Delft University of Technology

FACULTY MECHANICAL, MARITIME AND MATERIALS ENGINEERING
Department Marine and Transport Technology

Mekelweg 2
2628 CD Delft
the Netherlands
Phone +31 (0)15-2782889
Fax +31 (0)15-2781397
www.mtt.tudelft.nl

Specialization:	Transport Engineering and Logistics
Report number:	2016.TEL.8060
Title:	**Risk assessment of maritime transportation systems based on the Bayesian Belief Networks**
Author:	F.M. Sickler

Title (in Dutch)	Risicobeoordeling van maritieme transportsystemen gebaseerd op een probabilistisch netwerk (Bayesiaans netwerk).

Assignment:	Literature assignment
Confidential:	No
Initiator (university):	dr. ir. X. Jiang
Supervisor:	dr. ir. X. Jiang
Date:	November 04, 2016

Delft University of Technology

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Mekelweg 2
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Phone +31 (0)15-2782889
Fax +31 (0)15-2781397
www.mtt.tudelft.nl

Student:	F.M. Sickler	Assignment type:	Literature
Supervisor (TUD):	Dr. ir. Jiang	Report number:	2016.TEL.8060
Specialization:	TEL	Confidential:	No
Creditpoints (EC):	10		

Subject: **Risk assessment of maritime transportation systems based on Bayesian Belief Networks (BBN)**

Maritime accidents involving ships carrying passengers may pose a high risk with respect to human casualties. For effective risk mitigation, an insight into the process of risk calculation is needed. Most of the existing models for risk assessment are based on historical data on maritime accidents, and thus they can be considered reactive instead of proactive. Alternatively, Bayesian Belief Networks(BBN) provide opportunity to develop a systematic, transferable and proactive framework estimating the risk for maritime transportation systems.

This literature assignment aims to make an overview of risk assessment methods on maritime transportation systems. The following aspects are required to be illustrated in the report:

- Definition of maritime transportation systems, i.e., which parties / system components are involved in it and their inter-relationship?
- Which accident scenarios have been addressed in risk assessment of maritime transportation systems? Then, which parties / system components play a role in those accident scenarios?
- Available risk assessment methods /models on maritime transportation systems and their respective characters, i.e., which parties / system components are taken into account in these methods?
- The theory of BBN;
- The state of the art – using BBN for Risk assessment of maritime transportation systems

This report should be arranged in such a way that all data is structurally presented in graphs, tables, and lists with belonging descriptions and explanations in text.

The report should comply with the guidelines of the section. Details can be found on the website. If you would like to know more about the assignment, you may contact with Dr. X Jiang through x.jiang@tudelft.nl.

The supervisor,

X. Jiang

ME2110-10 Literature Assignment

Risk assessment of maritime transportation systems based on Bayesian Belief Networks (BBN)

Student	Femke Sickler	Assignment type	Literature
Supervisor	dr. ir. X. Jiang	Report number	2016.TEL.8060
Specialization	TEL	Confidential	No
Creditpoints (EC)	10		

Literature Assignment
2016.TEL.8060

TU Delft Delft University of Technology

3mE - Transport Engineering & Logistics

November 4, 2016

Preface

This literature review is part of the curriculum of the Master of Science Mechanical engineering, track Transportation Engineering and Logistics (TEL) of the Delft University of Technology (TUDelft). It has been an very educational and insightful process to learn more about the risk assessment of maritime transportation systems based on the Bayesian Belief Networks. I would like to express my gratitude to a number of people who have assisted me with this literature study.

First of all I would like to express my gratitude to my supervisor dr. ir. X. Jiang who has provided me with valuable insights and guidance. In addition to motivating me and reading all my work, I am very grateful for all the information she provided and the updates on relevant events such as the Vessel Traffic Risk Seminar.

Secondly I would like to thank my teacher S.W. Cunningham. Besides this literature study I have followed the course EPA1315 Data Analytics and Visualization. This course covers the theory of Bayesian statistics and applying it using a programming language called R. I am very grateful for his informative lectures and assistance in answering various questions I had regarding the Bayesian Belief Network.

Thirdly I would like to express my gratitude to the organizing committee of the Vessel Traffic Risk Seminar. This seminar has been very educational and insightful regarding the state-of-the art methods and models on risk analysis. It was also a unique opportunity to meet Professor Rene van Dorp from the George Washington University in the USA and ask some personal questions. Professor van Dorp is the author of several of the scientific literature assessed in this paper.

Finally I would like to thank my good friends Matthijs Meissner and Matteo Schiaretti for their valuable advice on report writing, motivation, discussions on the topic and help with obstacles I encountered.

Source front cover: Pluton Logistics [2013]

Summary

Maritime transportation has been used since ancient times for both freight and passenger transport. International shipping accounts for more than 80% of the global trade as it is the most efficient and cost-effective method of international transportation [International Maritime Organization, 2013]. The prediction for 2030 is that between 19 and 24 billions tons will be shipped per year [Lloyd's Register et al., 2013]. This increasing demand for cargo transportation results in either an increase of the number of ships or an increase in the size of ships. With the current status of maritime transportation this will result in an increase in accidents. Accidents may result in fatalities, environmental damage or large economic losses. The occurrence of several accidents have raised the awareness of both researchers and the maritime authorities of the importance of safety. For effective risk mitigation an insight is needed in the process of risk calculation. Most of the existing models for risk assessment are based on historical data on maritime accidents and are therefore reactive. For effective risk mitigation a proactive model is required. It is therefore of great importance to provide an overview of the current available risk assessment methodologies and research the possibilities of using state-of-the-art Bayesian Belief Network methodology for risk assessment of maritime transportation systems.

The main question answered in this report is: *"What are the existing and state-of-the-art approaches for risk assessment of maritime transportation systems with a focus on Bayesian Belief Networks?"*

The maritime transportation system is the entire value chain related to the transportation of cargo and passengers over water [Swales and Feak, 1996]. For the maritime transportation system the actors, maritime activities performed and the relevant systems and functions have been identified. In addition the risk factors that can increase or decrease the probability of an event happening and the severity of the consequences have been identified. The most important accident scenario's; collision, contact, grounding, foundering, hull & machinery damage and fire & explosion have been determined [Buzancic Primorac and Parunov, 2016].

Next research was conducted on the available risk assessment methods. Until now a large amount of studies has been performed on risk assessment. Risk is defined as $R = P \cdot C$; probability times consequence [Kristiansen, 2005]. Therefore the probability of an event and the consequence of that event has to be determined. To gain an insight in this calculation process risk assessment is needed. Risk assessment consists of three phases; risk identification, risk analysis and risk evaluation. [NEN-ISO/IEC 31010, 2012] and [Marhavilas et al., 2011] define several methods for determining risk assessment. These methods are classified in qualitative-, quantitative- and hybrid- (semi-quantitative) techniques. For risk assessment in maritime transportation much research has been done but many initialized by individual companies or researchers. This way many models and methods have been developed which mostly rely on historical data and are therefore reactive. The international maritime organization [International Maritime Organization, 2002] has developed an overall method called the Formal Safety Assessment which is a proactive, "structured and systematic methodology, aimed at enhancing maritime safety". [Faghih-Roohi et al., 2014] have analyzed several researches regarding risk assessment in maritime transportation as well as [Goerlandt and Montewka, 2015b].

A comparison of the different approaches in the risk assessment for maritime transportation is presented. Based on this the current challenges such as clarity on fundamental issues [Ozbas, 2013], data gathering [Merrick and Van Dorp, 2006], proactive models [Zhang et al., 2016], uncertainty incorporation [Montewka et al., 2014] are identified.

Some of these challenges such as data gathering, uncertainty incorporation and a proactive model can be addressed by using the Bayesian Belief Network. In the Bayesian Belief Network the probability is determined by the analyst's measure of degree of belief and this network can be updated as more information becomes available [Nielsen and Jensen, 2009]. It is a modeling technique which can present relative complex causal dependencies with uncertain variables [Kruschke, 2011]. If a situation with large uncertainty has to be addressed this updating process can be used. The founder of this approach is Tomas Bayes who is known for Bayes' rule: $P(A|B) = \frac{P(B|A)P(A)}{P(B)}$. The subjective initial belief is used (can be historial data, experience or prior) and evidence. This results in the posterior distribution which is what is currently known about the parameters after seeing the data. Various authors such as [Hänninen and Kujala, 2014], [Li et al., 2012], [Zhang et al., 2016] and [Trucco et al., 2008] have used Bayesian Belief Networks for risk assessment in maritime transportation systems.

