benchmarking of competitors proved to be a fruitful research setting, which provided the researcher with plentiful quantitative and qualitative materials. Similar arrangements can be recommended for other industries as well. A setting that could provide interesting data is safety co-operation within yards' sub-contractors. The role of sub-contractors with each other, and towards the yards is different to what it is in this study, where independent competitors were brought together. This type of research setting could promote new views for the risk management of supply chains.

Of all development themes considered in the study, automatic extinguishing systems seemed to have the greatest potential to prevent large losses. However, at the time of interactions in 2000-2003, they had received relatively little attention by the participants. Their early use required a change in the building philosophy of vessels at some yards: the safety systems should be ready to run when flammable installation materials first arrive in a compartment. This paradigm change occurred after the actions, which has considerably reduced the risk of large loss at the yards in recent years. The development should be continued.

The focus of the work has been on operational management. However, for safety management, a study of responses for top management at shipyards might provide additional benefits. Equally, studies with the people performing work on-board could provide new views on practical fire risk management. The concept and variables of risk size could be investigated further. Interesting future research topics could be found in the effects of the mobility of the workforce and multilingual subcontractor partnerships to fire risk management.

The shipbuilding process has profound effects on fire risk management at a yard, which offers several interesting research possibilities. Studies on reducing fire load, activating safety systems early, and the effects of design change, material logistics, alternative packaging possibilities as well as nonhazardous joining and cutting methods would be important research topics. Also the prevention of secondary damage could be investigated further. Possible topics include post-fire water damage from extinguishing, rain, leaking piping, wastewater, smoke, soot and corrosive chemicals in smoke. The actual secondary losses of insurance companies and owners would also be interesting.

Further, in recent years, the architectural design of cruise vessels has developed towards more innovation with the building of large public spaces such as atriums, high passageways and restaurants of several decks in height. This exposes vessels to new risks, which should be addressed, and research on building-time risks and the effectiveness of automatic suppression with, for example, dynamic fire simulations would be useful.

In particular, further statistical studies could be made with the unique European fire incident statistic database, which has grown steadily and, at the time of writing, covers over 1,200 incidents instead of the 221 used in this study. For example, the database would allow studies of complete series of sister ships, and investigations into the effects of long improvement campaigns. Finally, the case histories of the fire incidents could be utilised more, which would present possibilities to find the root causes of the events in even greater detail.

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APPENDIXES

Appendix A: Basic physics and chemistry of fire

The combustion process is the basis of fires. For completeness, a short summary is included below. In combustion, the reacting materials release more energy than is needed to create the reaction products, resulting in a self-sustaining process (Drysdale 1997 p. 1-55), a “self-sustained high-temperature oxidation reaction” (Babrauskas 2003 p. 7), where fuel, oxidation agent, heat and uninhibited chain reactions are needed (Cote & Bugbee 1988, p. 46), (Planer 1979, p. 18).

In fires of interest for this research, by far the most usual combustion process is due to the oxidation of a fuel (e. g. waste or solvent) in ambient air. Hereafter, the focus is on this process only.

Combustion can involve solid, liquid or gas fuels or combinations of these, and fires may be classified accordingly. They may occur in smouldering or flaming mode, but not all fuel-air concentrations are flammable. The flaming mode can be either *premixed*, where gaseous fuel and air are mixed before ignition, or *diffusive*, where the mixing of air and fuel occurs around the flame (Stollard & Abrahams 1999 p. 5). The premixed mode may give rise to an explosion. In shipbuilding projects, a typical example could be a fire where the evaporated glue solvent of a carpet layer causes a sudden fire.

The combustion process can start with either *piloted ignition* or *spontaneous ignition* (Friedman 1976 p. 92). Sax (1979, p. 236) lists eight common sources of ignition: open flames, electrical sources, overheating, hot surfaces, spontaneous ignition, sparks, static electricity and friction.

In piloted ignition, when the fuel has reached sufficient temperature with a suitable concentration of air, a heat source such as a spark or a flame will ignite the vapours. For liquid fuels, this temperature is commonly referred to as the *flash point*. For solid fuels, the surface temperature is used similarly. For sustaining the fire after the pilot heat source has been removed, a slightly higher fuel temperature is usually needed. This is called the *fire point* ((Drysdale 1997, p. 1-59), (Sax 1979, p. 235)).

In spontaneous ignition, no outside heat source exists, but the temperature is high enough to ignite the fuel-air mixture (Friedman 1976).

After ignition, the heat of the fire can spread to adjacent fuel by conduction, convection or radiation. In ships, one common heat spread mode involves *conduction* through steel structure to adjacent compartments (Darwin et al. 1994), (Gross & Davis 1988), (Veriö 1978, p. 46). During building, the fire insulation might not be in place, increasing the risk.

Convection is also important. It occurs typically when the heated gases of a fire rise upwards because their density is less than the density of the colder surrounding atmosphere. These buoyant hot gases heat the adjacent fuel. In an unfinished vessel, there may be several routes for the hot gases due to the building process: for example, the fire doors may not be operational, there may be uncovered holes in the structure, and vertical and horizontal ducts may be open between compartments. The third mode of heat transfer, *radiation* from flames to fuel, may account for 30-50% of the energy transfer in large fires (Drysdale 1997 p. 1-63), and is important in fire growth onboard.

The amount of available oxygen and fuel type is important in the smoke and toxic release of fires. Less oxygen and the presence of elements other than oxygen, hydrogen and carbon in the fuel tend to increase smoke and toxicity. Often, and especially in ships under construction, smoke damage is more extensive than actual fire damage.

The principles of fire protection stem from the issues discussed above:

- Oxygen, fuel and a heat source must be present for a fire to start
- Combustible material must be heated to its characteristic temperature before it can ignite or support a flame
- The burning rate of a fuel is governed by the heat transmitted from the fire to adjacent fuel
- Burning will continue until fuel is consumed, oxygen is removed, sufficient heat is removed from fuel or from flames, or the chain reaction is cut.

These four principles also form the backbone of the fire protection measures for ignition prevention and managing fire on ships under construction.

Appendix B: Some features of fire risk management of completed cruise vessels

During the shipbuilding process, the fire risk management of the cruise vessel varies considerably depending on such things as fire load and the degree of completion of the ship's fire protection systems. One target of the building process is to increase the fire risk management to its final level by making fire risk management features available one by one. On delivery, the crew must be trained and all systems must be operational. An introduction to these features of fire risk management is given below.

Fires occur regularly on ships under construction and repair, but fire onboard is not unknown in ships in operation either. Tragic events have occurred, and international regulations have been developed consequently. In addition to international regulations, the rules of the classification societies and flag states apply.

The most important safety regulation for ships that were built at the shipyards during the research was the International Convention for the Safety of Life at Sea, known as SOLAS (International Maritime Organization 2001a, 2004, 2006, 2007). In its Chapter II-2, the protection, detection and extinction of fire are regulated for vessels in operation. This chapter also has general provisions for all ships, and additional provisions for passenger ships, cargo ships in general and oil tankers in particular. About 60% of the content has a bearing on passenger vessels. The regulations are under development (International Maritime Organization 2002, 2004, 2005, 2006).

The general part of Chapter II-2 of SOLAS is applicable to all ships. The basic principles are (International Maritime Organization 2001a, p. 151):

The division of the ship into main vertical fire zones and the separation of accommodation from other parts of the vessel by structural and fire bulkheads and decks

- Restricted use of combustible materials
- Regulation of fire detection, containment and extinction
- Regulation of escape and fire-fighting route protection
- Minimisation of ignition probability of cargo vapour

It may be noted that both ignition prevention and management consequences of fires (e.g. extinguishing and protection) are included. The fire loads that are considered are the fixed fire load and the fire load due to cargo vapour. Moveable fire load is not explicitly included, but will be taken into account in future regulations.

Additional regulations for passenger vessels are included in part B of Chapter II-2 of SOLAS, “Fire safety measures for passenger ships”. These include detailed instructions according to the above principles, ventilation, windows, fire guards, ro-ro decks and also instructions for carrying dangerous goods (Haatainen 2000, p. 17-5). The principle for escapes is that two routes from a watertight compartment in the hull or from the main vertical zone above its bulkhead deck must be provided.

Use of non-combustible materials

The use of non-combustible construction has been an international requirement in passenger ships since the end of the 1960s (McDaniel 1972). For modern ships, “non-combustible material” is defined in SOLAS (International Maritime Organization 2001a) as “a material which neither burns nor gives off flammable vapours in sufficient quantity for self-ignition when heated to approximately 750 °C” in a fire test. All other materials are considered combustible. According to SOLAS, non-combustible materials are to be used in accommodation structures with some exceptions. For example, surface liners, decorations, refrigeration insulation surfaces and such may have “low flame-spread characteristics” only. A maximum limit calorific value of 45 MJ/m² is stipulated for these linings. This was considered too high by the committee of inquiry for a fire catastrophe on-board the passenger vessel Scandinavian Star (Schei et al. 1991, p. 206). The maximum permitted fire load in accommodation was under discussion by the Marine Safety Committee of the IMO, as alternative fire safety design criteria are considered (International Maritime Organization 2001b). The new design method should offer the yards more flexibility (Maccari & Vergine 2003, p. 159). The total allowed weight per deck area of all combustible construction and outfitting items varies from 5 kg/m² in corridors and stairways to 45 kg/m² in service spaces surrounded by “A” class divisions (International Maritime Organization 2001c). These design values can be used as a yardstick for measuring the amount of temporary moveable fire load of the cruise ship building process. The amount of combustible mass permitted by the rules varies from 5 to 45 kg/m², depending on the room type. If a typical calorific value of, say, 20 MJ/kg is used, the permitted fire load is 100 MJ/m² (stairways, corridors etc.) to 900 MJ/m² (service spaces with fire walls). In a U.S. study (Culver 1976, p. 112), the fire load of a typical office building was about 660 MJ/m². Remarkably, survey results for moveable fire load on-board averaged below 10 MJ/m² (Figure 4.17), which is a frac-tion of the figures quoted above. Naturally great variations from space to space existed on-board. However, in view of the large number of fire incidents that occurred in spite of the relatively low fire load, it can be concluded that the actual calorific value of the fuel has less influence on ignitions at the shipyards than its flammability: the majority of fires on-board start in waste and flammable fluids.

Structural fire protection

For structural fire protection, barriers on a ship are classified according to their ability to withstand fire. An "'A' class division" in ships is usually formed of steel or insulated aluminium to prevent the passage of smoke and flame for an hour in a standard test. It may fulfil additional time-based requirements for the rise in temperature of the unexposed side during a fire test. In A-class divisions, there are four alternatives, A-0, A-15, A-30 and A-60, where the number notifies the minimum time before the temperature rises above a limit value (International Maritime Organization 2001, Chapter II-2, Part A, Reg. 3, paragraph 3). The 'B' class division in ships is formed to prevent the passage of flame for half an hour in a standard test, and, similarly to the above, alternatively B-0 and B-15 divisions (International Maritime Organization 2001, Chapter II-2, Part A, Reg. 3, paragraph 4). Finally, the 'C' class division in ships is constructed of approved non-combustible materials, but has no requirements for the passage of flame or smoke.

Generally, a large cruise vessel is divided into vertical and horizontal fire zones by A-60 -class divisions. A main fire zone, (also: main vertical zone) is defined as "the section into which the hull, superstructure, and deck-houses are divided by 'A' class divisions, the mean length of which does not in general exceed 40m." An exception to 48m may be possible under certain circumstances. For the ships to be built according to later regulations, more flexible, performance-based rules are applicable (International Maritime Organization 2004, 2006, 2007).

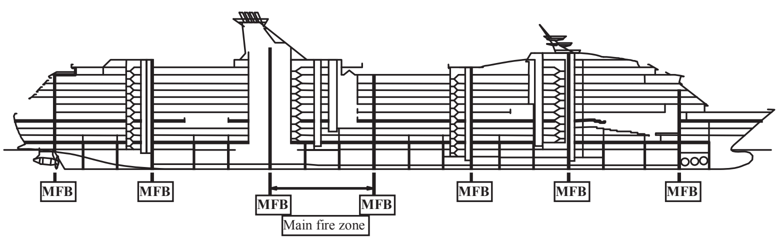

Figure B1 The principle of main fire boundaries (according to Levander & Sillanpää 2000)

For defining the bulkhead and deck fire classes other than the main fire barriers, there are tables of required division class between types of spaces on-board. For illustration, one of the two tables is reproduced below.

Table 26.1 – Bulkheads not bounding either main vertical zones or horizontal zones

Spaces		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Control stations	(1)	B-0[a]	A-0	A-0	A-0	A-0	A-60	A-60	A-60	A-0	A-0	A-60	A-60	A-60	A-60
Stairways	(2)		A-0[a]	A-0	A-0	A-0	A-0	A-15	A-15	A-0[c]	A-0	A-15	A-30	A-15	A-30
Corridors	(3)			B-15	A-60	A-0	B-15	B-15	B-15	B-15	A-0	A-15	A-30	A-0	A-30
Evacuation stations and external escape routes	(4)					A-0	A-60[d]	A-60[d]	A-60[d]	A-0[d]	A-0	A-60[b]	A-60[b]	A-60[b]	A-60[b]
Open deck spaces	(5)					—	A-0	A-0	A-0	A-0	A-0	A-0	A-0	A-0	A-0
Accommodation spaces of minor fire risk	(6)						B-0	B-0	B-0	C	A-0	A-0	A-30	A-0	A-30
Accommodation spaces of moderate fire risk	(7)							B-0	B-0	C	A-0	A-15	A-60	A-15	A-60
Accommodation spaces of greater fire risk	(8)								B-0	C	A-0	A-30	A-60	A-15	A-60
Sanitary and similar spaces	(9)									C	A-0	A-0	A-0	A-0	A-0
Tanks, voids and auxiliary machinery spaces having little or no fire risk	(10)										A-0[a]	A-0	A-0	A-0	A-0
Auxiliary machinery spaces, cargo spaces, cargo and other oil tanks and other similar spaces of moderate fire risk	(11)											A-0[a]	A-0	A-0	A-15
Machinery spaces and main galleys	(12)												A-0[a]	A-0	A-60
Store-rooms, workshops, pantries, etc.	(13)													A-0[a]	A-0
Other spaces in which flammable liquids are stowed	(14)														A-30

Figure B2 Minimum fire integrity of bulkheads according to SOLAS (International Maritime Organization 2001, p. 208), reproduced by kind permission of the International Maritime Organization.

The openings in the bulkheads and decks that may be exposed to fire are tight or made closable with covers, fire doors or watertight doors. The closure of doors is possible from a central control station. Air and smoke flows enclosed behind ceilings, panelling, and linings are limited by draught stops. The fire integrity of vertical casings, staircases and ventilation ducts are ensured, and fire dampers are used in the ducting. For a ship under construction, the fire integrity is naturally less due to unfinished installations.

Fire detection, alarms and extinguishing

Due to the bitter lessons of the past, large cruise vessels have comprehensive systems for fire detection, alarms and extinguishing (Heard 1988), (International Maritime Organization 2001a). Smoke and heat detector systems are connected to a constantly manned central control station, where alarms, sprinklers, fire door closure, watertight doors, ventilation and the public address system can be controlled. During most of the construction, these systems are not available. Similarly, the manual fire-fighting systems comprising portable extinguishers, fire pumps, mains and hoses and engine room fire extinguishing systems are fully operational only late in the building process. An accidental CO_2 release is feared (Longeroche 2001) because of the threat of the suffocation of the crew, and the engine room system is typically disabled until sailing. As the engines are running for a relatively small amount of time during the construction, this is justifiable.

The yards compensate for unfinished safety systems by building temporary systems. Some yards use temporary detection; all use temporary alarm and extinguishing systems. Clearly, the earlier the ship's own fire safety systems can be commissioned, the better.

Organisation of fire safety on-board

In a cruise ship in operation, all crew members on-board are drilled in fire safety monthly according to SOLAS, and they have competence in fire safety according to the IMO seafarers' training, certification and watchkeeping (STCW) code, the vessel is continuously manned, and safety systems are operational. This is in contrast with a vessel under construction, where the readiness of the work force is less drilled, the vessel has few persons on-board during breaks in work and the coverage of safety systems may be lacking.