Finally the challenges of using the Bayesian Belief Network are addressed such as that the conditional probability table grows proportionally to the amount of nodes added. This can lead to very long computation times. Therefore it is unclear if Bayesian Belief Networks are the optimal approach for solving these kind of complex problems [Hänninen, 2014]. It is therefore recommended that some more research is done on the fundamental issues and the underlying approach to determine if a model is suitable to be used in a certain situation. In addition more discussion and research should take place among researchers to improve existing models instead of developing new ones. Finally for a breakthrough, the method of Markov Chain Monte Carlo is suggested to be researched.

Dutch Summary

Maritiem vervoer wordt al sinds mensenheugenis gebruikt om personen en goederen over water te vervoeren. Het internationale verschepen van goederen is goed voor meer dan 80% van de wereldwijde handel [International Maritime Organization, 2013]. Dit is omdat verschepen de meest efficiente en kosteneffectieve methode is voor internationaal vervoer. De voorspelling voor 2030 is dat er tussen de 19 - 24 miljard ton per jaar zal worden verscheept [Lloyd's Register et al., 2013]. Deze toenemende vraag naar vrachtvervoer zal waarschijnlijk of lijden tot een toename van het aantal schepen of een toename van de grootte van schepen. Met de huidige situatie van zeetransport zal dit resulteren in een toename van het aantal ongelukken. Ongelukken kunnen leiden tot dodelijke slachtoffers, schade aan het milieu of grote economische verliezen. Nadat een aantal reeds gebeurde ongelukken wereldwijd grootschalig in het nieuws zijn geweest heeft het belang van de veiligheid van zeetransport de aandacht getrokken van onderzoekers en van de maritime authoriteiten. Voor een effectieve risicobeperking is inzicht nodig in het proces van de risicoberekening. Het grootste deel van de bestaalde modellen voor risicobeoordeling zijn reactief, betekenend dat ze gebaseerd zijn op historische gegevens. Voor een effective risicobeperking is een proactief model vereist. Het is daarom van groot belang om een overzicht te maken van de huidige beschikbare methoden voor risicobeoordelingen en onderzoek te doen naar de mogelijkheden voor het gebruik een state-of-the-art technologie; het Bayesiaanse netwerk voor de risicobeoordeling van maritieme transportsystemen.

De hoofdvraag die beantwoord wordt in dit rapport is *"Wat zijn de bestaande en state-of-the-art methoden voor risicobeoordeling van maritieme transportsystemen met een focus op het Bayesiaanse netwerk?"*

Het maritime transport systeem is de gehele keten van het vervoer van vracht en / of passagiers over water [Swales and Feak, 1996]. Voor het systeem zijn de belangrijkste actoren, maritieme activiteiten en relevante systemen en functies benoemd. Daarnaast zijn de risicofactoren bepaald, dit zijn factoren die de kans op een onverwachte gebeurtenis kunnen verhogen of verlagen en de ernst van de gevolgen kunnen beinvloeden. De belangrijkste scenario's zijn; aanvaring, contact, stranden, zinken, romp & machine schade en brand & explosie [Buzancic Primorac and Parunov, 2016].

Vervolgens is onderocht welke beschikbare methoden er zijn voor risicobeoordeling. Er zijn een meerdere studies gedaan naar risicobeoordeling. Risico is gedefinieerd als de kans maal het gevolg $R = P \cdot C$ [Kristiansen, 2005]. Om inzicht te krijgen in deze berekening is een risicobeoordeling nodig. Risicobeoordeling bestaat uit 3 delen: risico-identificatie, risico-analyse en risico-evaluatie. [NEN-ISO/IEC 31010, 2012] en [Marhavilas et al., 2011] definieren verschillende methoden voor het bepalen van de risicoanalyse. Deze methoden kunnen in categorieen worden ingedeeld: kwalitatieve-, kwantitatieve- en hybride- (semi-kwantitative) technieken. Naar risicobeoordeling van zeevervoer is redelijk wat onderzoek gedaan, vooral door individuele bedrijven en onderzoekers. Hierdoor zijn er veel methoden en modellen ontwikkeld die meestal afhankelijk zijn van databanken en historische gegevens en daarom reactieve modellen zijn. De internationale maritieme organisatie [International Maritime Organization, 2002] heeft een overkoepelende algemene methode ontwikkeld genaamd Formal Safety Assessment. Dit is een pro-actieve "gestructureerde en systematische methodologie, die gericht is op de verbe-

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tering van de veiligheid op zee". [Faghih-Roohi et al., 2014] heeft een overzicht gemaakt van diverse recente onderzoeken naar de risicobeoordeling van maritiem vervoer net als [Goerlandt and Montewka, 2015b]. Een vergelijking van de verschillende methoden voor risicobeoordelingen wordt gegeven. Op basis van hiervan worden er verschillende uitdagingen geidentificeerd namelijk duidelijkheid over fundamentele kwesties [Ozbas, 2013], het verzamelen van gegevens [Merrick and Van Dorp, 2006], proactieve modellen [Zhang et al., 2016] en het verwerken van onzekerheid in de modellen [Montewka et al., 2014].

Sommige van deze uitdagingen, zoals het verzamelen van gegevens, het verwerken van onzekerheid en een pro-actief model kunnen worden aangepakt met behulp van het Bayesiaanse netwerk voor risicobeoordeling. De waarschijnlijkheid (kans) in het Bayesiaanse netwerk wordt bepaald door hoe groot de analist acht dat de kans is, en dit kan worden bijgewerkt wanneer er meer informatie beschikbaar komt Nielsen and Jensen [2009]. Het Bayesiaanse netwerk is een modelleer techniek die relatief complexe causale afhankelijkheden kan presenteren met variabelen met een grote onzekerheid [Kruschke, 2011]. Als een situatie met grote onzekerheid geanalyseerd moet worden kan deze methode worden gebruikt. De ontdekker van deze aanpak is Tomas Bayes die bekend staat om de regel van Bayes: $P(A|B) = \frac{P(B|A)P(A)}{P(B)}$. Een subjectieve inschatting wordt geformuleerd op basis van historische gegevens, ervaring, oordeel van een expert, uitgevoerde simulaties, experimenten of onderzoeken, ontwerp standaarden etc. Deze wordt gebundeld met actueel verkregen informatie om zo tot een uitkomst te komen gebaseerd op kansrekening. Diverse auteurs zoals [Hänninen and Kujala, 2014], [Li et al., 2012], [Zhang et al., 2016] en [Trucco et al., 2008] hebben onderzoek gedaan naar het gebruik van het Bayesiaanse netwerk voor risicobeoordeling in maritieme transport systemen.

Tenslotte worden de uitdagingen van het gebruik van het Bayesiaanse netwerk bediscusseerd. De waarschijnlijkheids tabel groeit met het aantal elementen dat wordt toegevoegd aan het netwerk. Dit kan leiden tot een zeer lange computerberekentijd. Daarnaast zijn er nog een aantal obstacles waardoor is het onduidelijk of het Bayesiaanse Netwerk de optimale aanpak is voor het oplossen van dit soort complexe problemen Hänninen [2014]. Als aanbeveling wordt gegeven dat er meer onderzoek gedaan moet worden naar de fundamentele basis en de onderliggende gedachtes om te bepalen of een model geschikt is voor het gebruik in een bepaalde situatie. Daarnaast zou er meer discussie moeten plaatsvinden tussen de onderzoekers van bestaande modellen om deze te verbeteren in plaats van het ontwikkelen van nieuwe modellen. Ten slotte wordt er een suggestie gedaan voor verder onderzoek naar een methode genaamd Markov Chain Monte Carlo om het probleem van berekentijd van het Bayesiaanse netwerk op te lossen.

List of Abbreviations

Abbreviation	Definition
ALARP	As Low As Reasonably Practicable
BN	Bayesian Network
BBN	Bayesian Belief Network
CPT	Conditional Probability Table
CREA method	Clinical Risk and Error Analysis
DMRA technique	Decision Matrix Risk Assessment
ET	Event Tree
ETA	Event Tree Analysis
FMEA	Failure Mode and Effect Analysis
FMECA	Failure modes and effects and criticality analysis
FPSO	Floating, Production, Storage and Offloading
FSA	Formal Safety Assessment
FT	Fault Tree
FTA	Fault Tree Analysis
HACCP	Hazard Analysis and Critical Control Points
HAZOP	HAZard and OPerability studies
HEAT	Human Error Analysis Technique
HFEA	Human Factor Event Analysis
HOF	Human and Organizational Factor
HRA	Human Reliability Assessment
ID	Influence Diagram
IMO	International Maritime Organization
LOPA	Layers Of Protection Analysis
MCDA	Multi-Criteria Decision Analysis
McMC	Markov chain Monte Carlo
MTS	Maritime Transportation System
NASF	Non-Accidental Structure Failure
Pax	Passengers
PEA method	Predictive, Epistemic Approach
PRAT technique	Proportional Risk Assessment
PWS	Prince William Sound
QADS	Quantitative Assessment of Domino Scenarios
QRA technique	Quantitative Risk Assessment
RBM	Risk Based Maintenance
SA	Sneak Analysis
SCI	Sneak Circuit Analysis
STEP technique	Sequentially Timed Event Plotting
SWIFT	Structured "What If" Technique
VTS	Vessel Traffic Service
WRA	Weighted Risk Analysis

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1 Introduction

Maritime transportation has been used since ancient times for both freight and passenger transport. Due to newer, faster transportation possibilities such as aviation, the demand for passenger transportation has decreased but the demands for cargo transportation remains high. In 2014 the United Nations estimated the global seaborn shipments transported a total of 9.84 billion tons [Unctad, 2015]. According to the [International Maritime Organization, 2013], international shipping transports more than 80% of global trade all over the world. Shipping is the most efficient and cost-effective method of international transportation for most goods and it provides a dependable, low-cost means of transporting. [Lloyd's Register et al., 2013] predicts that the 9.84 billion tons will increase to between 19 and 24 billion tons by 2030. The increasing demand for cargo transportation results in an increase in accidents which may lead to economic losses, environmental damage and human casualties. The occurrence of several tragic accidents and environmental disasters have raised the awareness of both researches and maritime authorities. Safety of ships and risk analysis methods have received increasing attention in recent years. An insight into the process of risk calculation is needed for an effective risk mitigation. Most of the existing risk assessment models use historical data on maritime accidents. Therefore they can be considered reactive instead of proactive. Alternatively, Bayesian Belief Networks (BBN) provide the opportunity to develop a systematic, transferable and proactive framework for estimating the risk for maritime transportation systems. It is therefore of great importance to provide an overview of the current available risk assessment methodologies and research the possibilities of using the state-of-the-art BBN for risk assessment of maritime transportation systems (MTS).

The main purpose of this report is to provide an overview of the current risk assessment methods on maritime transportation systems, secondly to identify the deficiencies in these models, thirdly to research the possibilities of using Bayesian Belief Networks in maritime risk assessment and finally to identify the remaining challenges in maritime risk assessment and explore possible ways to address these challenges. The main question of this research is:

"What are the existing and state-of-the-art approaches for risk assessment of maritime transportation systems with a focus on Bayesian Belief Networks?"

The key questions answered in this literature study will be:

1. What are maritime transportation systems and the inter- relationship between its parties and components?
2. What are the available risk assessment methods / models in maritime transportation systems?
3. How can Bayesian Belief Networks be used for risk assessment in maritime transportation systems?
4. What are the remaining challenges in risk assessment in maritime transportation systems and how can they be approached?

This literature review was conducted by searching various databases. The databases provided by SCORPUS ®, ScienceDirect® and Google Scholar® were used because they are major databases for the engineering and science literature. In addition the university resources were used such as the digital library, the hard copy library of the Delft University of Technology and information provided by courses given by teachers of various faculties. Key words used for the search were "maritime" "marine" "risk" "assessment" "analysis" "methodology" "definition" "safety" "formal safety assessment" and "ship". Following the irrelevant results were discarded by reading the abstract, introduction and sometimes conclusion. Finally the references used by the selected papers were reviews to find any literature that might have been missed by the search with key words.

In Chapter 2 the definition of a maritime transportation system is given including the inter-relationship between its parties and components. Chapter 3 provides a detailed review of the existing risk assessment methodologies and the current challenges that are faced. Following Chapter 4 discusses the theory of Bayesian Belief Networks and how it can be applied for risk assessment or maritime transportation systems. Then the remaining challenges in maritime risk assessment are addressed in Chapter 5. Finally a conclusion and recommendation for further research is proposed in Chapter 6.

2 Maritime Transportation Systems

This chapter discusses what a maritime transportation system (MTS) is, the parties and system components involved and how they are interconnected. Finally the need of risk assessment is discussed.

2.1 Definition of Maritime Transportation Systems

According to the [Cambridge Dictionary, 2016] maritime has the definition: "connected with human activity at sea" , transportation: "the movement of people or goods from one place to another" and system: "a set of connected things or devices that operate together". Combining these definitions gives that MTS is: the complete picture of all things and devices that make the movement of people or goods from one place to another over sea possible. According to Swales [Swales and Feak, 1996] we can formulate the definition: "A MTS is the entire value chain related to the transportation of cargo and passengers over water (mostly sea)". Many more authors and researchers have determined definitions for the MTS. However the one organization that has most influence in the MTS, the one that determines the international rules and conventions of the MTS is presented below, the IMO.

The International Maritime Organization (IMO) is a specialized agency of the United Nations and the global standard-setting authority for the safety, security and environmental performance of international shipping [International Maritime Organization, 2016a]. According to the IMO the maritime transportation refers to the global shipping of cargo and passengers. The MTS includes all the governments, organizations and stakeholders involved with the day-to-day business of the shipping industry [International Maritime Organization, 2013]. In Figure 2.1 the total MTS is shown according to the [International Maritime Organization, 2013]. In this figure it can be seen that actors are included in this system from ship design, ship building, training and education till the cargo owners and final consumers. Officially the MTS is much broader including the actors beyond the shipping sector who are assisting in the logistics and delivery of the freight. For this literature review the system boundary is such that we will not include the entire value chain in our research.

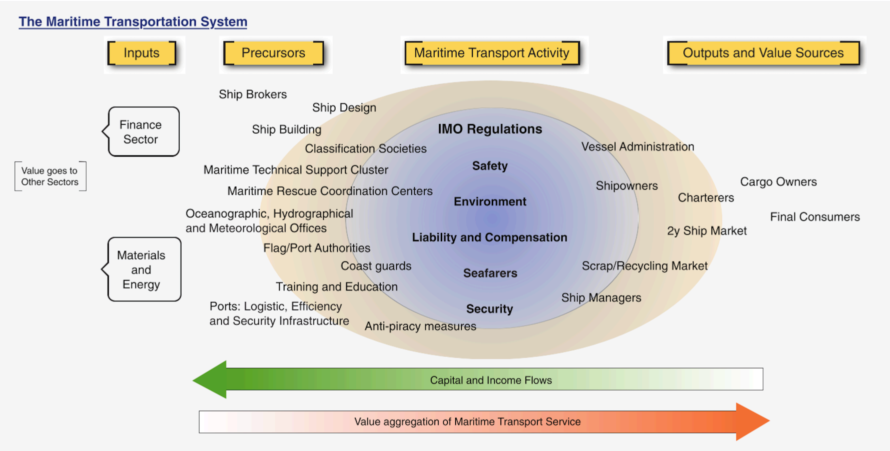


Figure 2.1: Maritime Transportation System [International Maritime Organization, 2013]

Many authors and researchers have published scientific literature on the MTS. [Mullai and Paulsson, 2011] defines the maritime transport system as a "very complex and large-scale socio-technical environment system comprising human and man-made entities that interact with each other and operate in a physical environment". Information and transport related activities link the means of transport with infrastructures and facilities. In the following sections these linkages are illustrated by identifying the parties and system components.

2.2 Parties and System Components Involved

This section describes the actors that are involved in the MTS, especially the actors that have an effect on the safety. Safety has become increasingly important over the years after the occurrence of several tragic accidents. Many elements have an influence on the occurrence of an accident. These numerous elements will be discussed in the following order: actors, maritime activities, systems & functions, risk factors, accident scenarios and the common traits found in accidents.

2.2.1 Actors

According to [Kristiansen, 2005] there are several actors involved in the shipping industry that have an influence on safety. These actors are shown in Table 2.1.