Another IMO code, the International Safety Management Code (International Maritime Organization 1997), requires the ship owner to establish a company safety management system (SMS). The background of the SMS is comparable to general safety management standards, such as ISO and IEC, where a positivist view is adopted, and feedback-correction loops are utilised at various organisation levels. Operational safety practices on-board, such as minimisation of moveable fire load, are subject to it. However, these procedures are not fully implemented before the ship-owner accepts responsibility for the vessel on delivery. Upon agreement, the owner may set up its own systems before delivery as well fire safety watches, for example.

In conclusion, the operation of a passenger vessel requires that the vessel is built according to good fire safety practices of SOLAS, the crew is trained, and that safety management systems according to the IMO ISM code are in place.

Appendix C: References to general fire safety literature in the response tables of Chapter 2.4

For clarity, the references to sources in general fire safety literature have been recorded in the tables below to complement the information shown in Table 2.1 of Chapter 2.4.

Table C1 Contributing factors to ignition and responses to them found in general fire safety literature review (continues on the following pages) **A=Arvidson and Månsson 1999, B=Babrauskas 2003, C=Cote and Bugbee 1988, CO=Cowley 2002, H=Howarth and Kara-Zaitri 1999, Ia,b,c,d,e=Industrial Insurance Ltd. 1970, 1978, 1992, 1997, 1998a, ING=Ingason and Arvidson 2001, IMO=International Maritime Organization 2002, K=Kallioniemi et al. 2001, KA=Kavanian & Wentz 1990, Na,b=National Fire Protection Association 1984, 2003c, Oa,b,c,d=OSHA 1998, 2003a,b,d, P=Planer 1979, PR=Proulx 2003, RAM=Ramachandran 1998, RAS=Rasbash et al. 2004, SAX=Sax 1979, SCH=Schroll 2002, SH=Shields and Silcock 1987, STE= Stecher and Lendall 1953, STO=Stollard and Abrahams 1999, T=Thomson 2002, W=Watts 2000, Z=Zalosh 2003**

Contributing factor for ignition	Reference (abbreviation and number relate to author and page number of literature references, see caption of the Table)	Responses
Arson	Ia:1, Ib:8, P:29, SCH:92, STE:438, STO:27, T:21, T:96, T:101, Z:17	Automatic suppression
		Good lighting
		Guarding of premises
		Housekeeping to avoid flammable waste
		Restricted access to compartments
Autoignition	B:46, B:186, B:369, Ia:3, K:27, K:28, KA:165, P:65, P:91, SAX:236, SCH:14, T:122, T:129, Z:17, Z:205	Avoiding incorrect storage and use of chemical products
		Managing the use of incompatible chemicals used in the plant
Electric phenomena	B:534, B:553, B:567, C:51, C:52, CO:181, Ia:1, K:2, K:21, K:32, KA:165, P:65, SAX:236, SAX:237, SCH:13, SCH:77, STO:23, T:21, T:24, T:108, T:121, T:156, Z:17	Static electricity: effecting a conductive path between the charged materials
		Use of lightning conductors, earthing in general
Electric systems	B:546, B:548, B:549, B:738, B:769, C:52, Id:3, K:21, K:31, K53, KA:165, SCH:13, SCH:76, SCH:77, STO:23, T:24, T:78, T:108, T:111, T:121, T:133, T:154, Z:17, Z:297	Ensuring overheating protection in electric systems
		Maintenance of electric systems
		Maintenance of thermostats, motors and transformers
		Overheating checks with IR equipment
		Prevent arcing
		Proper design, installation and maintenance of cabling
		Shutting down of electric appliances when not in use

Table C1 Contributing factors to ignition and responses to them found in general fire safety literature review (abbreviations and numbers relate to author and page numbers of literature references, see caption of first table). (Continues on the following page)

Contributing factor for ignition	Reference (abbreviation and number relate to author and page number of literature references, see caption)	Responses
Explosions, e.g. dust, explosives, gas, and vapors	B:43, B:141, C:53, CO:66, Ia:1, Ib:8, K:9, K:20, K:26, SAX:251, SCH:84, T:132, T:140, Z:17	Avoiding gas leaks and dust accumulations
		Explosion-proof machinery
		Special cautions for explosives
Fire load	B:142, B:183, B:401, C:73, C:78, C:84, CO:103, H:363, Ia:1, Ib:8, Ic:6, Id:1, Id:3, Ie:4, K:23, K:25, K:51, K:55, KA:164, KA:167, P:54, P:86, P:92, SAX:237, SCH:72, SCH:77, SCH:89, STE:427, STE:433, STE:437, STO:23, T:11, T:24, T:81, T:115, T:135, T:144, T:149, T:161, Z:117, Z:201	Avoiding accumulation of flammable substances in structures and dust clouds
		Avoiding highly flammable solvents for cleaning and gluing
		Control of combustible solids by design and work arrangement
		Good house-keeping in general
		Hazardous material control
		Installing emergency shutoff systems for liquids and gases in piping
		Limitation of fixed and moveable fire load
		Maintenance of gas distribution systems
		Minimal storages in production, no packaging materials in production
		Odorizing of gases to help in leak detection
		Precautions during fuelling
		Removal of flammable waste, waste logistics
		Safe handling and storage of flammable liquids and gases
		Use of non-sparking tools near flammable materials
Friction	B:549, Id:3, SAX:237, SCH:13, STE:428, STE:439, T:24, T:110, T:121, T:157	Maintenance of rotating machinery, e.g. gears, belts and bearings
		Overheating checks with IR equipment
Heating, drying and heat treatment	Id:2, Ib:8, K:21, K:30, K:52, K:56 KA:165, SAX:236, SCH:76, STE:442, STO:23, T:24, T:114	Good housekeeping near heaters
		Maintenance of blowers and heating systems
		Functional overheating protection in equipment

Table C1 Contributing factors to ignition and responses to them found in general fire safety literature review (abbreviations and numbers relate to author and page numbers of literature references, see caption of first table). (Continued from the previous pages)

Contributing factor for ignition	Reference (abbreviation and number relate to author and page number of literature references, see caption)	Responses
Hot surfaces and open flames	B:500, K:21, KA:165, P:65, SAX:236, STE:435, STO:23, T:21, T:24, T:115, T:120, T:157Z:17, Z:18	Thermal isolation of hot surfaces from fuels
		Avoiding work with open flames, protective procedures
Hot work (welding, cutting, grinding, torching)	B:506, B:941, Ia:1, Ic:1, Ic:5, Id:1, Ie:1, Ie:3, Nb:2, Nb:4, K:21, K:34, K:57, KA:165, Oa:31, Oa:41, Ob, Oc, P:40, P:65, SCH:91, STE:429, T:21, T:113, Z:17, Z:303	Fire watch system
		Flammable waste management systems
		Gas concentration measurements before hot work
		Hot work permit system
		Hot work safety exam and card
		Hot work supervision plan
		Instructions for hot work in special circumstances, e.g. in tanks
		Training
		Use of protective coverings
		Using alternative methods instead of hot work
Machinery	B:507, C:52, CO:70, Ia:1, Ib:8, IMO, K:21, KA:165, P:65, SAX:236, SCH:13, STE:426, T:24, T:78, T:111, T:157	Equipment maintenance
		Isolation of spark-producing machinery from fuel
		Jacketing of high pressure oil lines
		Risk management of combustion engines
		Safe location of compressors
		Safe parking of motor vehicles
Painting	Ib:8, K:21, K:21, KA:167, P:68	Good housekeeping with solvents and waste
		Proper earthing of substances
		Use of suitable non-sparking equipment
Smoking of tobacco	B:716, C:21, Ia:1, Id:1, K:51, KA:165, P:41, P:65, SCH:71, STE:434, STO:23, T:24, T:11, T:160, Z:17	Education of fire safety
		Inspections
		Smoking restricted with designated smoking places
Miscellaneous	B:517, B:575	Avoiding ignition by shock and impact with material and tool choices
		Avoiding light energy ignitions by education

Table C2 Consequences of established fires and responses to them found in general fire safety literature review (abbreviations and numbers relate to author and page numbers of literature references, see caption of Table C1.)

Consequences of established fires	Reference (abbreviation and number relate to author and page number of literature references, see caption)	Responses
Human damages in fire	A:20, C:18, C:19, C:21, C:38, CO:121, CO:140, CO:147, I:4, Ia:1, Ib:8, Ic:2, Id:1, Id:2, Id:4, Ie:3, IMO, ING, K:10, K:16, K:36, K:46, KA:169, Na:312, Od, P:25, P:30, P:31, P:101, PR:1-3, RAM:104, RAM:110, RAS:227, RAS:237, RAS:243, RAS:245, RAS:246, SAX:239, SAX:240, SAX:242, SCH:51, SCH:61, SCH:97, SCH:99, SCH:100, SCH:110, SCR:51, STO:22, STO:35, T:21,T:25, T:57, T:71, T:74, T:76, T:80, Z:21, Z:78, Z:91, Z:118	Clear escape routes
		Closing of temporary and permanent openings
		Communication of alarms
		Confinement of fire by barriers
		Early manual detection, alarming and suppression
		Ensuring structural stability in fires
		Fire compartments
		Possibly smoke ventilation
		Practiced evacuation procedures
		Reviews of personnel risks and safety culture
		Safety training
		Sufficient extinguishing capacity
		Sufficient safety personnel capacity
		Use of automatic detection and extinguishing systems
		Use of portable extinguishers by all employees
Direct material damages in fire	C:18, C:20, C:60, CO:26, CO:45, CO:78, IC:5, IC:6, ib:8, Id:4, IMO, K:7, K:11, K:39, K:46, K:55, K:64, KA:175, Na:312, P:30, P:159, P:219, RAS:227, SAX:241, SCH:103, SCH:145, SCH:173, SCH:193, SH:319, STO:16, W, Z:7, Z:23	Avoiding smoke and water damages by fast suppression
		Avoiding structural collapse with isolation
		Fast responses with portable extinguishers
		Fire brigades
		Fire detection, alarming and suppression capability is essential for fire safety
		Fixed suppression systems in machinery spaces
		Sufficient supply of pressurized water to premises
		Use of temporary detection and alarming
Secondary damages	K:17, K:27, K:42, P:29, SAX:245, Z:8	Avoiding loss of information by backup
		Avoiding lost production by rapid suppression
		Avoiding delayed deliveries to customers by reserves in schedule
		Avoiding damages to environment by containment

Table C3 Production process arrangements as responses to fire risk found in general fire safety literature review (abbreviations and numbers relate to author and page numbers of literature references, see caption of Table C1.)

Arrangements for managing fire risk	Reference (abbreviation and number relate to author and page number of literature references, see caption)	Responses
Production system arrangements for managing fire risk	CO:216, Ia:1, Ib:8, Id:1, Id:4, K:54, K:58, K:62, K:65, P:26, P:35, SCH:27, SCH:183, STO:33, T:77, T:84	Audits, surveys and inspections
		Fire guarding system
		Fire safety training of personnel
		Including fire safety in contracts
		Organized risk management and safety personnel

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Appendix D: References to shipbuilding literature in the response tables of Chapter 2.4

For clarity, the references to sources in shipbuilding literature have been recorded in the tables below to complement the information shown in Table 2.1 of Chapter 2.4

Table D1 Contributing factors to ignition and responses to them found in shipbuilding literature review (continues on the following pages)

GR=Gross and Davis 1988, HAA=Haatainen 2000, HÄ= Häkkinen et al 1997, HE=Heard 1988, Ia,b=Industrial Insurance Company 1970, 1998, IMOa,b,c,d=International Maritime Organization 2001, 2004, 2006, 2007, M=Maccari & Vergine 2003, MAT=Matthews 1984, MCD=McDaniel 1972, N=Netterstrom 1972, Na,b=National Fire Protection Association 1984, 2000c, Oa,b,c,d,e,f =OSHA 2003a,b,c,d,e,f, R=Räisänen & Kanerva 2000, RO= Robinson 1984, RU=Rushbrook 1961, SCH=Schei et al. 1991, ST=Stokoe 1964, T=Toppan 2000, V=Van Brunt 1984, VE=Veriö 1978, W=Walmerdahl 1999.

Contributing factor for ignition	Reference (abbreviation and number relate to author and page number of literature references, see caption)	Responses
Electric phenomena	Na:312-5, VE:164	Static electricity: proper grounding of vessel and its temporary and permanent parts, especially pipes
Electric systems	Na:312-5, Na:312-6, V:453, V:454, VE:162	Damage control of cabling
		Proper installation of temporary electric systems
		Shutting electric appliances on-board off when not in use
		Systematic maintenance of electric appliances
		Use of explosion-proof appliances in hazardous areas
Explosions, e.g. dust, explosives, gas, and vapours	Na:312-5, V:454	Restricted storage on board for highly flammable materials

Table D1 Contributing factors to ignition and responses to them found in shipbuilding literature review (abbreviations and numbers relate to author and page numbers of literature references, see caption of the first table). (Continues on the following page)

Contributing factor for ignition	Reference (abbreviation and number relate to author and page number of literature references, see caption)	Responses
Fire load	Hä:6, Ia:1,Ib:1, MCD:29, Na:312-5, Na:312-6, NE:199, Oe, RO:1049, SCH:206, V:443, V:448, V:454, V:459	Avoiding accumulation of flammable substances in structures and dust clouds
		Avoiding highly flammable solvents for cleaning and gluing
		Control of flammable material
		Control of hazardous materials
		Fuel oil fire risk
		Good house-keeping, especially waste logistics
		Installing emergency shutoff systems for liquids and gases in piping
		Removal of flammable scaffolding parts
		Restricted use and storage of combustible materials on-board
		Safe handling and storage of flammable liquids and gases
		Unpacking flammable packaging before materials are taken aboard
		Use of non-combustible construction materials, furniture and decorations
		Use of safety precautions with fuel oil or lubrication oil in connection with hot machinery
		Use of temporary flame proofed coverings over materials
Heating, drying and heat treatment	Ia:1, Na:312-5, V:454, VE:161,	Special caution for unattended heating systems

Table D1 Contributing factors to ignition and responses to them found in shipbuilding literature review (abbreviations and numbers relate to author and page numbers of literature references, see caption of the first table). (Continued from the previous pages)

Contributing factor for ignition	Reference (abbreviation and number relate to author and page number of literature references, see caption)	Responses
Hot work (welding, cutting, grinding, torching)	Ia:1, Ib:1, Na:312-5, Nb:1, MAT:495, NE:197, NE:199, Oa, Ob, Oc, Of, V:453, V:454, VE:145, VE:154	Disconnecting gas and electricity when not in use
		Effective hot work procedures
		Measuring gas content in room before hot work
		Precautions during fuelling of ship systems
		Systematic maintenance of gas systems
		Use of non-sparking tools near flammable materials
		Using alternative methods instead of hot work
Machinery	V:458	Maintenance of flame or spark producing equipment
		Maintenance of rotating machinery
		Systematic procedures for using motor vehicles on board
Painting	Na:312-6, NE:199, V:443, VE:157	Precautions for hot work, cleanliness, ventilation and chemical reactions
Sea trials	HÄ:2, HÄ:6, IMOa,b,c,d	Proper engine operation
		Tested fire alarm, detection, public announcement and extinguishing systems
Smoking of tobacco	Na:312-5, V:454	Restricted smoking in designated positions

Table D2 Consequences of established fires and responses to them found in shipbuilding literature review (abbreviations and numbers relate to author and page numbers of literature references, see caption of Table D1).