Table 2.1: Actors in shipping that influence safety [Kristiansen, 2005]

Actor	**Influence on safety**
Shipbuilder	The vessels' technical standard
Shipowner	Can order a ship with technical standards above minimum requirements Selects management company for operation Selects crew Decisions on operational and organizational safety policies
Cargo owner	Pays for the transport service Quality and safety of the vessel operation Can perform independent assessments of the quality of the shipper
Insurer	Takes the main part of the risk on behalf of the shipper and cargo owner (i.e. vessel, cargo, third party) May undertake independent assessment of the quality of the shipper
Management company	Responsible for crewing, operation and upkeep (i.e. maintenance) of the vessel on behalf of the shipowner
Flag state	Control of vessels, crew standards and management standards
Classification society	Control of technical standards on behalf of insurer Undertakes some control functions on behalf of the flag state
Port administration	Responsible for safety in port and harbour approaches May control safety standard of vessels, and in extreme cases deny access for substandard vessels

However these are only the actors involved with the safety of the ship. IMO adds to this list several other actors involved in the design, construction, ownership, operation, management and crewing, training, as well as classification, finance, and liability and insurance aspects of shipping as shown in Figure 2.1. [Mullai and Paulsson, 2011] emphasizes that the elements are embedded in very complex, interdependent and dynamic relationships.

Additional actors to the ones stated in Table 2.1 can be identified when researching the regulation of maritime safety and the actors in the safety control [Kristiansen, 2005]. Additional actors are: the parliament, IMO, European commission, foreign & industry department, maritime administration etc.

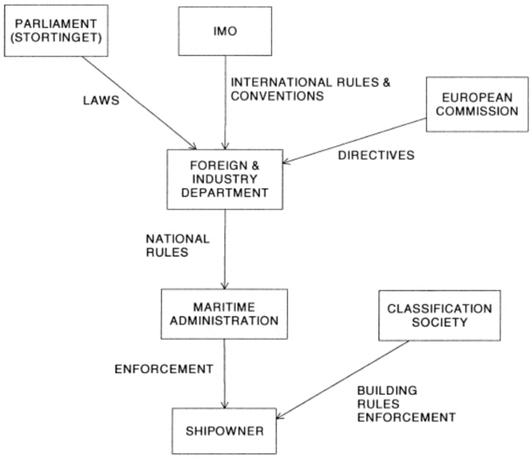


Figure 2.2: Regulation of maritime safety [Kristiansen, 2005]

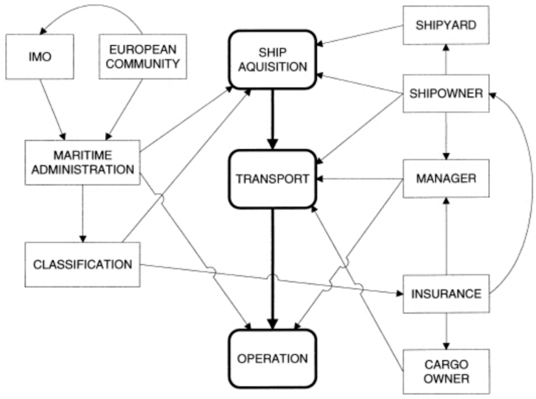


Figure 2.3: Actors and interactions in safety control [Kristiansen, 2005]

The interrelationship between associated partners can be illustrated in Figure 2.2. In this figure it can be seen that the 'IMO' determines the international rules and conventions, the 'parliament' determines the laws and the 'European commission' the directives for the 'foreign & industry department'. Following the 'maritime administration' will act as the flag state for a certain country. They have to ensure that the 'shipowners' follow the regulations by performing proper control and certification. Finally the 'classification society' enforces the tasks from the 'maritime administration' such as insurance of the vessel, cargo etc.

Figure 2.3 illustrates the actors involved in safety control. The regulatory influence described in Figure 2.2 has most influence on the ship acquisition in Figure 2.3. The 'insurance company' will take on the risk related of the shipowner and cargo owner. The insurer will have a regulatory influence on the transport and operation. Many of the actors have also been mentioned in Table 2.1 but also some additional actors as mentioned above are involved such as the IMO, European community and maritime administration.

2.2.2 Maritime Activities

Not only actors have an influence on the safety in the maritime industry. Also the activities taking place have a large influence. There are multiple activities that can be performed under the category 'maritime activities', some having a higher risk to lead to an accident than others. The maritime activities that can be performed are: [Kristiansen, 2005].

- Maritime transport
    - Coastal shipping
    - Transport of people both inland and overseas
    - International shipping
    - Cruise shipping
- Fishing
- Marine farming
- Continental shelf operations (i.e. oil and gas)

    - Rig operations
    - Supply services
    - Pipeline laying
    - Underwater activities
- Science and survey

2.2.3 Systems and Functions

In addition to actors and the maritime activity that is performed having an effect on the safety of MTS, the systems and functions also play a large role. As stated in Section 2.1 a system is a set of connected things or devices that operate together. According to [Kristiansen, 2005] the systems of a ship consists of the items shown in Table 2.2. [Wang, 2006] also identifies the above named systems and emphasizes the importance of these systems. The systems and functions of a ship are important because to analyze the nature of the accident the systems or functions that have failed need to be identified.

In the category maritime shipping the lifetime of a ship consists of various phases. Each of these phases can have a large influence on the safety of a ship. For example the technical standard of a vessel is determined in phase 1, the design, construction and commissioning of the ship. The major phases of shipping consists of:

1. Design, construction and commissioning
2. Entering port, berthing, unberthing and leaving port
3. Loading and unloading
4. Dry docking
5. Decommissioning and disposal

In each of these phases the status of the ship functions changes [Wang, 2006]. A failure of a system may have disastrous consequences. Therefore a risk estimation has to be carried out for each phase of shipping and for each system. Below the systems and functions of a ship are illustrated. Some system have a more crucial function than others. For example, the machinery and propulsion have a large impact on safety, contrasting accommodation and hotel service has less impact on safety. Likewise some functions are more crucial than others, structure and maneuverability have a larger influence on the safety of a ship than for example carriage of payload.

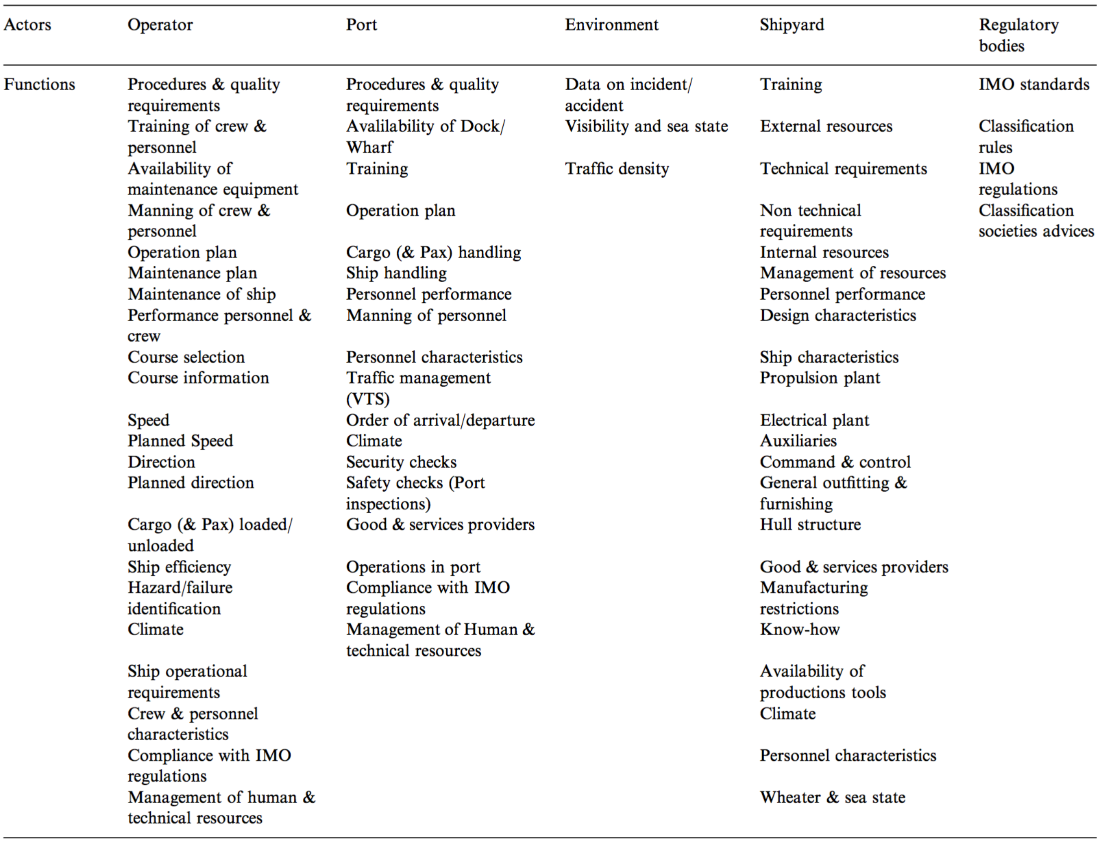
Table 2.2: Systems of a ship [Kristiansen, 2005] [Wang, 2006]