Consequences of established fires	Reference (abbreviation and number relate to author and page number of literature references, see caption)	Responses
Human damages in fire	HAA:17-5, HÄ:111, IMO a,b,c,d, Na:312-6	Early division of the ship into functional main vertical fire zones, and separation of rooms by structural and fire bulkheads and decks
		Escape and fire-fighting routes built early and kept functional
		Fire integrity of vertical casings, staircases and ventilation ducts built early
		Functional fire detection, alarming and public announcing systems
		Installation of windows early in the production process
		Keeping fire doors always closed
		Temporary closing of vertical ducts during building process, especially cable ducts
Direct material damages in fire	HAA:17-5, HE:223 Ia, IMOa,b,c,d, Na:312-6, Na:312-7, Od, SCH:206, V:453, V:460, V:461, W:38	Availability of portable extinguishing systems close to work locations
		Functional fire suppression, both temporary and ship's own system, preferably automatic
		Good liaison with local fire brigade
		Prevention of accidental CO_2-release in engine rooms
		Sufficient fire pumps, hose connections, pressure and water supply
		Trained shipyard fire brigade available fast
Secondary damages	GR:7, N:312-7, R:6-3, RU:408, ST:85,T:1, VE:38, W:31	Isolation of conductive surfaces for structural stability and to prevent fire conduction to adjacent compartments
		Making pump capacity available for draining of suppression water
		Removing obstacles from drainage paths

Table D3 Production process arrangements as responses to fire risk found in shipbuilding literature review (abbreviations and numbers relate to author and page numbers of literature references, see caption of Table D1).

Arrangements for managing fire risk	Reference (abbreviation and number relate to author and page number of literature references, see caption)	Responses
Shipyard arrangements for managing fire risk	Ia:1, M:159, Na:312-4, Na:312-6, Oc:3, S:206, V:443, V:444, V:453,V:454, V:462	Alternative fire safety design criteria
		Arrangement of fire watch systems and inspections
		Constantly manned central control station
		Safety training of personnel
		Surveillance of hazardous behaviour onboard
		Systematic fire risk management program and safety plans

Appendix E: Some characteristics of action research by Eden and Huxham

The first instances of using action research as a scientific tool are most often connected with the work of Kurt Lewin (1951) in the USA in late 1940s. He worked on his field theory framework in the US and then became involved in social development research in the UK during the 1950s and 1960s. The Tavistock Institute, sometimes referred to as the Tavistock School of Social Scientists, came to make extensive use of action research in various social science settings (Hawk 2002). It became a basic method of research intervention of socio-technical systems (Emery & Trist 1978, p. 14). The acceptance of the AR method grew from this well-regarded basis and is now widely used in various fields of social sciences. During the 1970s and 1980s, the classical action research method, as introduced above, was further developed into several related but different methods that were termed action inquiry, participatory action research, action science and action learning (Argyris 1980), (Reason & Bradbury 2004). To increase the rigour and objectivity of the method, Eden and Huxham (1997, p. 539) have postulated a useful list of 15 characteristics of action research, duplicated below, which was used to check the relevance of the research. The characteristics are as follows:

1) Action research demands an integral involvement by the researcher in an intent to change the organisation. This intent may not succeed - no change may take place as a result of the intervention - and the change may not be as intended.

2) Action research must have implications beyond those required for action or generation of knowledge in the domain of the project. It must be possible to envisage talking about the theories developed in relation to other situations. Thus it must be clear that the results could inform other contexts, at least in the sense of suggesting areas for consideration.

3) As well being useable in everyday life, action research demands valuing theory with theory elaboration and development as an explicit concern of the research process.

4) If the generality drawn out of the action research is to be expressed through the design of tools, techniques, models and method then this, alone, is not enough. The basis for their design must be explicit and shown to be related to the theories which inform the design and which, in turn, are supported or developed through action research.

5) Action research will be concerned with a system of *emergent theory* in which the theory develops from a synthesis or that which emerges from the

data and that which emerges from the use in practice or the body or theory, which informed the intervention and research intent.

6) Theory building, as a result of action research, will be incremental, moving through a cycle of developing theory to action to reflection to developing theory, from the particular to the general in small steps.

7) What is important for action research is not a (false) dichotomy between prescription and description but a recognition that description will be prescription even if implicitly so. Thus presenters of action research should be clear about what they expect the consumer to take from it and present it with a form and style appropriate to this aim.

8) For high-quality action research, a high degree of systematic method and orderliness is required in reflecting about, and holding on to, the research data and the emergent theoretical outcomes of each episode or cycle of involvement in the organisation.

9) For action research, the processes of exploration of the data - rather than collection of the data - in the detection of emergent theories and development of existing theories must either be replicable or, at least, capable of being explained to others.

10) The full process of action research involves a series of interconnected cycles, where writing about research outcomes at the latter stages of an action research project is an important aspect of theory exploration and development, combining the processes of explicating pre-understanding and methodical reflection to explore and develop theory formally.

11) Adhering to characteristics 1 to 10 is a necessary but insufficient condition for the validity of action research.

12) It is difficult to justify the use of action research when the same aims can be satisfied using approaches (such as controlled experimentation of surveys) that can demonstrate the link between data and outcomes more transparently. Thus in action research, the reflection and data collection process - and hence the emergent theories - are most valuably focused on the aspects that cannot be captured by other approaches.

13) In action research, the opportunities for triangulation that do not offer themselves with other methods should be exploited fully and reported. They should be used as a dialectical device, which powerfully facilitates the incremental development of theory.

14) The history and context for the intervention must be taken as critical to the interpretation of the likely range of validity and applicability of the results of action research.

15) Action research requires that the theory development, which is of general value, is disseminated in such a way as to be of interest to an audience wider than those integrally involved with the action and/or with the research.

Appendix F: The history and documentation of fire risk management interventions of this study

During this research, the participating shipyards had a good workload, as cruise vessel operators invested heavily in new tonnage: various series of building projects have enabled systematic safety process adjustments. In the period 1999-2003, progress in fire risk management was apparent at many yards. The researcher initiated and participated in the actions as explained in sub-chapter 3.1 and summarised in Table 3.1. In this Appendix the research events and issues that were discussed are described briefly in free form, according to good Action Research practices, and as a complement for the chain of evidence presented in Chapter 3.

The history of obtaining a pre-understanding of the problem through first intervention cases 1999-2001

In addition to the literature described in Chapter 2, pre-understanding of the research problem was sought by preliminary interactions with three shipyards. The inquiry was divided into three parts according to project management practices: fire risk identification, assessment and response development. The duration of the pre-understanding phase was approximately two years.

Broadly, the participants of the research belonged to four categories: ship **project managers**, **mariners** in the ship owner's organisation, **health and safety professionals** and the shipyard **production line organisation** (Chantiers de l'Atlantique 2001, p. 48, Kvaerner Masa-Yards 1999 p. 65, 2003, p. 11, Wähler 2002a). The participants had a common goal: to avoid fires and mitigate their effects, should an incident occur. However, first priorities could differ between the groups and work tasks. For example, the ship-owner and shipyard project manager organisation are familiar with project risks, and the wish to minimise disruption in the delivery process may be the immediate focus. On the other hand, the shipyard health, safety and environmental organs (HSE) and the production organisation may be grounded more in the safe operation of the production facilities. After a major fire at Turku shipyard during the spring of 1999, the owner wanted a better view of fire risk management issues at the three European yards it was working with. A preliminary identification of the factors that would be important in a project on fire risk management was put together by the researcher, using information from literature, from experiences of earlier fires, and of safety consultants' views that were available. It became obvious that some combination of human error, hot work and flammable waste (often packaging or protective covering material) or flammable liquids was important in fire incidents on-board. Consequently, an improvement campaign directed at the three shipbuilding companies was launched. During the campaign, the shipyard participants' views and their data provided material for conclusions and led to the pre-understanding reported in this chapter, and to the further action phase of the study. In addition to participants' views and literature, three others sources were available. The views of the risk management consultants Det Norske Veritas, the owner's consultants and two insurance companies were used. The pre-understanding of fire risk was formed based firstly on several interviews and discussions with participants, consultants and insurance companies as well as from their internal documentation (Bergen Hull Club 2000), (Det Norske Veritas 1999), (Egeland 2000), (Hauge 2000), (Interaction with Holmberg 2000), (If and Vesta Insurance 2000) (Longeroche 2001), (Interaction with Miorelli 2001), (Servanto 2000a, 2000b, 2001a, 2001b). Secondly, the incident reports (Interactions with Fire Chief, Yard AAA 2000), (Interactions with Fire Chief, Yard AAA 2001) and the literature referenced in Chapter 2 were used. The research process history up to the action phase is described briefly below. During the second half of 1999, the operative pattern of the building sites had been consolidated; one of the owner's consultant, Baltic Ship Safe Ltd. (BSS), was hired by RCCL to carry out audits and to interact with the yards to provide suggestions for improvement. Other consultants were also involved. A representative of the classification society Det Norske Veritas (DNV) joined an early inspection of one of the yards, and a review was prepared, which also contributed to the first set of identified risks for the research. By June 2000, the owners' consultants had produced several reports of yard safety levels. The themes of the first reports recurred, and similarities were found in comparisons between yards. In addition, the impact due to reports of yard actions was diminishing from early successes. This led the researcher to experiment with the audit process: it should be suitable for producing quick feedback on the hazard type and location of the yards, and be able to generate comparative statistics. The audits were adjusted in co-operation with the owner's consultants. This allowed the addition of another practitioner's estimate on the researcher's pool of identified fire risks. The BSS was encouraged to develop an auditing checklist along the lines of the principles above, and new ideas were encouraged. Their view was based on experience in fire-fighting and fire safety training onboard operating ships. The first version (Servanto 2000a) was a table, to be filled out during the fire risk management inspections. The inspections were targeted to be about three days in duration, and to occur approximately every three weeks. During the inspections, the fire risk of practically all spaces on-board was audited. A trial inspection was carried out in August 2000 in Turku. During the autumn of 2000, three inspections with a modified inspection table had been carried out. Some time series were produced and a new fire risk index was constructed at this time to start discussion with the participants. The interesting questions for the research were the practicability of the produced information and its representation for maximum impact. The trial surveys were found useful by the owner's management, and this resulted in the extension of them in early spring 2001 to all three yards building ships for RCCL. They were scheduled at about 3-5 week intervals. After establishing schedules and input forms, and introducing the process to the yards, experimentation for finding the best type of output was started. The surveys continued until late 2001.

Other metrics of interest were also gleaned from the surveys (Räisänen 2001b). In order to compress the audit data into a single fire risk-related quotient that could describe the risk level of the shipbuilding operation for comparisons between vessels and shipyards, a general fire risk index was introduced to the trial programme. This index was based on the Swiss standard SIA 81 (Fontana 1984) described in Appendix I, and had analogies with the SOLAS index method for cargo vessel damage stability calculations (International Maritime Organization 2001, p. 95), and the risk index presented in Nordic work on the fire risk assessment of timber-frame buildings (Magnusson & Rantatalo 1998). The test was kept simple as were the factors selected by a quick literature review, as the aim was to find out if such indices would gain acceptance at the yards. Although this particular index used is for the use of buildings only, the exercise was considered worthwhile in assessing the usability of such numbers in shipbuilding practice. The input values for the index were provided in the BSS surveys during 2001. The changing input and the only one related to the normal operation of the project was simply the observed amount of moveable fire load on-board during the surveys. All the other inputs relate to shipyards emergency operations. Examples of the input functions and the output are given in Figure 3.13 and in Figure 3.14. The calculated risk by this method became 2-7 times larger than the assumed acceptable risk for ordinary buildings. The exact value is of minor interest, as the aim was to test the idea of using an index as an aid to monitoring the changes in status, and as a dialectical device with the participants. A major shortcoming of the SIA 81 for use in shipbuilding is its lack of factors for taking the prevention of ignition into account. Of a list of possible risks identified in literature and by participants discussed on previous pages, such as combustible waste, combustible paint/solvent, gas leaks, hot work, dangerous hot work, tobacco smoking on-board and uncovered bulb lights, only the amount of fire load is included numerically in the index. Some plans for developing a new index were discussed, but a decision was made first to provide the SIA index only slightly modified for the participants, and then ask for their estimate on its usability in their work. The fire risk index outputs from several surveys were provided to the participants, but did not gain wide acceptance, as it was deemed by the participants not to be tangible enough. Therefore, further development of such indices was discontinued after presenting them to the safety managers in November 2001.

A short inquiry at this phase was directed towards learning from insurance companies. To triangulate the applicability of practices of risk management described in literature, the management of two RCCL's insurance companies, Vesta and Bergen Hull Club, were interviewed and their risk management questionnaires reviewed ((Moore 2000), (If & Vesta Insurance 2000), (Egeland 2000), (Bergen Hull Club 2000), (Hauge 2000)). Their practices were found to agree with the generic project risk management approach of literature described in sub-chapter 2.1 . Both insurance companies had a process for transmitting to the clients the lessons learned from casualties. Similar processes were found to be less developed at the shipyards. Consequently, the item "lessons learned" was added to the development request list of the yards. In addition, practical models for this kind of project feedback were found in the processes of the insurance companies. This formed the basis for experimental management reviews. After the work on identification of project fire risks, risk assessment and response development were started. The main inputs were the audits on-board and the safety practices of the yards. The shipyards have safety instructions (Di Pieri & De Marco 2001), (Chantiers de l'Atlantique 2001), (Kvaerner Masa-Yards 1999), (Wähler 2002a), which cover the prevention of ignition, fire extinguishing and personnel evacuation and the organisation of safety issues at the yards. These were also used as material in the inquiry. When the fire statistics of the yards were compared with the safety instructions available at the time (before the action phase of this study), strong indications were found that if the prescribed procedures were followed to the point, the majority of ignitions could have been avoided.

In the first phase of the research, the fire incident statistics of one of the yards were obtained (Preliminary Statistics, see Table 3.4). The statistics covered the whole area of the yard, not only the ship under construction. For example, electrical fires in cars in parking spaces are included.

Fuel	Per cent
Vehicles	3 %
Electric appliances	10 %
Gas hoses or distribution network	12 %
Yard structures	5 %
Garbage, packing material etc.	66 %
Ship structures	5 %

Figure F1 Fuel for fires within shipyard gates 1998-2001

Ignition cause	Per cent
Flame cutting	39 %
Welding	31 %
Electric	11 %
Autoignition	0 %
Cigarrette	4 %
Other	14 %

Figure F2 Ignition causes within shipyard gates 1998-2001

Before the start of the actions in late 2001, the yards already had wide experience of fire risks, and these were also used to augment the existing pre-understanding. The safety arrangements of the yards were based on a relatively small core of personnel, and the safety tasks were included in the work of the production departments and of the subcontractors. All the shipyards had fire brigades, and had good co-operation with the municipal fire-fighting forces. During the pre-understanding interventions with the yards, it was found that in some cases the attention of the participants was focused more on fire-fighting readiness than on managing the exposed property and people. However, the protection of people also came up often in the discussions with the owners' safety consultants, the shipyard people in general, and especially their safety professionals. For the ship owners' representatives, however, the managing of the exposed dominated, and their focus of was often on the protection of property, as the yard is responsible for fire-fighting and the people on-board. An exception was found to be the time close to delivery, when large numbers of crew may already be on-board. The safety management arrangements of the yards were documented in the safety instructions, which were used in research. Job descriptions for the safety manager and his staff are included, and fire brigade and fire team procedures and equipment, and co-operation and training with municipal fire brigades are addressed. The fire brigades at the studied shipyards have several tasks besides fire-fighting. For example, they may participate in the administration and execution of hot work, they may do fire safety surveys, and maintain fire detection and extinguishing systems. The yard CCC had a formal system of safety audits every six months, where each safety rule of the safety instructions was audited. There were 11 audits per year for a team of 5 persons. This means that compliance with 40-45 rules was checked yearly, such as the use of personal safety gear. In the audit, the percentages of the use of safety goggles, safety shoes, hearing protection and helmets on-board was calculated.

The last interventions of the pre-understanding phase were the interviews with the RCCL project manager (Miorelli 2001) and the yard's Safety Manager (Longeroche 2001) in France. The conclusions were in line with the findings described earlier. The project manager stressed fire-fighting capability and cleanliness, the safety manager waste management and moving work to workshops. With the above steps, a ship owner-driven fire risk auditing and improvement programme, which lasted until 2001, was carried out. After that the action cycles (Numbers 2-12 in Table 3.1) started in co-operation with the shipyards. A summary of these topics collected during the early interactions is presented in tables F3 and F4.

Table F3 Contributing factors related to ignition after the first preliminary interactions (x = factor included in the participant, consultant or insurance company material)

	DNV note June 1999	BSS first report June 1999	BSS reporting until mid-June 2000	RCCL Fire safety index proposal June 2000	First version of fire safety inspection method	Insurance companies risk management practices	Method used on first BSS surveys	Revised method with deck plans	Swiss standard SIA 81
Chemical reactions									X
Combustible liquids							X	X	X
Combustible trash, trash removal	X				X		X	X	X
Control of access to vessel	X				X				
Electric systems									X
Fixed fire load									X
Gas leaks					X		X	X	
Hot work (cutting, welding and grinding)					X		X	X	X
Lighting system hazards	X				X		X	X	
Maintenance of electric and gas systems									X
Mechanical systems									X
Smoking on board									X
Tidiness							X	X	X

Table F4 Responses for mitigating consequences of fires related to project management after the first preliminary interactions (x = information included in the participant, consultant or insurance company material)

	DNV note June 1999	BSS first report June 1999	BSS reporting until mid-June 2000	RCCL Fire safety index proposal June 2000	First version of fire safety inspection method	Insurance companies risk management practices	Method used on first BSS surveys	Revised method with deck plans	Swiss standard SIA 81
Active sprinkler systems					X		X	X	X
Closing of openings between decks									X
Danger of corrosion/toxicity									X
Evacuation routes					X		X	X	
Evacuation signage					X		X	X	
Fire brigades									X
Fire guard systems	X				X		X	X	
Heat and smoke ventilation systems									X
Location, number and type of extinguishing systems	X				X		X	X	X
Number of decks									X
Open cabin doors					X		X	X	X
Open fire doors	X				X		X	X	X
Room height									X
Smoke formation									X
Temporary and permanent fire detection and alarm systems					X	X	X	X	X

The history of action intervention cases 2001-2003

The yards had similar problems, and all had best practices that others could benefit from. When approached by the researcher, the yards expressed an interest in sharing experiences with each other. The number of the owner's own audits and direct steering of safety was reduced. Instead, the researcher encouraged the yards to take more responsibility and introduced the competing yards' safety personnel to each other. In addition to the research methods used in the pre-understanding phase of the study, the co-operation opened new possibilities. Interactions with participants increased, all fire incident statistics of the yards became available and some archival analysis was possible. Quarterly (later biannual) group visits by co-operation safety management personnel to all yards were arranged, and development meetings were held. Incident causes, as well as statistics were discussed, and development possibilities aired. The findings were explicated in meeting minutes and a common Best Practices document where the emergent theory and proposals for further actions were offered for scrutiny. There were 12 action cycles altogether, the first of which was the pre-understanding phase discussed in previous pages. In the following, the histories of development of theory and actions are described for the corresponding period. The numbers of action cycles correspond to numbers of Table 3.1.

Action cycle 2:

After the first work for pre-understanding of the study had been carried out, a new action strategy was devised with RCCL new-building management (Räisänen & Fetten 2001). The aim was to lead the three shipyards that were building ships for RCCL to co-operate in fire risk management. The yards responded positively and, in November 2001, a co-operation start-up meeting with the safety managers of two of the yards was arranged by the researcher. At that time, the third yard was searching for a suitable person to take over safety duties. Therefore, the first meeting was held with two yards representatives only.

Action cycle 3:

A fire risk management workshop was held at the initiative of the safety manager of a yard and the owner's representatives. The researcher of this study wrote the agenda and minutes (Räisänen 2002c), which were afterwards submitted to the participants for review. The aim of the workshop was to discuss progress and plan the further development of fire risk management both at the yard and at RCCL, and, for the purposes of the research, to simultaneously obtain information from the participants to solve the research problem. The issues that had been the focus of the yard were:

- The building area team quality rounds
- Firemen's patrolling procedures
- Flammable waste reduction measures, such as negotiations with suppliers for non-flammable packing.

Metrics of relevant issues:

- Use of ceramic fire protection covering
- Number of hot work permits
- Fire brigade alarm causes at the yard 1998-2001
- Total number of fire brigade alarms 1998-2001
- What has burned at the yard 1998-2001
- Causes of ignition 1998-2001
- First aid 1998-2001

The results of these metrics were discussed. For example, the number of fires due to gas leaks was on the rise at the yard, so active renewal of the gas distribution system was ongoing. The yard's statistic on fire starts 2000-2001 was also presented. The majority of the fires were a result of hot work. Both the yard and RCCL representatives saw this as a development issue. A keynote speech on yard safety was given (Holmberg 2002). Management, emergency training and attitude issues dominated, as did arrangements for fire-fighting. The most important issues were:

- Support of the yard management in safety work
- Continuous safety training
- Crisis training
- Training with local officials
- Constant availability of trained fire chiefs

Furthermore, BSS OY Ltd presented a comparison of the three yards based on subjective observations during the on-board surveys. This gave a good basis for further benchmarking (sub-chapter 3.3.7.4).

Action cycle 4:

A visit of the safety manager of yard BBB at yard AAA had been arranged earlier by BSS OY Ltd. A chance to discuss fire risk management was eagerly accepted by the researcher, some discussions were arranged, and documents were exchanged during the introductory visit. The researcher held the same presentations as in the November 2001 inaugural meeting for the larger audience of two BSS surveyors, the safety managers and the fire chiefs.

Action cycle 5:

All the three yards were represented at the meetings on April 15 and 16, 2002, which gave rise to the subsequent joint efforts. Again, the invitation, agenda and meeting minutes were the duty of the researcher. The topics of the discussions have evolved from meeting to meeting, and best practices and lessons learned have always been items of interest. To enhance spontaneity among the participants, the discussions have not been taped, but a written record has been kept (Räisänen 2002d). The key best practices have been recorded in the new versions of the Best Practices document, and referenced in the two joint conference publications with the safety managers (Räisänen et al. 2003a), (Räisänen et al. 2003c). Thus the participants have been requested to accept the minutes and give continuous feedback of the recorded information.

Action cycle 6

The second meeting of the full Safety Interest Group was held only about a month after the first one in May 2002. The reason was to try to introduce the safety and logistics personnel to each other as soon as possible, and introduce co-operation ideas for the fourth large European shipbuilding company. In the following, the shipbuilding companies are renamed AAA, BBB, CCC and DDD to preserve anonymity. The names AAA, etc. do not necessarily denote the same yards as before. Others present were the safety managers, fire chiefs of yards BBB and AAA, the employees' health and safety delegate of yard AAA and the logistics managers of all yards. Discussions followed the lines of the previous meeting. The logistics managers had a largely separate programme with waste management-related issues. The researcher presented the co-operation ideas from the previous meetings, repeating the main points of comparison and a vision of future work (Räisänen 2002f). The main points of presentation are given below, as they describe well the status of the work at that time. The co-operation work was outlined as:

- Comparisons between yards
- Pooling of experience and best practices
- Sharing of information
- Writing an industry guideline on how to arrange fire risk management work in practice

The researcher also presented a summary of the yard comparisons by Baltic Ship Safe Ltd (Figure 3.15). The greatest variations between the three yards were reported in:

- Quality systems and certifications
- Safety reporting
- Fire door closing practices
- Fire load removal
- Temporary fire detection
- Training and attitudes

Next, the sharing of information that had been agreed upon was described:

- Lost Time Incident statistics (i.e. accidents requiring absence from work)
- Injury and fatality reports, lessons learned
- Fire Incident statistics
- Fire lessons learned
- Fire reports for fires resulting in over €50,000 of damage

In addition, the vision of the previous meeting on future work was shown to the observers:

- Write a draft guideline on all important issues of fire risk management at a passenger vessel shipyard
- Publish and encourage feedback from industry
- Biannual meetings of safety personnel
- Shipyards' own reporting and safety interest group work takes over RCCL surveys
- Shipyard fire guarding
- Hot work procedures
- Hot work card system
- Temporary fire detection
- Fire load removal practices
- Incident reporting
- Draft guidelines for the industry

In the meetings, the researcher again acted as the initiator and secretary. The minutes of the meetings were taken, the key points of the discussions were noted down (Räisänen 2002g), and findings added to the Best Practices document. Minutes and best practices were subjected to participant approval. After introductions, unstructured discussion started. Major problems were found in subcontractor behaviour, and yards QA staff had started to make inspections. Yard BBB stated that night-time behaviour was a problem. Typically, dirty jobs like painting are done at night. The yard DDD had two shifts per day, and any night-time work must be authorised separately. Fire guarding depends on the type of work. The organisation has a production manager in charge of safety organisation; and the human resources manager is in charge of the formalities. Yard BBB had started a stringent campaign against safety violations, and over 120 "red" warnings and 14 dismissals had been carried out. The safety manager reported his current problem in not reporting the near misses and failures. Yard CCC: every week two fire zones of seven are tested. After the first test, 40% more lights were added. Yard DDD: evacuation test once per month, two tests in combination, first evacuation, then and a blackout test, where the electricity is cut off and recovery checked. Communication on-board is sometimes a problem; VHF and mobile phones may not work because of the metal structures. Yard BBB has acquired a VHF communication system in the smoke-diving masks. Fire risk management during sea trials was also seen as an interesting topic for the future.

Action cycle 7:

The third meeting of the safety interest group took place on September 17-18, 2002. The researcher controlled the agenda and documented the meeting in a memorandum (Räisänen 2002h). Those present were the safety and logistics managers and the fire chiefs, except for one yard that had the safety manager, two fire specialists and a project manager. During the two days, the main topics were the role of subcontractors in fire incidents, fire incident reporting and statistics, moveable fire load, hot work practices, best practices of fire risk management, and publication policy of the interest group.

Action cycle 8:

In December 2002, a shipyard had arranged a training day for its fire personnel. All except those on duty were present. The researcher wanted to give good feedback about the fire guard surveys, and showed synthesis slides (Räisänen 2002o), similar to the slides of the previous safety interest group meeting. The topics were the variation of the observed fire load, fire load and weekday, remarks on area types and remarks on yard/subcontractor. Comparative slides with Baltic Ship Safe Ltd surveys and a comparison of ignitions at some European yards were also shown. Individual comments arose about the owner's fire risk management consultants, who were not unanimously welcome on-board. One or two persons felt that the comparative surveys of BSS were insulting. On the whole, however, the presence of the owner's representative seemed to be acceptable. The meeting contributed to the research in the sense that the researcher had a chance to meet the persons who did information collecting work for the yard, and possibly to contribute to their motivation.

Action cycle 9:

Further sessions were conducted with the outfitting work supervisors of one yard and its subcontractors. These were requested by the owner's management on the advice of the researcher. The idea was to talk directly with the persons who are responsible for daily safety management. The shipyard was responsive to the request, especially as there had been several fire incidents over a short period of time. The four sessions took place between February and April, 2003. Altogether about 70 supervisors of the yard and its subcontractors attended. All sessions had approximately the same programme, which consisted of an introduction by the RCCL site manager, a presentation by the safety manager of the yard, and finally a presentation (Räisänen 2003a) and a brainstorming session by the researcher. The duration of the meetings was about two hours. The researcher logged the items of interest in the discussions and brainstorming sessions (Räisänen 2003c). The yard safety manager discussed the past fire events and development targets. He stressed the responsibility of all in safety, as well as waste handling, hot work practices and replacing hot work with other work methods.

Action cycle 10:

The next meeting of the safety managers was in March 2003, again at the one of the yards. Those present all the time were the ordinary members of the safety interest group, safety managers, the fire chiefs of two yards and the logistics manager of one yard. In addition, the representatives of the safety and production organisations of the hosting yard participated when items of interest to them were discussed. The third day was dedicated to discussions with other participants in the industry, and one other ship owner and three classification societies sent their representatives. During the first two days, all members (Elice 2003a), (Elice 2003b), (Elice 2003c), (Furic 2003b), (Moisio 2003a), (Moisio 2003b), (Moisio 2003c), and (Wähler 2002) had a presentation on the safety progress of their respective yards. The researcher held a comparative presentation based on the fire incident statistics of the yards (Räisänen 2003f), a preview of the paper (Räisänen et al. 2003c) and slides for the safety interest group presentation at a conference, due the following month. A distribution of ignitions relative to the phase of building process was recorded in the fire incident statistics of the yards and presented at the meeting (Räisänen 2003e). The distributions of the yards are given below. The data has been normalised as described on p. 70. To meet the confidentiality requirements of the yards, the presented data has been made unidentifiable and the yard letters A to F are redistributed. The original data is a subset of Main Statistics (see Table 3.4 on p. 67). The four shipbuilding companies have seven shipyards altogether, and some typical statistics are presented below. Clearly, there were differences between the yards, which caused lively discussion.

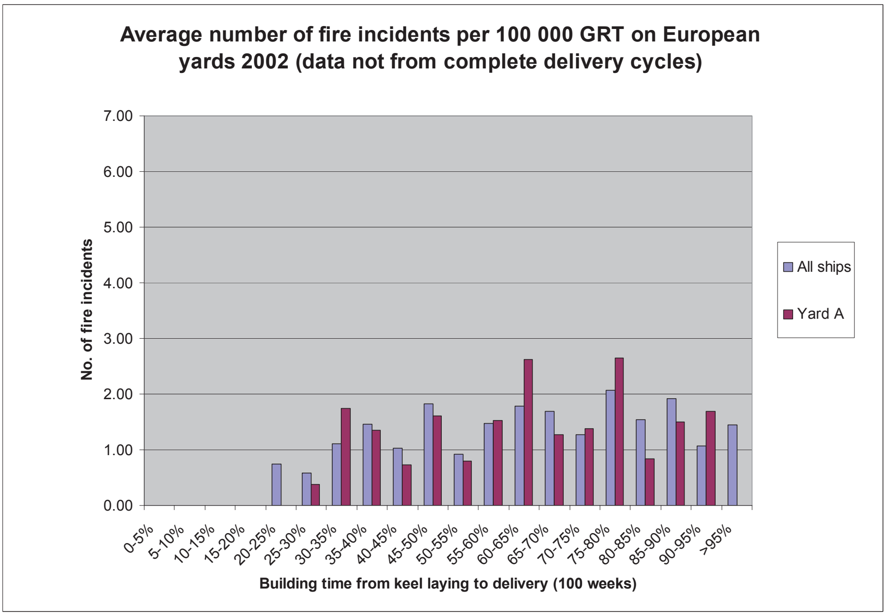

Figure F5 Fire incidents of yard A during 2002 (Räisänen 2003e). The column "All ships" refers to the average of all incidents.

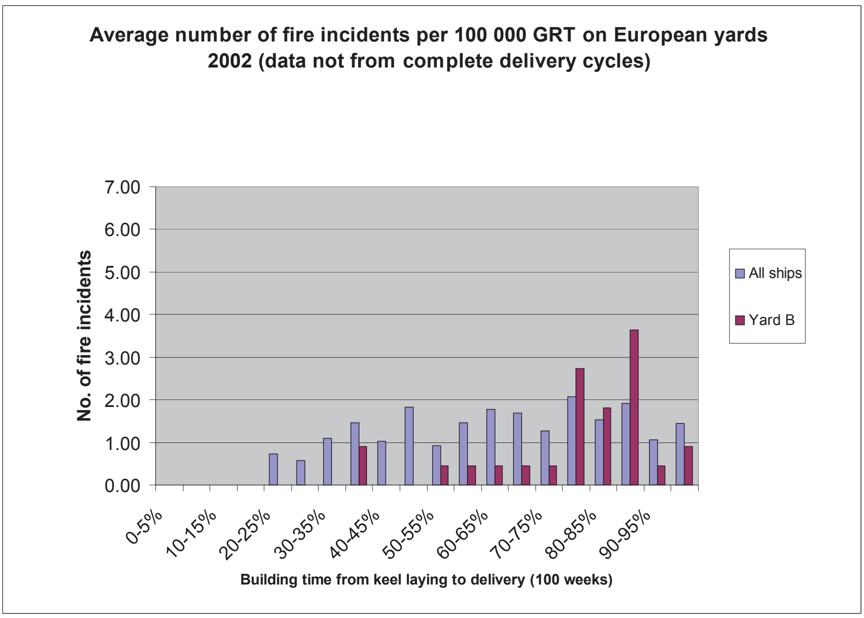

Figure F6 Fire incidents of yard B during 2002 (Räisänen 2003e). The column "All ships" refers to the average of all incidents.