Systems
Accommodation and hotel service
Communications
Control
Electrical
Ballast
Lifting
Machinery and propulsion
Management support systems
Positioning, thrusters
Radar
Piping and pumping
Pressure plant, hydraulics
Safety

Table 2.3: Functions of a ship [Kristiansen, 2005]

Functions
Anchoring
Carriage of payload
Communications
Emergency response and control
Habitable environment
Maneuverability
Mooring
Navigation
Pollution prevention
Power and propulsion
Bunkering as storing
Stability
Structure

[Trucco et al., 2008] defines a more elaborate list of actors with functions as shown in Figure 2.4. They have only considered a limited number of actors, namely, operator, port, environment, shipyard and regulatory body, as can be seen in the top row of the table. Following the functions that are performed by each actor are listed. This list of functions is used to create a Bayesian Belief Network as will be explained in Section 4.2.



Actors	Operator	Port	Environment	Shipyard	Regulatory bodies
Functions	Procedures & quality requirements	Procedures & quality requirements	Data on incident/ accident	Training	IMO standards
	Training of crew & personnel	Avalilability of Dock/ Wharf	Visibility and sea state	External resources	Classification rules
	Availability of maintenance equipment	Training	Traffic density	Technical requirements	IMO regulations
	Manning of crew & personnel	Operation plan		Non technical requirements	Classification societies advices
	Operation plan	Cargo (& Pax) handling		Internal resources	
	Maintenance plan	Ship handling		Management of resources	
	Maintenance of ship	Personnel performance		Personnel performance	
	Performance personnel & crew	Manning of personnel		Design characteristics	
	Course selection	Personnel characteristics		Ship characteristics	
	Course information	Traffic management (VTS)		Propulsion plant	
	Speed	Order of arrival/departure		Electrical plant	
	Planned Speed	Climate		Auxiliaries	
	Direction	Security checks		Command & control	
	Planned direction	Safety checks (Port inspections)		General outfitting & furnishing	
	Cargo (& Pax) loaded/ unloaded	Good & services providers		Hull structure	
	Ship efficiency	Operations in port		Good & services providers	
	Hazard/failure identification	Compliance with IMO regulations		Manufacturing restrictions	
	Climate	Management of Human & technical resources		Know-how	
	Ship operational requirements			Availability of productions tools	
	Crew & personnel characteristics			Climate	
	Compliance with IMO regulations			Personnel characteristics	
	Management of human & technical resources			Wheater & sea state	

Figure 2.4: List of functions divided into actors [Trucco et al., 2008]

2.3 Identification of Risk Factors

The above mentioned actors, interrelationship between actors, maritime activities and systems & functions have a large influence on the safety of shipping. Maritime safety regarding accidents depends on many elements and criteria. These are called risk factors as they can increase or decrease the probability of an event happening and the severity of the consequence (the probability and consequence aspect will be addressed in Section 3.2). The risk factors are of importance because by managing these factors the risk can be managed. Many authors [Mullai and Paulsson, 2011], [Balmat et al., 2011], [Balmat et al., 2009], [Sage, 2005], [Merrick et al., 2002], [Psaraftis et al., 1998] have identified risk factors as shown in Table 2.4.

Table 2.4: Risk Factors

Category	**Risk Factor**
Ship's characteristics	Type of ship
	Year of construction
	Flag
	Gross tonnage
	Type of hull (single or double)
Ship's history elements	Number of companies
	Duration of Detention
Ship's trajectory	Position
	Speed
	Last known port
	Destination
Meteorological conditions	Sea state
	Wind speed
	Visibility
	Night or day
Human	Crew experience
	Shipboard environment
	Training (knowledge and skills)
	Perceptions and understandings
Organizational factors	Management practices

Table 2.4 shows the various risk factors that have been identified by many authors. There are six categories; ship's characteristics, ship's history elements, ship's trajectory, meteorological conditions, human factors and organizational factors. The number of companies refers to the number of owners that the ship has had during its life. Switching of owner can have a number of reasons and this reason may have a large influence on the occurrence of a risk with this ship. The duration of detention is the time that a ship is held in the port and is not allowed to sail as the seaworthiness is not approved. Below the importance of the location and management practices is explained.

Position

[Allianz, 2015] states that the region is very important. In 2015 more than 25% of all accidents occurred in the South China, Indochina, Indonesia and Philippines region as can be seen in Figure 2.5. This has therefore been the loss hotspot of the past decade.

This hotspot is created by the extreme weather conditions such as hurricanes.

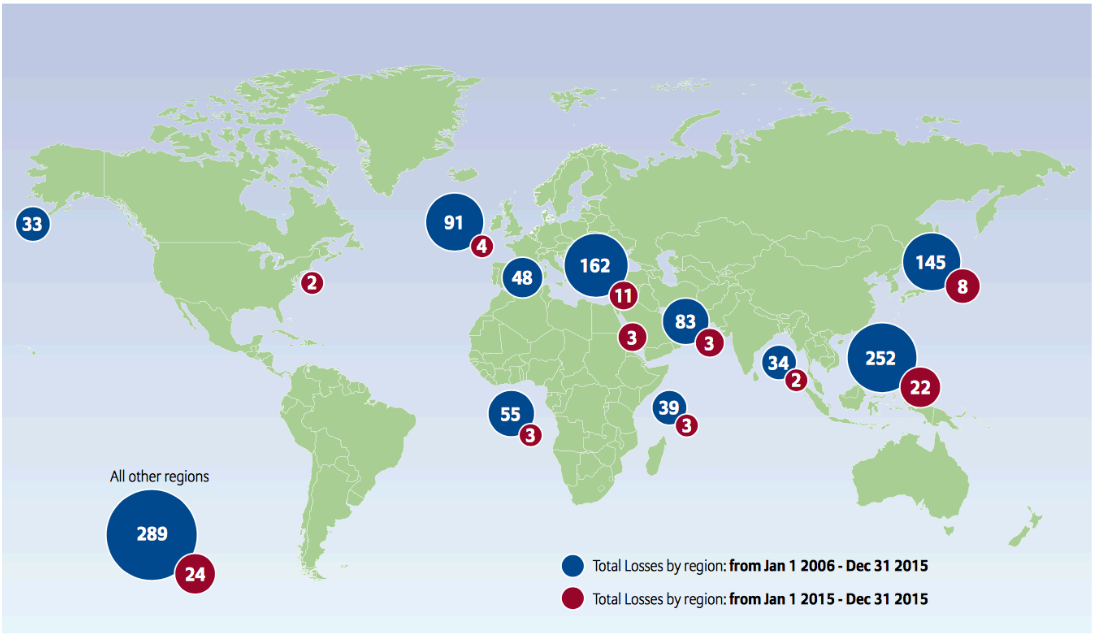


Figure 2.5: Total losses by top 10 regions between 2006-2015 [Allianz, 2015]

Management pratices

The management practices are greatly influenced by the economy. This has large influence on the occurrence of accidents as the maritime industry is a very competitive industry. Since 2008 the economic crisis has greatly influenced the shipping industry, with a weak global economy, depressed commodity prices and excess of ships the costs have to be as low as possible. The first savings are often preventative measures and vessel maintenance and repair. The statistics show that 36% of the accidents are due to machine damage. Other savings include crew conditions and training, passenger ship safety and safe cargo carrying. Passenger ship safety is often seen in Asian routes where they are not up to date with international standards resulting in many losses in the South East Asian waters [Allianz, 2015].

In addition the management practices have certain environmental goals to achieve imposed by higher actors. Keeping in mind the global warming, the shipping industry tries to lower their emissions. However this sometimes results in unexpected safety problems with the new types of fuel resulting in engine and power problems. In addition the harsh maritime environment especially in locations such as the arctic, results in machine damage or failure [Allianz, 2015].

In Figure 2.6 the factors that influence the risk of an accident are illustrated according to Stornes [Stornes, 2015]. In this figure the ship characteristics (vessel qualities), ships trajectory (geographical qualities), meteorological conditions (weather qualities) can be found, which in combination may result in an accident. Other factors that also have a large influence on the occurrence of accidents are the time, certification and operational stage. The accident can have several consequences with different severity of injuries & fatalities, environmental damage and economic losses.

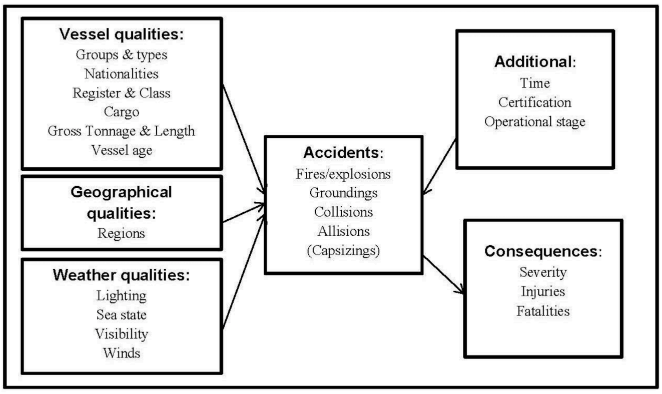


Figure 2.6: Risk factors [Stornes, 2015]

2.4 Which Accident Scenarios have been Addressed

Shipping accidents are recorded and classified according to their type of energy release involved [International Maritime Organization, 2013]. It is important to identify accident scenario's so that the nature of the accident can be analysed and the system or function malfunctioning can be determined. If the responsible function or system is known, mitigation actions can be determined. Accident scenarios that have been addressed in the MTS are shown in Table 2.5 [Lloyd's Register et al., 2013], [International Maritime Organization, 2013], [Wang, 2006], [Eleftheria et al., 2016], [Soares and Teixeira, 2001], [Stornes, 2015] and [Buzancic Primorac and Parunov, 2016].

Table 2.5: Accident phenomena

Type	**Comments**
Collision	Striking between ships
Contact	Striking between and other surface objects
Grounding	Hitting the seabed or shore
Foundering	Opening and flooding of the hull
Hull and machinery	Hull or machinery failure is directly responsible for the accident & NASF
Fire and explosion	Fire, explosion or dangerous goods release
Missing	
Miscellaneous	

The ships that are lost as a result of striking or being struck by another ship are in the accident scenario: collision. Contact is the category when ship accidents are caused by collision with another external body, which is not a ship, nor the bottom. Sometimes the term allision is also used. Ships that are lost as a result of touching the sea bottom are placed in the category grounding. Sometimes other names are also used such as stranding of wrecked. Foundering is the category of ships that sank as a result of heavy weather, spraining of leaks or breaking in two. Terms related to foundering in literature are flooding or capsizing. Ships that are lost due to hull and / or machinery failure are located in the hull and machinery failure category. The Nonaccidental structure failure (NASF); when the hull presents cracks and fractures affecting the ship's seaworthiness is also placed in the hull and machinery failure category. Fire and explosion is the category in which fire and explosion were the first event reported. Missing refers to the cases where the ships fate is undetermined as after a reasonable period of time there is still no news received of the ship. Finally the category miscellaneous refers to ships which are lost or damaged and no sufficient information is available or cannot be classified.

In Table 2.5 the accident phenomena are stated. It should be noted that in the data bases such as Lloyd's, contact and collision were a combined category before 1980. After 1980 the distinction between contact with another ship (collision) and contact with another external body (contact) was made. Another important note is that sometimes a combination of accident phenomena cause the ship accident. In this case the ship accident is reported in the category that was the fist event. For example if a collision (striking with another ship) was the first event which caused an explosion on board, then the accident will be registered in the category collision and not in the category fire and explosion.

[Buzancic Primorac and Parunov, 2016] have analyzed the statistical data of accidents. Using the data from [Eleftheria et al., 2016], [Butt et al., 2015] and [Allianz, 2015] Figure 2.7 was constructed illustrating the percentage of total losses by accident category. From this figure it can be seen that the largest category is 'foundered'. [Allianz, 2015] states that the reason for foundering accounting for almost 75% of the accidents is often driven by bad weather. The following categories in order of magnitude are stranded, fire & explosion, collision, hull & machinery and finally contact.

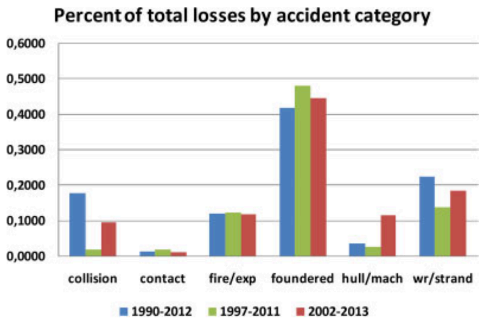


Figure 2.7: Percentage of total losses by accident category for different periods [Buzancic Primorac and Parunov, 2016]

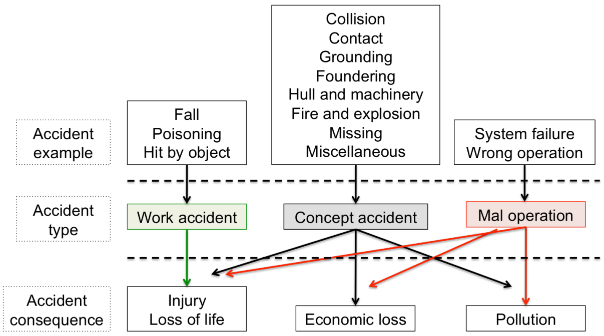


Figure 2.8: Maritime accident types and consequences [Kristiansen, 2005]

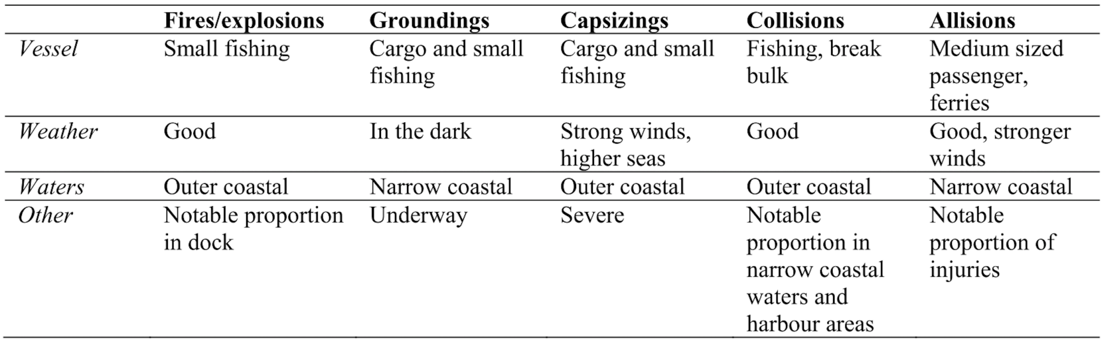
One category that is often not included in the literature is the human factor and operation of the ship. According to [Soares and Teixeira, 2001] operation is the main contributor to accidents and 80% of the shipping accidents are caused by human errors. [Kristiansen, 2005] does include the human factor as 'maloperation' in his analysis as shown in Figure 2.8. In this figure the accident type and the following accident consequence can be seen. Some examples have been given for each accident type.

2.5 Which Parties / System Components Play a Role in these Accident Scenarios

The scenario's explained in the previous section are caused by (a combination of) certain parties / system components. These parties, system components and functions are listed in Section 2.2. Also the risk factors from Section 2.3 play an important role in the accident scenarios. Some of these risk factors play a larger role than others. Certain types of vessels have for example a larger risk of being included in a certain accident scenario. In this section we will link the various risk factors (traits) with the accident scenarios. Thus connecting the previous sections and highlighting their importance. This link can aid in improving the safety of shipping as measures can be taken to prevent future accidents. First the common traits in the accident scenarios are stated, elaborating on which type of ship occurs often in which accident, which weather conditions or geographical locations play an important role in accident scenarios.