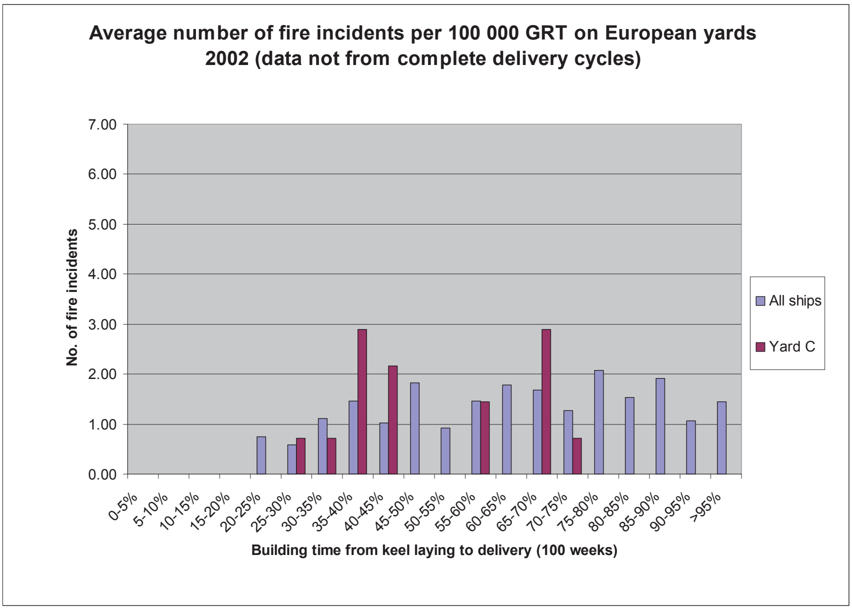

Figure F7 Fire incidents of yard C during 2002 (Räisänen 2003e). The column "All ships" refers to the average of all incidents.

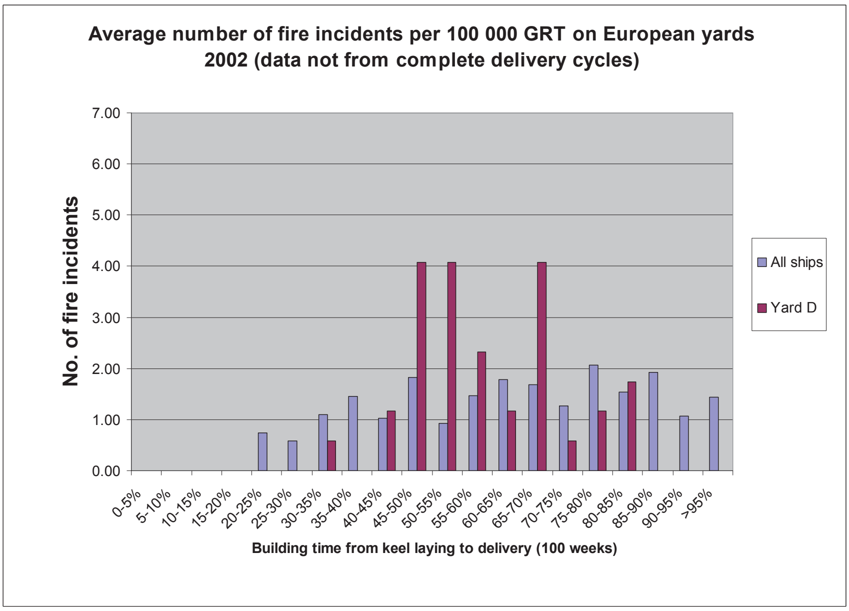

Figure F8 Fire incidents of yard D during 2002 (Räisänen 2003e). The column "All ships" refers to the average of all incidents.

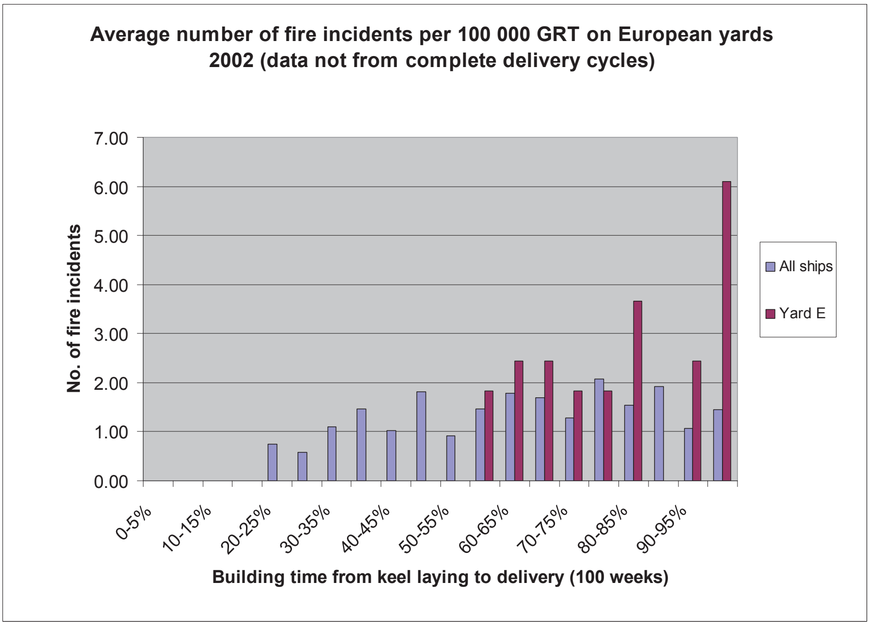

Figure F9 Fire incidents of yard E during 2002 (Räisänen 2003e). The column "All ships" refers to the average of all incidents.

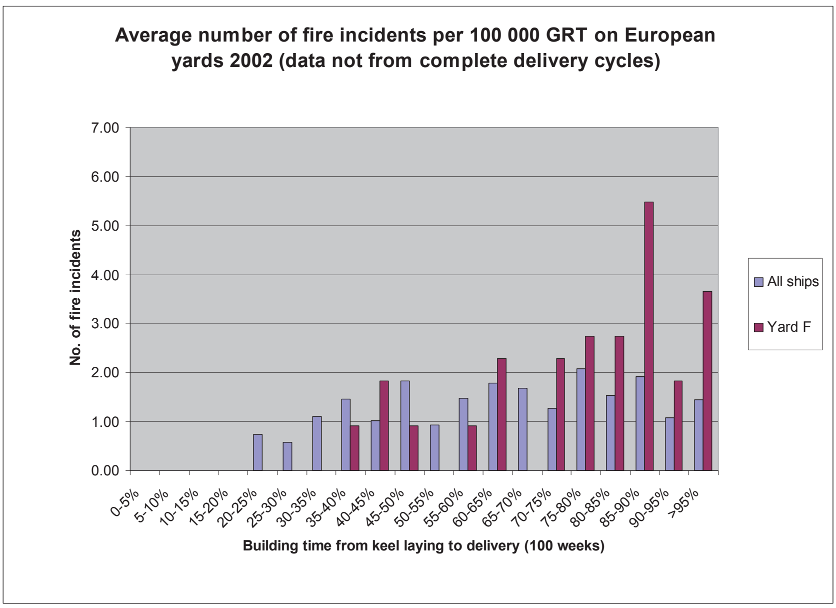

Figure F10 Fire incidents of yard F during 2002 (Räisänen 2003e). The column "All ships" refers to the average of all incidents.

For the purpose of this research, the incident statistics were divided further into causes and fuels, for the enabling of qualitative conclusions during the actions. The two-day meeting allowed the researcher to extract some issues for the Best Practices document. In addition, the importance of the temporary closing of openings came up as a potential response to be studied further.

Action cycle 11:

The actions were carried out as an extension of ordinary ship project meeting with some two hours of duration, and the results added to the research evidence.

Action cycle 12:

Event tree results were calculated and presented in the last Safety Managers meetings, and discussed individually with the Safety Managers to steer the focus at the yards, which was a success and caused rapid changes in shipyards processes. The first ones to change were the yards, which had had recent large fires.

Appendix G: Ship orders during the research

The yards that participated in the research had 31 ships on their order books during the action stage of the research 2001-2003, and of these about 25 were in active production, the rest having delivery dates further into the future (Elice 2003d), (Furic 2003a), (Moisio 2003d), (Wähler 2003). Below, a compendium is presented. The expected month and year of delivery at the time and the size of the vessel have been given. The number of the vessel is composed of the yard initials and the yard building code (the "newbuilding number"). The overlapping nature of the production process is clearly visible in the compendium: a certain yard may be seen to have several deliveries during one year although the production takes a longer time, for instance vessels 1347 and 1348, which are part of a series of five vessels.

The size of the vessels in the list varies from 59,000 to 150,000 GT, which means roughly a three-fold difference in volume between the largest and smallest vessel.

Ship number	Delivery date	GRT	
CATA32	January-08	100000	
CATC32	December-02	88000	
CATD32	May-03	88000	
CATG32	December-03	150000	
CATH32	June-03	64000	
CATK32	March-03	59000	
CATL32	March-04	59000	←
CATT31	January-08	100000	←
CATU31	May-02	91000	
CATV31	January-08	100000	←
CATX31	March-02	58600	
JLM649	December-02	110000	
JLM650	March-04	110000	
JLM656	July-02	110000	
JLM657	August-03	110000	
JLM658	April-04	110000	←
KMYH501	August-02	85900	
KMYH502	May-03	85900	
KMYH503	December-03	85900	
KMYT1347	November-02	138300	
KMYT1348	October-03	138300	
MA6075	November-02	82000	
MA6076	June-03	82000	
MA6077	April-04	82000	←
MA6078	January-05	82000	←
MA6079	October-05	82000	←
MO6057	October-02	109376	
MO6058	June-03	109376	
MO6067	March-04	109376	←
SC6086	October-03	101350	

Figure G1 The cruise vessels on order during the statistics collection period of the research according to the yards. All of the ships did not contribute to the main fire incident statistics of 2002-2003, for example because their production was started later. These ships are marked above with arrows. [CAT= Chantiers de l'Atlantique (Furic 2003a), JLM = Jos. L. Meyer GmbH (Meyer Werft) (Wähler 2003), KMYH = Kvaerner Masa-Yards Helsinki yard, KMYT = Kvaerner Masa-Yards Turku yard (Moisio 2003d), MA= Fincantieri Marghera yard, MO= Fincantieri Monfalcone yard, SC= Fincantieri Sestre yard (Elice 2003d). In the Figure, the acronym GRT is used to denote gross tonnage GT.]

Appendix H: Results of experts' survey on fire risks, and the potential of their mitigation by the responses, and feasibility of the responses

Table H1. Eleven experts' estimate (see sub-chapter 3.3.6) on the potential of responses to mitigate fire risk and their feasibility for shipyard use on scale 1 - 3 (3 = high). The numbers of responses refer to Table 5.5, Table 5.6 and Table 5.7.

Factors which contribute to ignition	No.	Available responses	Expert estimate on potential of the response to mitigate the risk	Expert estimate on suitablility of the response to shipyard process and ease of implementation
1) Arson	1	Automatic suppression	2,6	2,1
	2	Good lighting	1,8	2,0
	3	Guarding of premises, control of access to vessel	2,3	2,4
	4	Housekeeping to avoid flammable waste	2,6	2,1
	5	Restricted access to compartments	2,0	1,4
2) Autoignition	6	Avoiding autoignition of glues and plastic, ignition of incompatible chemicals	2,4	2,1
	7	Managing the use of incompatible chemicals used in the plant	2,5	2,0
3) Electric phenomena	8	Static electricity: proper grounding of vessel and its temporary and permanent parts, especially pipes	1,9	1,9
	9	Use of lightning conductors, earthing in general	2,0	1,9
4) Electric systems	10	Careful electricity off (blackout) testing	1,9	1,7
	11	Damage control of cabling	2,0	1,6
	12	Ensuring overheating protection in electric systems	2,1	1,9
	13	Overheating checks with IR equipment	2,3	1,6
	14	Prohibiting domestic appliances onboard, e.g. coffee-makers	2,3	1,8
	15	Proper installation of temporary electric systems	2,8	2,4
	16	Shutting down of electric appliances when not in use	2,6	2,0
	17	Systematic maintenance of electric appliances and cabling, e.g. motors, transformers and welding machines	2,4	2,1
	18	Use of explosion-proof appliances in hazardous areas	2,5	2,0
	19	Use of protected work lights instead of unprotected bulb lights	2,1	2,0

Table H1. Eleven experts' estimate on the potential of responses to mitigate fire risk and their feasibility for shipyard use on scale 1 - 3 (3 = high). The numbers of responses refer to Table 5.5, Table 5.6 and Table 5.7.

Factors which contribute to ignition	No.	Available responses	Expert estimate on potential of the response to mitigate the risk	Expert estimate on suitablility of the response to shipyard process and ease of implementation
5) Explosions, dust, gas, and vapors	20	Avoiding gas leaks and dust accumulations	2,9	2,6
	21	Explosion-proof machinery	2,0	1,6
	22	Pressure relief structures	1,9	1,6
	23	Restricted storage on board for highly flammable materials	2,9	2,1
	24	Special cautions for explosives	2,5	2,3
6) Fire load	25	Avoiding accumulation of dust	2,5	2,3
	26	Avoiding highly flammable solvents for cleaning and gluing	2,6	1,9
	27	Good house-keeping, especially waste logistics, and near heat sources	3,0	2,4
	28	Installing emergency shutoff systems for liquids and gases in piping	2,4	2,4
	29	Maintenance of gas distribution systems	3,0	2,5
	30	Odorizing of gases to help in leak detection	2,7	2,9
	31	Requesting non-flammable packaging from suppliers	2,9	2,1
	32	Restricted storage of installation materials onboard	3,0	2,4
	33	Restricted use of flammable temporary materials onboard, e.g. scaffolding	2,6	2,5
	34	Storage of flammable liquids on outer decks in a protected container	2,8	2,0
	35	Use of trash chutes at sides of the ship	2,6	2,5
	36	Unpacking flammable packaging before materials are taken aboard	2,9	2,3
	37	Use of non-combustible construction materials, furniture and decorations	2,8	2,1
	38	Use of safety precautions with fuel oil or lubrication oil in connection with hot machinery	2,5	2,4
	39	Use of temporary flameproofed coverings over materials	3,0	2,6
	40	Utilizing statistics of yearly volumes, materials and densities of flammable waste in a shipyard	2,4	2,0

Table H1. Eleven experts' estimate on the potential of responses to mitigate fire risk and their feasibility for shipyard use on scale 1 - 3 (3 = high). The numbers of responses refer to Table 5.5, Table 5.6 and Table 5.7.

Factors which contribute to ignition	No.	Available responses	Expert estimate on potential of the response to mitigate the risk	Expert estimate on suitablility of the response to shipyard process and ease of implementation
7) Heating and ventilation	41	Maintenance of blowers and heating systems	2,0	2,3
	42	Functional overheating protection in equipment	2,3	2,0
	43	Special caution for unattended heating systems	2,3	1,9
8) Hot surfaces and open flames	44	Thermal isolation of hot surfaces from fuels	2,3	2,5
	45	Avoiding work with open flames, protective procedures	2,5	2,5
9) Hot work (welding, cutting, grinding, torching)	46	Disconnecting gas and electricity of hot work tools when not in use	2,8	2,3
	47	Effective hot work procedures	2,8	2,6
	48	Fire watch system	2,9	2,9
	49	Gas leak detection by listening hissing at night, or before hot work	2,3	1,8
	50	Hot work permit system	2,9	2,8
	51	Hot work prohibited during holiday times	2,5	2,4
	52	Hot work transfer to workshops	2,5	2,3
	53	Hot work safety exam and personal hot work card	2,8	2,5
	54	Hot work supervision plan	2,6	2,5
	55	Measuring gas content in room before hot work	2,4	2,1
	56	Precautions during fuelling of ship systems	2,4	2,5
	57	Precautions for hot work in special circumstances, e.g. in tanks	2,9	2,9
	58	Reduction of amount of hot work by design	3,0	1,9
	59	Strict policy to unauthorized hot work	2,9	2,8
	60	Systematic maintenance of gas systems	3,0	2,6
	61	Training, own personnel and subcontractors, special courses for foreign workforce	2,6	2,4
	62	Use of non-sparking tools near flammable materials	3,0	2,0
	63	Use of protective coverings	3,0	2,4
	64	Using alternative methods instead of hot work	3,0	1,9

Table H1. Eleven experts' estimate on the potential of responses to mitigate fire risk and their feasibility for shipyard use on scale 1 - 3 (3 = high). The numbers of responses refer to Table 5.5, Table 5.6 and Table 5.7.

Factors which contribute to ignition	No.	Available responses	Expert estimate on potential of the response to mitigate the risk	Expert estimate on suitablility of the response to shipyard process and ease of implementation
10) Machinery	65	Jacketing of high pressure oil lines	2,0	1,6
	66	Maintenance of flame or spark producing equipment	2,3	2,1
	67	Maintenance of rotating machinery	1,9	2,0
	68	Maintenance of sliding surfaces in machinery	1,9	1,9
	69	Risk management of combustion engines and compressors	2,0	1,7
	70	Safe location of compressors	2,4	2,1
	71	Systematic procedures for using motor vehicles on board	2,4	2,3
11) Painting	72	Good housekeeping with solvents and waste	3,0	2,4
	73	Precautions for hot work, cleanliness, ventilation and chemical reactions	3,0	2,4
	74	Proper earthing of substances	2,6	2,5
12) Sea trials	75	Proper engine operation	2,5	2,5
	76	Seaworthiness checks before sea trials	2,6	2,9
	77	Tested fire alarm, detection, public announcement and extinguishing systems	3,0	2,8
13) Smoking of tobacco	78	Education of fire safety	2,8	2,4
	79	Inspections	2,5	2,3
	80	Smoking restricted with designated smoking places	2,5	2,4
14) Miscellaneous	81	Avoiding ignition by shock and impact with material and tool choices	2,4	1,9
	82	Avoiding light energy (e.g. halogen) ignitions by education	1,8	1,5
	83	Avoiding sparks in lifting and moving operations	2,6	2,4

Table H1. Eleven experts' estimate on the potential of responses to mitigate fire risk and their feasibility for shipyard use on scale 1 - 3 (3 = high). The numbers of responses refer to Table 5.5, Table 5.6 and Table 5.7.

Consequences of established fires	No.	Available responses	Expert estimate on potential of the response to mitigate the risk	Expert estimate on suitablility of the response to shipyard process and ease of implementation
Human damages in fire	84	Adequate emergency lighting and signage	2,6	2,5
	85	Closing of temporary and permanent openings	2,6	2,3
	86	Counting systems for the personnel left on board after evacuation	2,6	2,4
	87	Control of access to vessel	2,6	2,1
	88	Early division of the ship into functional main vertical fire zones, and separation of rooms by structural and fire bulkheads and decks	2,9	2,3
	89	Early manual detection, alarming and suppression	3,0	2,4
	90	Escape and fire-fighting routes built early and kept functional	2,9	2,3
	91	Fire compartmentation	2,9	2,3
	92	Fire integrity of vertical casings, staircases and ventilation ducts built early	2,8	2,0
	93	Functional temporary and permanent fire detection, alarming and public announcing systems	3,0	2,3
	94	Installation of windows early in the production process	2,6	2,6
	95	Keeping fire doors always closed	3,0	2,3
	96	Locking of cabin and storage doors	2,5	2,1
	97	Possibly smoke and heat ventilation	2,6	2,0
	98	Practiced evacuation procedures	3,0	2,7
	99	Reviews of personnel risks and safety culture	2,9	2,1
	100	Safety training (general , other than fire safety)	2,7	2,4
	101	Smouldering fires left behind a workshift mitigated with fire watches or overlapping shifts	2,6	2,1
	102	Sufficient extinguishing capacity	3,0	2,4
	103	Sufficient safety personnel capacity	2,7	2,4
	104	Use of automatic detection and extinguishing systems	3,0	2,1
	105	Use of portable extinguishers by all employees	2,7	2,4
	106	Temporary closing of vertical ducts during building process, especially cable ducts	2,9	1,7
	107	Thermal isolation for structural stability in fires	2,1	1,9

Table H1. Eleven experts' estimate on the potential of responses to mitigate fire risk and their feasibility for shipyard use on scale 1 - 3 (3 = high). The numbers of responses refer to Table 5.5, Table 5.6 and Table 5.7.

Consequences of established fires	No.	Available responses	Expert estimate on potential of the response to mitigate the risk	Expert estimate on suitablility of the response to shipyard process and ease of implementation
Direct material damages in fire	108	Automatic suppression in storage containers of flammable liquids and gases	2,3	1,8
	109	Availability of portable extinguishing systems close to work locations	2,9	2,5
	110	Avoiding smoke and water damages by fast suppression	2,9	2,1
	111	Avoiding structural collapse with material choices	2,4	1,6
	112	Early commissioning of onboard suppression systems	2,9	2,0
	113	Fast responses with portable extinguishers	3,0	2,6
	114	Fire brigades	2,9	2,8
	115	Fixed suppression systems in machinery spaces	3,0	2,0
	116	Functional fire suppression, both temporary and ship's own system, preferably automatic	3,0	2,4
	117	Good liaison with local fire brigade	2,8	2,9
	118	Isolation of conductive surfaces for structural stability built early	2,4	1,9
	119	Prevention of accidental CO_2-release in engine	2,9	2,6
	120	Sufficient fire detection, alarming and suppression capability in cabins immediately after installation	2,9	1,6
	121	Sufficient fire pumps, hose connections, pressure and water supply for uppermost decks of the vessel	2,8	2,6
	122	Sufficient supply of pressurized water to premises	2,9	2,5
	123	Trained shipyard fire brigade available fast	2,9	2,8
	124	Use of temporary detection and alarming near waste bins	2,8	2,1

Table H1. Eleven experts' estimate on the potential of responses to mitigate fire risk and their feasibility for shipyard use on scale 1 - 3 (3 = high). The numbers of responses refer to Table 5.5, Table 5.6 and Table 5.7.

Consequences of established fires	No.	Available responses		Expert estimate on potential of the response to mitigate the risk	Expert estimate on suitablility of the response to shipyard process and ease of implementation
Secondary damages	125	Avoiding damages to environment by containment		2,4	2,0
	126	Avoiding delayed deliveries to customers by reserves in schedule		2,4	1,8
	127	Avoiding loss of information by backup		2,7	2,3
	128	Avoiding lost production by rapid suppression		2,6	2,1
	129	Isolation of conductive surfaces for structural stability and to prevent fire conduction to adjacent compartments		2,6	2,0
	130	Making pump capacity available for draining of suppression water to prevent vessel capsize		2,0	1,8
	131	Removing obstacles from drainage paths for extinguishing water to prevent capsize of vessel		1,8	1,6

Table H1. Eleven experts' estimate on the potential of responses to mitigate fire risk and their feasibility for shipyard use on scale 1 - 3 (3 = high). The numbers of responses refer to Table 5.5, Table 5.6 and Table 5.7.

Shipyard arrangements for managing fire risk	No.	Available responses		Expert estimate on potential of the response to mitigate the risk	Expert estimate on suitablility of the response to shipyard process and ease of implementation
General shipbuilding fire risk mitigation	132	Alternative ship design criteria for fire safety		2,4	2,1
	133	Fire safety training of personnel		2,9	2,3
	134	Including fire safety in contracts		2,9	2,4
	135	Organized risk management and safety personnel		2,7	2,4
	136	Safety attitude PR and communication for the yard and suppliers		2,4	2,1
	137	Systematic fire risk management program and safety plans		2,7	2,4
Arrangements onboard	138	Arrangement of fire guard systems and inspections		2,7	2,4
	139	Audits, surveys and inspections		2,4	2,6
	140	Constantly manned central control station		2,7	2,3
	141	Surveillance of hazardous behaviour onboard		2,7	2,4

Appendix I: Other research material

Some minor parts of research material were obtained during brief encounters with the participants. The methods of inquiry are described below.

Inquiry of management perception of risk using a risk matrix as a dialectical tool

A small check of risk perception of experienced shipyard managers and DNV consultants was carried out at one yard with a proposed risk matrix. Risk classes and impact categories were chosen according to an IEC standard (International Electrotechnical Commission, 2000, Fig. 4, p. 35), and the definitions were adapted for the shipbuilding process. The definitions were subjected to industry scrutiny at a risk management meeting between the owner's senior representatives, shipyard senior management and two consultants from DNV. At the meeting, the probability-impact grid was presented (Räisänen 2002p) to the participants, and discussed (sub-chapter 3.3.7.2). The risk classes and impact categories are explained in Figure I2. According to the resulting risk matrix (Figure I1) and the views of the managers of the yard, in the past cruise vessel building probably has belonged to the category "high risk". The fact that all major passenger vessel shipyards have suffered risk events of major impact within the last 15 years seems to support the above. The matrix allowed a way to quantify and classify risks, and thus helped the participants to form a view of the overall risk scene. The matrix has an output of four risk classes: high, intermediate, low and trivial, which are a product of the frequency of occurrence and severity of impact. In literature, it is also termed a probability impact grid (e.g. Chapman & Ward 1997) or risk criterion (or event) status (PMI 1992).

Frequency of occurrence	Indicative frequency (per year)	Severity of impact			
	Numbers from Dutch law or other source	Catastrophic	Major	Severe	Minor
Frequent	>1	H	H	H	I
Probable	1 – 0.1	H	H	I	L
Occasional	0.1 – 0.01	H	H	L	L
Remote	0.01 – 10^{-4}	H	H	L	L
Improbable	10^{-4} – 10^{-6}	H	I	L	T
Incredible	<10^{-6}	I	I	T	T

Figure I1 A proposed representative fire risk matrix of passenger shipbuilding

Risk classes:	
H = High risk, I = Intermediate risk, L=Low risk, T=Trivial risk	
Consequence categories for shipbuilding:	
Catastrophic	Virtually complete loss of vessel. Fatalities probable
Major	Extensive damage to the ship. Possibly fatalities or severe injuries
Severe	Severe injury, significant damage for the ship or a ship system
Minor	Minor injury, minor system damage

Figure I2 Risk class and impact categories (adapted from International Electrotechnical Commission 2000, p. 35)

Fire risk index

The choice of most suitable method for the quantitative fire risk assessment of new-build vessels depends on the required accuracy and effort. To improve the situation, the merits of semi-quantitative and quantitative methods were judged. From a brief literature analysis, it was concluded that obviously the sophisticated fire dynamics models with stochastic processing were not tools for judging whether fire risk management was good or bad on a certain day in a certain area in a ship under construction. A fire risk ranking index method was developed, based on the existing information on such indices (e.g. (Fontana 1984), (Magnusson & Rantatalo 1998)) and tested with the participants (sub-chapter 3.3.7.3). The literature is related to the fire risk management of buildings that are in normal use. In the test of this study, the results were extended to ship fire risk management during construction. The main idea was to compare the different elements of the fire risk management of a vessel under construction with each other. For the purposes of this work, the term "fire risk index" was used for an approach, which uses empirical weighing for the quantified hazards and safety features of the system under construction, and results in one comparative number. (Interestingly, the method was familiar to some participants of the action research process, as a similar indexing approach is used by the marine community in the damage stability assessments of ships, where an attained damage safety index is compared to a required index (International Maritime Organization 2001, p. 95)). Fire risk (safety) indices are in use in general fire safety. Watts (2002) lists insurance ratings such as the Specific Commercial Property Evaluation Schedule and the Swiss SIA 81 (Gretener)

Method (Fontana 1984), and chemical industry indices such as Dow's Fire and Explosion Index, Mond Fire, Explosion and Toxicity Index and the Fire Safety Evaluation System for institutional occupancies. In addition to these relatively simple methods, the evaluation can be done at several levels according to a hierarchical system. Rasbash et al. (2004) link these methods to multi-attribute decision analysis of the management science. According to Watts (2002, p. 5-126), risk index methods may be appropriate if greater sophistication is not needed, risk screening is cost-effective or there is a need for risk communication. All these conditions were valid for the research at hand. The idea was to take an established index method and apply it to the shipbuilding environment as well as possible and, consequently, to ask participants for opinions, should a similar approach be developed for shipbuilding use. The requirement of simplicity ruled the multi-attribute methods out of the demonstration, which was based on the Swiss SIA 81 method (Fontana 1984) summarised below.

The method was based on a calculated fire risk index R that has to be less than an empirical, accepted risk coefficient. The index R is calculated as a quotient of a potential danger factor P and the product of all protection factors. P is an empirical function of moveable fire load, combustibility, smoke formation, danger of corrosion/toxicity, fixed fire load, structure height and the area and form of fire compartments.

$$R = \frac{P}{M} = \frac{P}{N \cdot S \cdot F} \cdot A$$

where

A = Activation danger, relative to building type; mechanical engineering facilities are more risky than dwellings

N = Ordinary protection measures, empirical functions relative to, for example, extinguishers and staff preparation

S = Special measures, empirical functions relative to, for example, fire detection and level of public fire brigade

F = Empirical functions of structural measures

Appendix J: Event tree and its applications concerning early use of sprinklers on-board

The event tree is one of the available tools for estimating the probabilities of possible outcomes following an initiating event (Watts & Hall 2002, p. 5-5). For this research, it provided a way of illustrating quantitative fire risk management evaluation for the participants.

An event tree is a visualization of probabilities of events arranged in ascending temporal order. For each branch of the tree, a probability is assigned (see Figure J1). The combined probability of final branches can then be used in fire safety decision-making. Event trees can be produced for fire risk management of a cruise vessel under construction. However, in practice, obtaining reliable estimates for the branch probabilities is a challenge, as the statistics and reporting have limited sample sizes, and projects differ from each other, as do the local circumstances at each yard. A possible aid to decision-making for a cruise vessel project may lie in comparing technical alternatives. In this research, an event tree estimate for the increased protection of an operational sprinkler system was presented to the participants. The tree that was used to provide an example for the shipyards is discussed in the following pages.

During the actions, the question of their effectiveness came up several times. All participants were unanimous about its benefits, but discussions remained on an abstract level. To start a discussion on the merits of such protection during the cruise vessel building process, and to provide the participants with some input for investment calculations, some rough numbers on the probability of large fires were calculated and presented at a later safety managers' meeting (Räisänen 2003i). "Large fires" were defined for the purpose as fires, which involve two or more fire compartments. A fire in one fire compartment (max. size 1,600 m^2 (International Maritime Organization 2001a)) may spread to the deck above or to the neighbouring compartment through openings or by conduction, and the time available for extinguishing is short.

The chosen fire scenario represents the most usual type of fire on-board: hot work and waste-induced fire. The aim of the exercise was not to attempt to calculate an accurate frequency of large fires, but to use the event tree to help participants to reflect and to support feasibility studies at the yards. Therefore, it was deemed sufficient that the assigned probabilities were of the correct order of magnitude, and that the participants were happy with them. Two examples of event trees for the scenario may be found in Figure J1 and Figure J2, for 0% and 100% coverage of extinguishing. The "without sprinklers" scenario represents the situation at the yards during 2002. Coincidentally, the obtained ratio of one large fire per 150 ignitions is a realistic figure when compared with the available incident histories of the statistics, which was fortunate for the purpose of the exercise, the stimulation of discussion. However, a considerable amount of further evidence on probabilities of various branches is needed before any realistic calculation of probability of large fires on-board may be made.

The workers themselves or the first-wave firemen extinguish most of these kinds of fires, and the 98% probability assigned to the first branch of the tree is supported somewhat by the statistics available. Next, the branch of the effect of sufficient fire load in the compartment needs more study, but a 75% chance of having sufficient fire load was chosen as a representation of current working practices, where a lot of installation material goes on-board relatively early. A better estimate might be obtained through calculation of the fixed fire load of the vessel and the moveable fire load from waste surveys, as a function of building time.