2.5.1 Common Traits in Accident Scenarios

[Stornes, 2015] has researched the association that risk factors, as described in Section 2.3, have with the occurrence of accidents scenarios, described in Section 2.4. The accident scenario's are: collision, contact, grounding, foundering, hull and machinery, fire and explosion, missing and other / miscellaneous. Figure 2.9 shows an overview of the common traits in accidents. These common traits found in accident categories are elaborated below.



	Fires/explosions	**Groundings**	**Capsizings**	**Collisions**	**Allisions**
Vessel	Small fishing	Cargo and small fishing	Cargo and small fishing	Fishing, break bulk	Medium sized passenger, ferries
Weather	Good	In the dark	Strong winds, higher seas	Good	Good, stronger winds
Waters	Outer coastal	Narrow coastal	Outer coastal	Outer coastal	Narrow coastal
Other	Notable proportion in dock	Underway	Severe	Notable proportion in narrow coastal waters and harbour areas	Notable proportion of injuries

Figure 2.9: Common traits in accidents [Stornes, 2015]

Fire

Ships that statistically have a larger risk of an accident in the category fire and / or explosion are ships with a large gross tonnage or longer vessels. For smaller vessels, such as fishing vessels fire often happens in outer coastal waters in the Northern regions. For all vessels most fires happen in outer coastal waters but also a significant proportion happens in dock along the quay side. Weather has little influence on the risk of fire.

Grounding

Ships that statistically have a larger risk of an accident in the category grounding are cargo vessels. Vessels in narrow coastal waters and in the northernmost region of the coastline also have an increased risk. Foreign vessels and vessels sailing in the dark and at night also have a high risk of grounding.

Foundering

Ships that statistically have a larger risk of an accident in the category foundering involve smaller fishing and cargo vessels. The northernmost region of the coastline and outer coastal waters have a high risk as strong winds and high seas (severe weather) are influential.

Collision

Ships that statistically have a larger risk of an accident in the category collision fishing vessels and break bulk vessels. Collisions occurs in all locations, outer coastal waters, narrow coastal waters and harbour seas. Collisions often happen in good weather conditions but little or no visibility increases the risk of collision. Collisions are more likely to happen by day.

Contact

Ships that statistically have a larger risk of an accident in the category contact are high speed vessels of medium tonnage and a longer length, particularly ferries. Most of the contact accidents happens in narrow coastal waters and in the harbour area. Often they hit the quay due to strong winds. Contact accidents are more likely to happen at arrival of port than at departure.

2.5.2 Actors

All the actors stated in Section 2.2.1 play an important role in the accident scenarios. As shown in Figures 2.2 and 2.3 the parliament, IMO, european commission and classification all have an influence on the rules, conventions, laws and standards of the ship building and the enforcement and certification of the ship building. The shipyard and ship owner have an important role in ship type and characteristics. The ship owner is responsible for the operation, safety and current state of the ship. Many other actors such as crew training have an influence on the occurrence of accidents.

2.5.3 System Components

All the systems stated in Table 2.2 play an important role in the accident scenario's. The most important are: communications (e.g. communication with other ships to avoid collision), control (e.g. control of the vessel to avoid contact), electrical (e.g. avoid power problems), ballast (e.g. avoid capsizing in heavy weather conditions), machinery and propulsion (e.g. avoid machinery and propulsion failure in hash conditions and need for regular maintenance), positioning, thrusters (e.g. avoid contact, collisions and extreme weather conditions such as hurricanes), radar (e.g. detect static objects or other vessels), piping and pumping (e.g. avoid foundering/flooding), pressure plant, hydraulics (e.g. avoid failure of controlling of ship, machine failure), safety (in case of an accident ensure that there are no human casualties).

2.6 System boundaries

In the above sections the MTS is discussed. In Section 2.1 the definition of maritime transportation systems was determined. In Section 2.2.1 the parties and system components involved were discussed. Following in Section 2.3 the risk factors were determined and in Section 2.4 the accident scenarios. Following the risk factors and accident scenarios were linked by analyzing the common traits. From this chapter we can conclude that there are many elements that influence the safety of shipping in the MTS. Each of these elements need to be analyzed individually to determine the cause of an accident. These controls of the elements can then be evaluated and maybe preventive measures can be implemented. This process is called risk assessment and will be discussed in the next chapter.

The system boundaries of the risk assessment will be as followed. The MTS consists of the entire value chain related to maritime transportation, including all the logistics after the shipping phase. Only the actual maritime transportation 'shipping' phase of the MTS will be analyzed. In addition for this literature study not all maritime activities are studied. There are many maritime activities as explained in Section 2.2.2. As shipping is essential for the global economy and Lloyd's register predicteds that the 9.84 billion tons of shipments will increase to between 19 and 24 billion tons by 2030 [Lloyd's Register et al., 2013], the largest sector should be selected. According to [International Maritime Organization, 2012] around 90% are cargo vessels: 42.9% bulk carriers, 28.5% oil tankers,12.8% container ships, 4.9% cargo ships, 4.3% offshore, 2.7% gas tankers,1.4% chemical tankers and 0.3% ferries and passenger ships. Therefore the sector 'cargo vessels' will be the main category analyzed in this report.

3 Risk Assessment

This chapter discusses the risk assessment of the MTS. First, the important key technical terms and concepts are defined. Secondly the need for risk assessment is discussed including what risk is and the benefits of risk assessment. Thirdly the risk assessment methods and models that exist in literature and in standards are discussed. Risk assessment is build up of three phases; risk identification, risk analysis and risk evaluation. For each phase the methods and models are shown. Following the risk assessment methods and models used in maritime transportation are discussed including the Formal Safety Assessment from the IMO and other methods by researchers. A comparison is made and how to select a method is explained. Finally the current challenges in risk assessment methods and models are highlighted.

3.1 Definition of Risk Assessment

Many definitions of risk assessment are provided by [Det Norske Veritas, 2001], [Wang, 2006] and [Kristiansen, 2005]. However for this literature review the definition from the NEN standards will be used. Risk assessment: risk assessment is the overall process of risk identification, risk analysis and risk evaluation [NEN-ISO/IEC 31010, 2012]. Risk assessment provides insight in the causes, consequences and probabilities of risks.

Several authors have provided a definition for the terminology used in risk studies [Kristiansen, 2005], [Mullai and Paulsson, 2011], [Wang, 2006] and [Merrick et al., 2002]. In this literature review we will mainly follow the definitions used by the reports of the IMO for the key technical terms [International Maritime Organization, 2013] and [Li et al., 2012].

- **Risk**: probability (frequency) times the consequence (severity) of the accident.
- **Accident**: an unintended event involving fatality or injury, environmental damage or economic losses (ship loss or damage, other property loss or damage).
- **Consequence**: outcome of an accident.
- **Frequency**: number of occurrences per unit time (e.g. per year).
- **Hazard**: a potential to threaten human life, health, property or the environment.

The consequences of hazards can be classified based on their degree of damage [International Maritime Organization, 2013]:

- Accident
- Incident
- Operating disturbance
- Non-conformance

The definition of an accident is given by IMO. The difference between an accident and an incident is that an incident is an event which is unpleasant or unusual [Cambridge Dictionary, 2016]. Accidents may have three kinds of consequences: first; human injuries and / or fatalities, second; evironmental damage and third; economic losses [Kristiansen, 2005]. An operating disturbance is a situation where for a system or component the operating criteria are violated [Kristiansen, 2005]. An operating disturbance can have several consequences; reduced efficiency, reduced capacity, loss of function, operating in emergency mode, outside operating performance limits or a temporary idle system. A non-conformance is a situation where the criteria that define what is acceptable are crossed [Kristiansen, 2005]. In this literature review mainly accidents will be addressed.

The occurrence of several tragic accidents and environmental disasters as explained in Section 3.2 raised the awareness of both researchers and maritime authorities. Safety of ships and risk analysis methods have received increasing attention in recent years. An insight into the process of risk calculation is needed for effective risk mitigation. This includes estimating risks and factors influencing the level of safety by studying how hazardous events or states develop and interact to cause an accident, or shortly, risk assessment.

Through literature the terms risk analysis, risk assessment and risk management are sometimes used interchangably. However [Mullai and Paulsson, 2011], [Wang, 2006], [Det Norske Veritas, 2001] clearly define the differences.

- **Risk analysis**: hazards are identified and the risk to people, environment and property is estimation by systematic use of the available information.
- **Risk assessment**: the total process of risk identification, risk analysis and risk evaluation.
- **Risk management**: selecting the appropriate risk reduction measures and implementing.