However, the interest lay in fires in which the first intervention fails or is non-existent, i.e. the "large fire" scenario (event S3 onwards): the cases where early intervention by people on-board has failed, and there is sufficient fire load for escalation. The sprinkler in the room was assumed to release, if it was available. The availability of the system is represented in the calculation simply by the input value of percentage of the area covered with operating sprinklers. Several coverage values were calculated. The probability of system malfunction was set to 5%, derived as the complement probability from known data of their probability of satisfactory operation 92% to 97% (various sources, quoted by Rasbash et al., 2004, p. 226). This may also be compared with the quoted success rates of 86% to 99%, which indicate that the selected probability of malfunction has a correct order of magnitude.

In the branch where release was not successful, the fire brigade was assumed to attack the initial room. The branch probability of "confinement by fire brigade" was assumed to be 0.5 in the initial room. For a more accurate estimate of this value, some evidence might be found from the yards' statistics, or might be obtainable through numerical simulations.

The next branch represented the possibility that the fire brigade attack in the initial room was not successful. Then the system in the whole fire compartment was assumed to release, if it was available. The availability was assumed to be a function of the coverage percentage and initial room sprinkler status. The correlation between system availability in the initial room and the whole fire compartment is an interesting question to be studied: if release has failed to occur in the initial room, there is a correlation that the surrounding area may not experience it either. For example, the system at that location may be under construction or there may be a power or water supply failure. This is represented by the input value "Probability of failure of the fire compartment sprinklers if the initial room sprinkler is not functional". In Figures J1 and J2, the value was taken as 0.8, and in Figure J3 some variations was shown.

If the release in the whole fire compartment was not successful, it was assumed that the fire brigade would try to confine the fire within the fire compartment barriers. For the whole fire compartment, the probability of successful confinement by the brigade and fire barriers was assumed to be 0.1. This low value is backed by some experience of the yards, but again statistics and simulations could be used to gain more insight.

The limit values for system coverage variations and their malfunction as a group are shown in the graphs for "large fire" probability (Figure J3). In the discussions, the graph was used to illustrate to participants that the unknown probability may lie somewhere between the curves. The graph was used to illustrate fire escalation from one fire compartment to another, if early intervention has failed and there is sufficient fire load. At a shipyard, this typically would mean the outcome of a fire that requires smoke diving and fire brigade attack with water extinguishing. Without the use of automatic extinguishing, as was the situation during the action, the calculated event probability would mean that approximately every other runaway fire in one compartment escalates to the neighbouring fire compartment. From the small amount of large fires in the statistics, no firm probabilities could be drawn.

However, in the light of the calculations, the message to the participants was that it seemed probable that significant loss risk reduction could be possible with active automatic extinguishing systems during construction. The figure of the current situation of approximately one large fire per 150 fire incidents was put forward, and was compared to a frequency of 10-20 times less, should the sprinkler systems be available continuously during the building process. The unanswered question “what other means are there to make the “large fire” risk ten times smaller?” hints at future development possibilities.

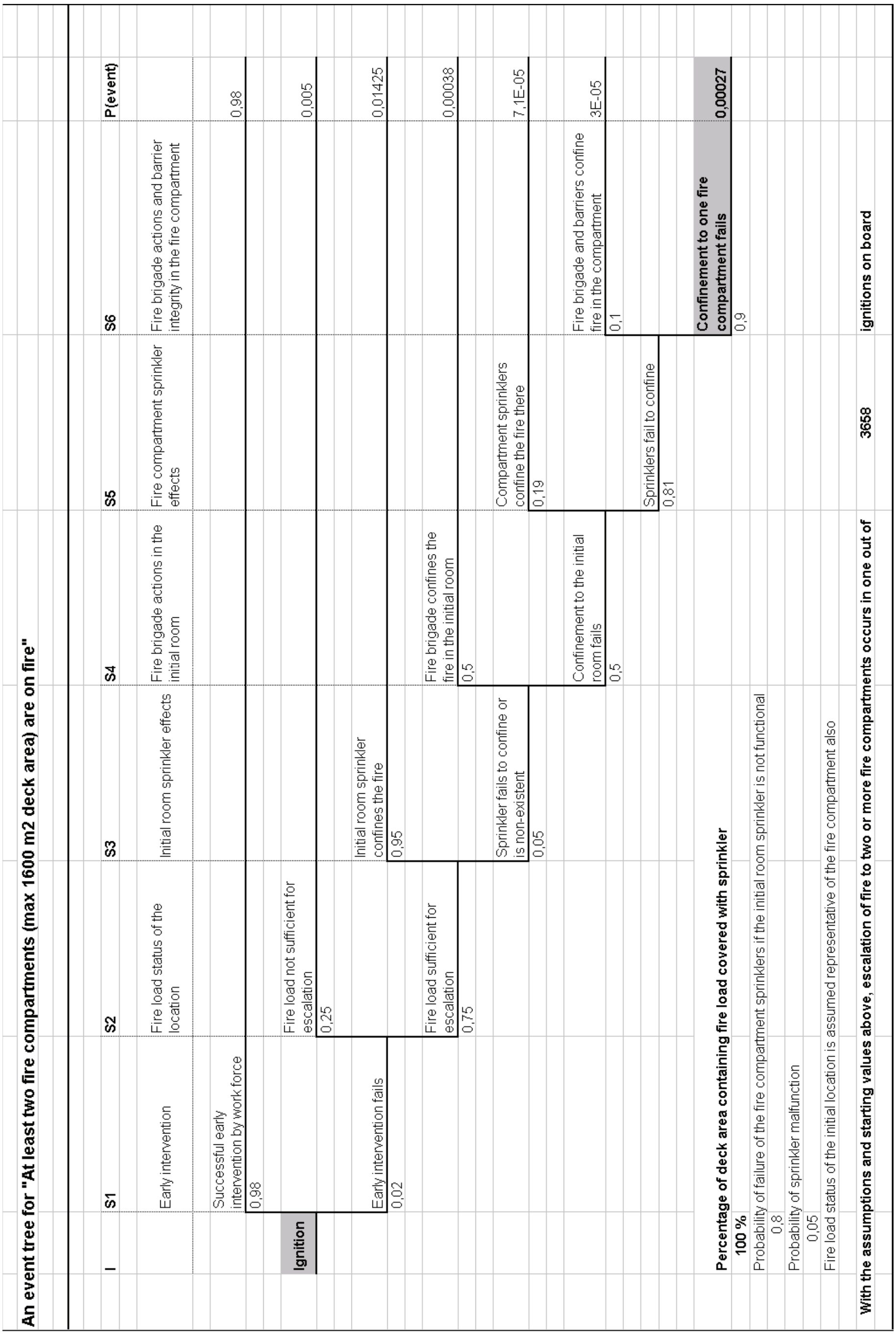

Figure J1 An event tree for "sprinklers fully operational" case

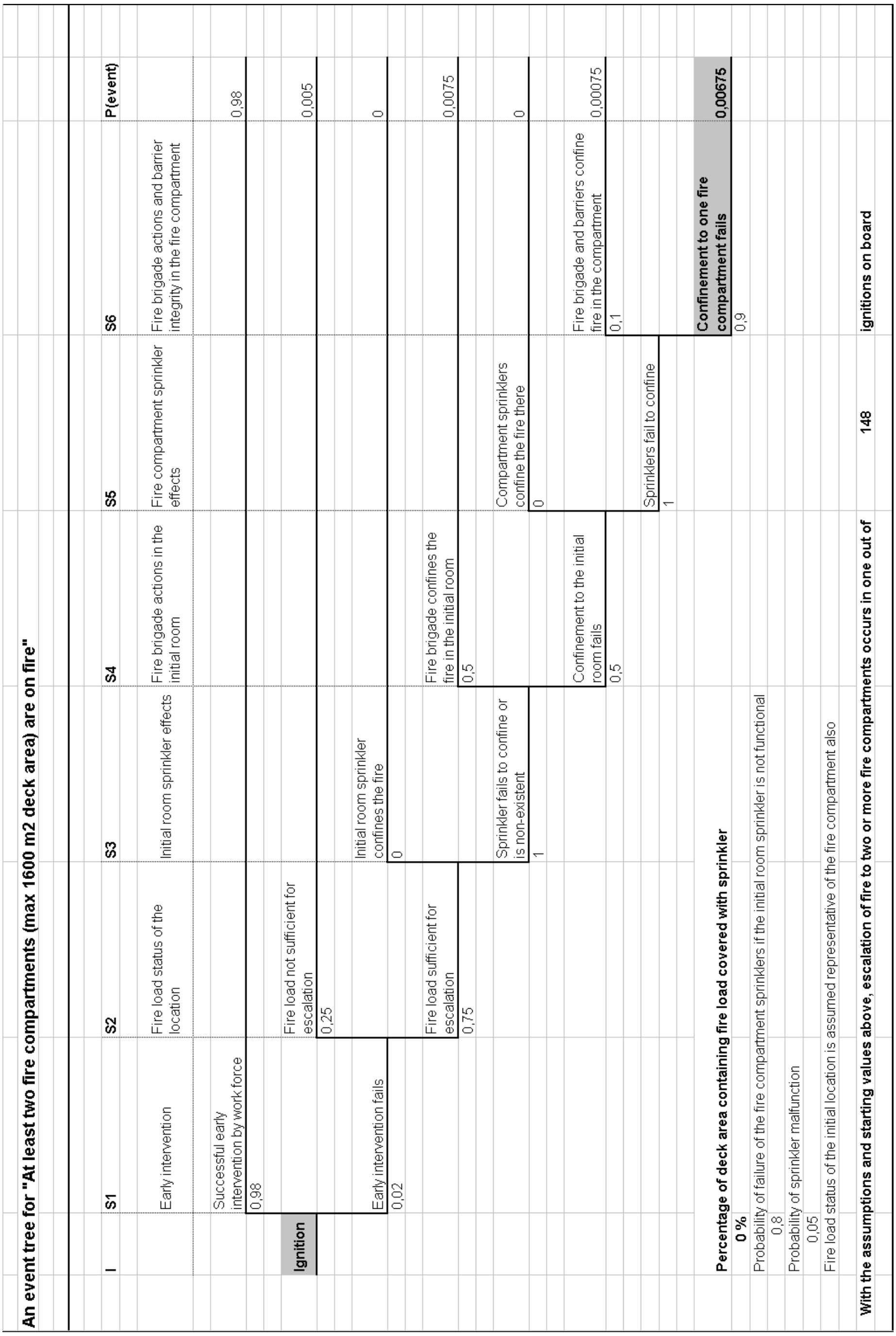

Figure J2 An event tree for "no sprinklers" case

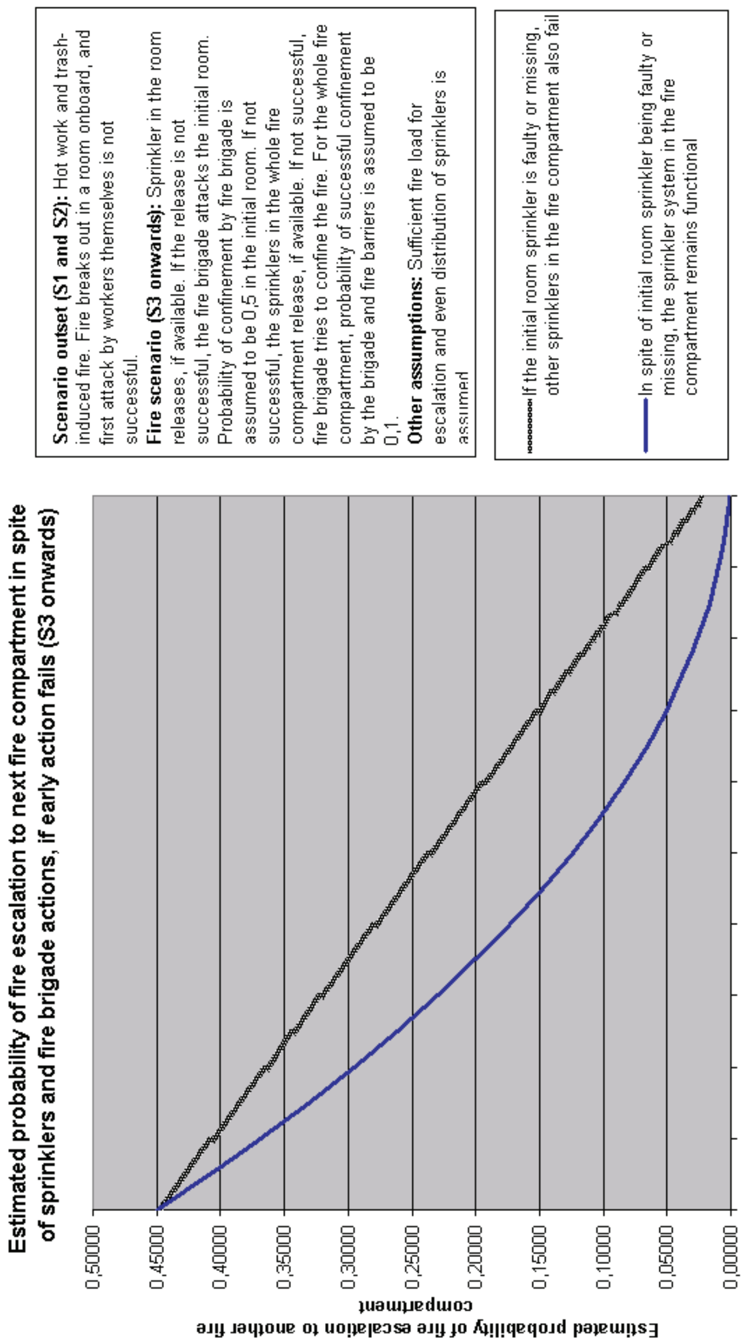

Figure J3 Estimated probability of escalation to next fire compartment

Appendix K: Summary matrix of empirical evidence on fire risk on-board

During the research action cycles, a large amount of qualitative and quantitative information was generated with several different research approaches as discussed in sub-chapter 3.3. The information gave a description of the 14 contributing factors of ignition and the three consequence categories that represented the fire risk in cruise vessel construction. In this Appendix, the findings are summarised in matrix format to give an overview of the coverage of some of the evidence.

Table K1 Quantitative evidence on contributing factors to ignition (continues on the following page)

QUANTITATIVE APPROACH					
Factors that contribute to ignition	**One yard's fire incident statistics 1998 - 2001 (227 incidents)**	**European fire incident statistics 2002 - 2003 (222 incidents)**	**Owner´s fire safety surveys onboard 2000 - 2003 (17 surveys of 3 to 5 days in duration)**	**One yard´s fireguards' surveys onboard 2001 - 2003 (151 overnight surveys)**	**Questionnaire survey of risks and response feasibility**
1) Arson		Suspected			Associated risk ranked as "Elevated" by the experts (Table 4.2)
2) Autoignition					Associated risk ranked as "Elevated" by the experts (Table 4.2)
3) Electric phenomena					Associated risk ranked as "Low or average" by the experts (Table 4.2)
4) Electric systems	11 % of fires were due to electrical reasons (Fig. F2 in Appendix F)	12 % of fires were due to electrical reasons (Figs. 4.5, 4.7)	Relevance for on-board fire risk partially supported by the empirical evidence (Fig. 3.10)		Associated risk ranked as "Elevated" by the experts (Table 4.2)
5) Explosions, dust, gas, and vapors	12 % of fires concerned gas hoses or distribution network (Fig. F1 in Appendix F)	7 % of fires concerned gas distribution (Figs. 4.8, 4.12)	Relevance for on-board fire risk partially supported by the empirical evidence (Fig. 3.10)	Relevance for on-board fire risk supported by the empirical evidence (Fig. 3.11)	Associated risk ranked as "High" by the experts (Table 4.2)
6) Fire load	66 % of fires concerned waste and packaging material 12 % of fires concerned gas hoses or distribution network (Fig. F1 in Appendix F)	47 % of fires concerned waste and packaging (Figs. 4.8, 4.9, 4.10), 19 % installation material, (Fig. 4.8, Fig. 4.11), 7 % gas distribution (Figs. 4.8, 4.12)	Relevance for on-board fire risk supported by the empirical evidence (Fig. 3.10)	Relevance for on-board fire risk supported by the empirical evidence (Fig. 3.11)	Associated risk ranked as "High" by the experts (Table 4.2)
7) Heating and ventilation		At least one fire due to the risk was evident in the statistics			Associated risk ranked as "Elevated" by the experts (Table 4.2)

Table K1 Quantitative evidence on contributing factors to ignition (continued from the previous page)

Factors that contribute to ignition	QUANTITATIVE APPROACH				
	One yard's fire incident statistics 1998 - 2001 (227 incidents)	**European fire incident statistics 2002 - 2003 (222 incidents)**	**Owner´s fire safety surveys onboard 2000 - 2003 (17 surveys of 3 to 5 days in duration)**	**One yard´s fireguards' surveys onboard 2001 - 2003 (151 overnight surveys)**	**Questionnaire survey of risks and response feasibility**
8) Hot surfaces and open flames					Associated risk ranked as "Elevated" by the experts (Table 4.2)
9) Hot work (welding, cutting, grinding, torching)	70 % of fires were due to hot work (Fig. F2 in Appendix F)	80 % of fires due to hot work (Figs. 4.5, 4.6)	Relevance for on-board fire risk supported by the empirical evidence (Figs. 3.9 and 3.10)		Associated risk ranked as "High" by the experts (Table 4.2)
10) Machinery					Associated risk ranked as "Elevated" by the experts (Table 4.2)
11) Painting		12 % of fires concerned flammable chemicals and liquids (Fig. 4.8)	Relevance for on-board fire risk partially supported by the empirical evidence (Figs. 3.9 and 3.10)	Relevance for on-board fire risk supported by the empirical evidence (Fig. 3.11)	Associated risk ranked as "Elevated" by the experts (Table 4.2)
12) Sea trials					Associated risk ranked as "Elevated" by the experts (Table 4.2)
13) Smoking of tobacco	At least one fire due to the factor was evident in the statistics	At least one fire due to the factor was evident in the statistics			Associated risk ranked as "Elevated" by the experts (Table 4.2)
14) Miscellanous	Varies	Varies	Varies	Varies	Varies

Table K2 Qualitative evidence on contributing factors to ignition (continues on the following page)

	QUALITATIVE APPROACH				
Factors that contribute to ignition	**Archival material from the yards**	**Mentions in formal interviews (out of five interviews)**	**Interactions with stakeholders and documents of good practices**	**Shipyard benchmarking by Owner's consultants**	**Other**
1) Arson					Few incidents but potential escalation
2) Autoignition			Relevance for on-board fire risk supported by the empirical evidence		Factor recognized in literature
3) Electric phenomena					Factor recognized in literature
4) Electric systems	Relevance for on-board fire risk supported by the empirical evidence	Three out of five interviews	Relevance for on-board fire risk supported by the empirical evidence		Unattended machinery can cause fire ignition and escalation before it is detected
5) Explosions, dust, gas, and vapors	Relevance for on-board fire risk supported by the empirical evidence	One out of five interviews	Relevance for on-board fire risk supported by the empirical evidence	Relevance for on-board fire risk supported in the evaluation topics (Fig. 3.15)	Danger of explosive fires
6) Fire load	Relevance for on-board fire risk supported by the empirical evidence	Five out of five interviews	Relevance for on-board fire risk supported by the empirical evidence	Relevance for on-board fire risk supported in the evaluation topics (Fig. 3.15)	Danger of explosive fires
7) Heating and ventilation			Relevance for on-board fire risk supported by the empirical evidence		Factor recognized in literature

Table K2 Qualitative evidence on contributing factors to ignition (continued from the previous page)

	QUALITATIVE APPROACH				
Factors that contribute to ignition	**Archival material from the yards**	**Mentions in formal interviews (out of five interviews)**	**Interactions with stakeholders and documents of good practices**	**Shipyard benchmarking by Owner's consultants**	**Other**
8) Hot surfaces and open flames			Relevance for on-board fire risk supported by the empirical evidence		Factor recognized in literature
9) Hot work (welding, cutting, grinding, torching)	Relevance for on-board fire risk supported by the empirical evidence	Five out of five interviews	Relevance for on-board fire risk supported by the empirical evidence	Relevance for on-board fire risk supported in the evaluation topics (Fig. 3.15)	Factor recognized in literature
10) Machinery	Relevance for on-board fire risk supported by the empirical evidence		Relevance for on-board fire risk supported by the empirical evidence		Factor recognized in literature
11) Painting	Relevance for on-board fire risk supported by the empirical evidence	Two out of five interviews			Factor recognized in literature
12) Sea trials	Relevance for on-board fire risk supported by the empirical evidence		Relevance for on-board fire risk supported by the empirical evidence		Factor recognized in literature
13) Smoking of tobacco			Relevance for on-board fire risk supported by the empirical evidence		Factor recognized in literature
14) Miscellanous	Varies	Varies	Varies	Varies	Varies

Table K3 Quantitative evidence on the consequences of fire

QUANTITATIVE APPROACH						
Consequences of established fires	**One yard's fire incident statistics 1998 - 2001 (227 incidents)**	**European fire incident statistics 2002 - 2003 (222 incidents)**	**Owner´s fire safety surveys onboard 2000 - 2003 (17 surveys of 3 to 5 days in duration)**	**One yard´s fireguards' surveys onboard 2001 - 2003 (151 overnight surveys)**	**Event tree calculation for sprinkler effectiveness**	**Questionnaire survey of risks and response feasibility**
1) Human damages in fire		The consequence was evident in the statistics	Relevance for on-board fire risk supported by the empirical evidence (Fig. 3.10)	Relevance for on-board fire risk supported by the empirical evidence (Fig. 3.11)		Associated risk ranked as "High" by the experts (Table 4.3)
2) Direct material damages in fire		The consequence was evident in the statistics	Relevance for on-board fire risk supported by the empirical evidence (Fig. 3.10)	Relevance for on-board fire risk supported by the empirical evidence (Fig. 3.11)	Relevance for on-board fire risk supported by the calculation scenario (Figs. J2, J3, and J4 in Appendix J)	Associated risk ranked as "High" by the experts (Table 4.3)
3) Secondary damages		The consequence was evident in the statistics			Relevance for on-board fire risk supported by the calculation scenario (Figs, J2, J3, and J4 in Appendix J)	Associated risk ranked as "Elevated" by the experts (Table 4.3)

Table K4 Qualitative evidence on the consequences of fire

	QUALITATIVE APPROACH				
Consequences of established fires	**Archival material from the yards**	**Mentions in formal interviews (out of five interviews)**	**Interactions with stakeholders and documents of good practices**	**Shipyard benchmarking by Owner's consultants**	**Other**
1) Human damages in fire	Relevance for on-board fire risk supported by the empirical evidence	Five out of five interviews	Relevance for on-board fire risk supported by the empirical evidence	Relevance for on-board fire risk supported by the empirical evidence (Fig. 3.15)	Consequence was recognized in literature
2) Direct material damages in fire	Relevance for on-board fire risk supported by the empirical evidence	Five out of five interviews	Relevance for on-board fire risk supported by the empirical evidence	Relevance for on-board fire risk supported by the empirical evidence (Fig. 3.15)	Consequence was recognized in literature
3) Secondary damages	Relevance for on-board fire risk supported by the empirical evidence	Five out of five interviews	Relevance for on-board fire risk supported by the empirical evidence	Relevance for on-board fire risk supported by the empirical evidence (Fig. 3.15)	Consequence was recognized in literature

Appendix L: Evaluation specifically against some action research criteria

The action research method has been criticised for lack of objectivity, repeatability and concrete evidence. Questions of the validity and reliability of the outcome specifically in action research have been debated intensely (Bradbury & Reason 2002, p. 447). For this study, two specific AR quality criteria were examined for an extra view: the criteria of Eden and Huxham (1997), p. 239) and Bradbury and Reason (2002, p. 454). Eden and Huxham (1997, p. 239) have postulated characteristics of rigorous organisational action research in a set of 15 criteria (reproduced in Appendix E). In the following, the criteria are referred to by their numbering, and denoted in parentheses. They emphasise rigorous documentation. In this study, the theory development and its explication during the action cycles were in the form of unpublished internal explication documents. A list has been added to the end of the study after the "References"-section. The internal documents and their use were summarised in sub-chapter 3.4.

Eden and Huxham start their criteria with the notion that (1) for AR, there must be an intent to change the organisation, and that there is an integral involvement of the researcher. The starting point of the research was a need to improve fire risk management, and the researcher has been fully immersed in the reported actions. The criteria (2) to (6) and (14) refer to theoretical contribution and applicability. The contribution should extend beyond the context of the current change project, and have a cyclically emergent valuing theory that connects to other theory used in the design. In this study, the resulting theory is applicable to all new cruise vessel building projects as well as to other branches of shipbuilding. The theory has also been developed cyclically from existing fire risk management principles. Criteria (7), (10) and (15) refer to presentation, expectations cyclic explication of findings and the interest of the audience. On the basis of the results of interaction, the reduced number of fires at many of the shipyards and the continuance of the development projects beyond the scope of the research, it seems likely that the above qualities of dialogue with the participants and also a wider audience in the industry in general have been reached to some degree. Also, a classification society provided a new service in the fire risk assessment of shipyards in general (Schnitler 2004), (Det Norske Veritas 2004). Criteria (8) and (9) refer to systematic methods and the defensibility of the conclusions made from evidence. This has been done in written explications of findings after each action cycle, as described in sub-chapter 3.4. Re-writing the Best Practices documents, maintaining statistics and on-board survey results, and continuously cross-examining the conclusions of the various research approaches also served the systematic approach. Based on the above, the chain of evidence presented in the research seems sufficient for the conclusions made. The fact that there have been no other researchers involved in the project may introduce bias. However, the issue was judged not to require special attention: many of the participants had a good education combined with excellent expertise on the subject, and thus were able to reduce the bias. Criteria (11) and (12) refer to fulfilling the criteria and selecting the research method, stating that AR should not be used if the same results can be obtained by more transparent methods, such as surveys or controlled experiments. In the researcher's opinion, the subject and the setting of this research were such that the use of AR was possible, and the rich results that were obtained seem to confirm this. Lastly, the criterion (13) concerns the use of triangulation as a dialectical device. This has been utilised in many instances when the participants' results produced with various methods and data sets were compared to each other.

Based on the above, it is concluded that the research fulfils the criteria postulated by Eden and Huxham for rigorous action research.

Similarly, Bradbury and Reason (2002, p. 454) list five issues for the quality of action research (numbered (1) to (5) below). They question whether the research is explicit in the quality of the relational praxis (1), so that the participation and involvement of the participants are maximised. This has been attempted: all information has been published for participants, and a democratic method of decision has been used, as has voluntary participation into all interactions. Considering that the participants have all been active in participation, and that all interactions have had full attendance, there are indications that the criteria may be fulfilled. However, this has not been inquired of the participants. The criterion (2) concerns whether the participants of research obtain the practical outcomes. The fact that the findings formed the basis of the participants' own development efforts and the projects proceeded further after the research had ended warrant a conclusion on the wider applicability of the outcome of this research. For Bradbury and Reason, theory is also important. Criterion (3) concerns practice-theory interaction, extending ways of knowing and choosing appropriate methods, resembles Eden and Huxham's criteria (2) to (6) and (14), and was thus deemed to have been fulfilled. Bradbury and Reason state the possibility of "knowing beyond intellect", which may be interpreted in the context of this research as tacit knowledge of fire risk management that certainly exists at the shipyards. The criteria (4) and (5) concern the significance of the research and forming new and enduring infrastructure. The fire risk management of cruise vessels has been, and will be, improved at the shipyards because of this research: the theoretical framework presented in the study is in use in the industry, and practical arrangements for further development are in place.

Based on the above, it is concluded that the research has merits for being judged as “quality action research”.

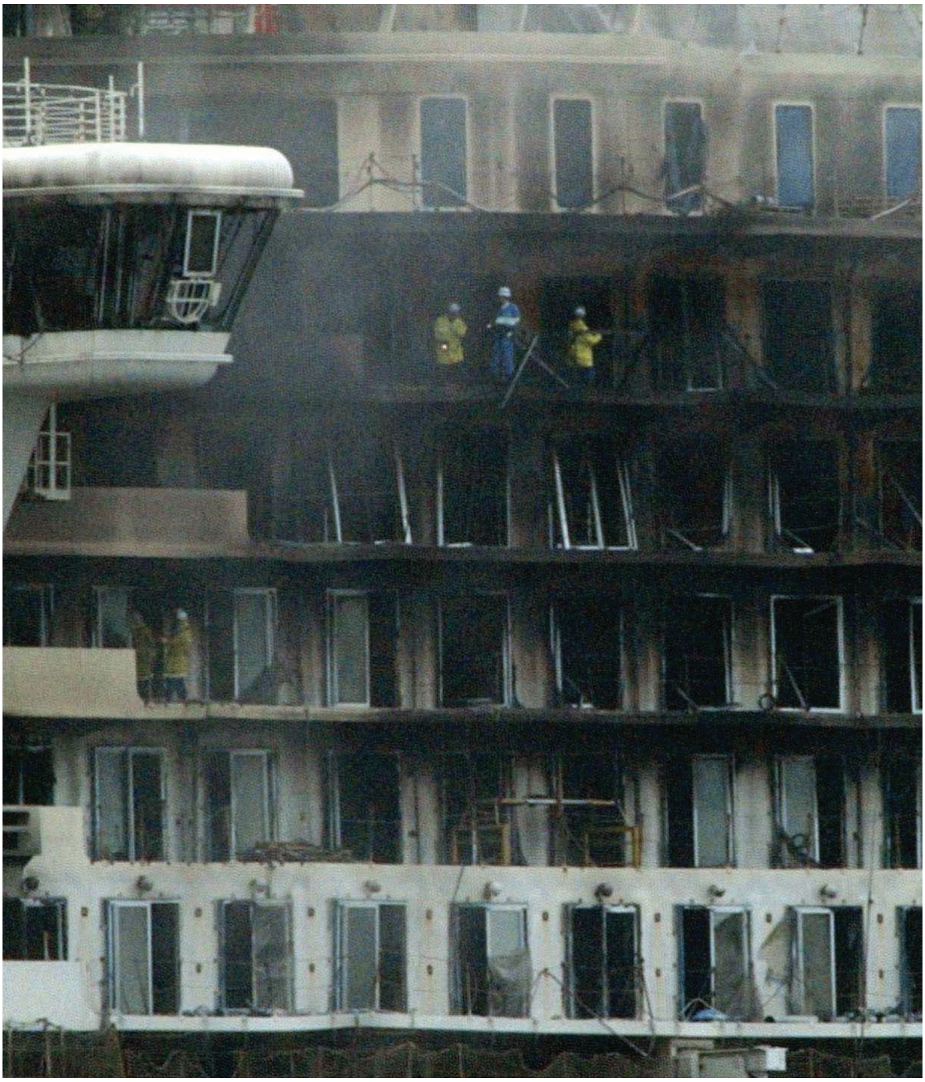

Illustration: Damage after a fire on-board. The photo is not from the yards that participated in the research. Source: AP/Lehtikuva

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The research on project fire risk was carried out with seven shipyards of four European cruise vessel building companies, which represented 85 - 90% of the world building capacity. Extensive quantitative and qualitative empirical material was produced in improvement and benchmarking action cycles with the shipyards. The findings include 14 categories of contributing factors for ignition, three types of consequences, 27 key metrics for risk assessment and 141 practical responses to fire risk. An important contribution of the study has been the forming of a unique European fire incident statistics database for the shipyards. Many of the key findings were directly adopted at the participant shipyards. Of these, commissioning the ship's own sprinkler systems early in the building process was estimated to reduce the risk of a large loss by an order of magnitude. With its thorough analysis and extensive data, the study presents a broad view of fire risk management in cruise vessel construction.

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