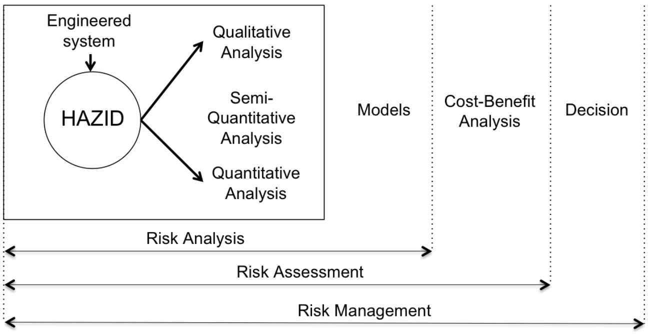


Figure 3.1: Risk assessment according to [Det Norske Veritas, 2001]

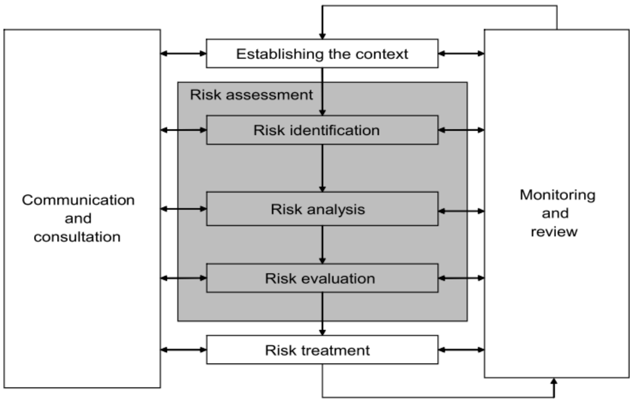


Figure 3.2: Risk assessment according to [NEN-ISO/IEC 31010, 2012]

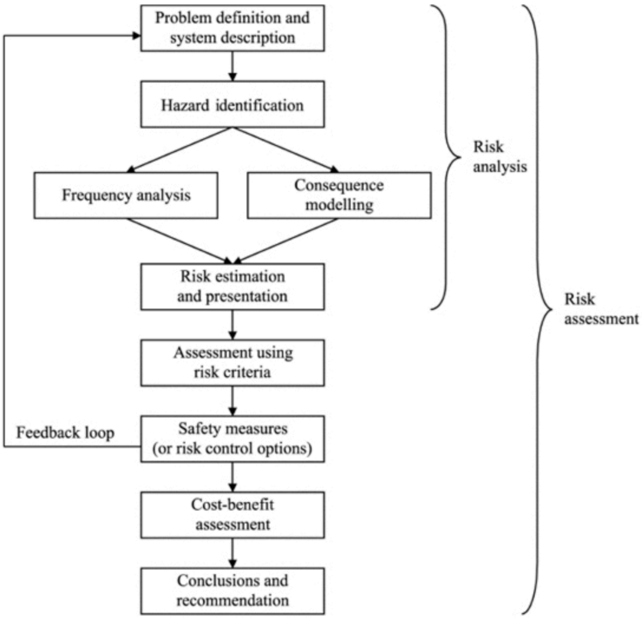


Figure 3.3: Risk assessment according to [Kristiansen, 2005]

In Figures 3.1, 3.2 and 3.3 the relation between risk analysis, risk assessment and risk management are illustrated by various authors. According to [Det Norske Veritas, 2001], Figure 3.1 risk analysis includes hazard identification (HAZID). A hazard is a situation with a potential for causing harm to human safety, the environment, property or business as explained above. Following a qualitative, semi-quantitative or quantitative analysis is chosen to be performed on this hazard. Risk assessment includes risk analysis but also performing the assessment using several techniques such as fault trees, bow ties etc. Using these techniques the approaches for risk reduction can be identified. Finally the risk management adds a cost-benefit analysis and the decision making.

The [NEN-ISO/IEC 31010, 2012] shown in Figure 3.2 show that the risk assessment consists of risk identification, risk analysis and risk evaluation. Risk identification includes finding the risk, recognizing the type of risk and recording the risk. The risk analysis phase focuses on determining the consequences and probabilities of the identified risks. Finally the risk evaluation phase compares the estimated level of the risk with the risk criteria to determine the risk level and type.

[Kristiansen, 2005] disagrees as shown in Figure 3.3 and includes the cost-benefit analysis in the risk assessment instead of addressing it in the risk management phase.

Comparing the three above mentioned approaches they are alike with some minor differences. All include hazard identification, risk analysis with risk estimation and comparing this with the set risk criteria. The difference lies in whether the cost-benefit analysis should be included or not. This literature review will focus on the risk assessment method including the method of cost-benefit analysis.

3.2 Need for Risk Assessment

In Figure 3.4 the current shipping density data is shown. The red represents high shipping density, the yellow average shipping density and the blue low shipping density. With the predicted increasing demand for cargo transportation this density will increase significantly in the future and the probability of the occurrence of an accidents will also increase. Maritime accidents adversely affect the economy, marine environment and human life [Mullai and Paulsson, 2011].

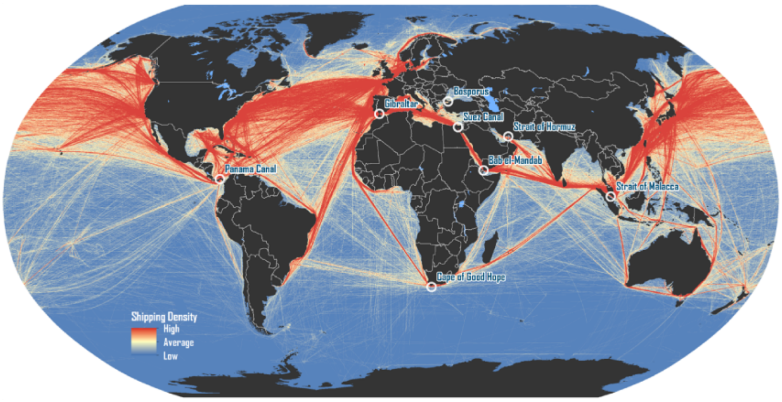


Figure 3.4: Shipping density data [Rodrigue et al., 2016]

Tragic accidents such as the collision of the Titanic with an iceberg (1912) resulting in the death of 1522 people, the Harald Free Enterprise (1987) resulting in 193 deaths, Derbyshire (1980) with 91655 gross tons lost and resulting in 44 deaths due to a typhoon, Piper Alpha (1988) a large scale explosion at an oil rig resulting in 167 deaths and environmental damage, Estonia passenger ferry (1994) resulting in 852 deaths. Environmental disasters such as the grounding of the Exxon Valdez (1989) spilling between 41 and 132 millions of liters of crude oil in sea, Prestige (2002) spilling 11.000 ton crude oil or the Deepwater Horizon oil spill (2010) have emphasized the need for risk assessment in the maritime industry [Wang, 2006][Merrick and Van Dorp, 2006] [Ozbas, 2013] and [Wang et al., 2004].

3.2.1 What is risk?

The definition of risk that is often applied among engineers is [Kristiansen, 2005]:

$$R = P \cdot C \tag{3.1}$$

Where R is the risk, P is the probability of the occurrence of an undesired event and C is the expected consequence in terms of injuries & fatalities, environmental damage or economic losses.

Probability of the occurrence

The number of serious accidents per ship type that occurred between 2000 and 2012 have been analyzed by [Eleftheria et al., 2016] and is shown in Table 3.1.

Table 3.1: Accident numbers [Eleftheria et al., 2016]

Type	**Number**
General Cargo	3228
Bulk Carriers	1609
Fishing vessels	456
Reefer ships	210
Ro-Ro Cargo	184
Car Carriers	194
LPG Ships	140
LNG Ships	21
Fully Cellular Container	1090
Large Crude Oil	259
Passenger Ro-Ro Cargo	888
(Pure) Passenger Ships	356
Cruise ships	217

Consequences

The consequences of these accidents ranged from large-scale loss of life, environmental damage, as many are carrying dangerous or damaging goods, or economic losses for companies. The expenses for the clean-up of the Exxon Valdez cost Exxon $2.2 billion [Merrick and Van Dorp, 2006]. This caused researchers and the maritime industry to focus on the safety risks involved in maritime operations [Ozbas, 2013]. The demand for improved safety in the MTS requires a comprehensive risk analysis to be developed [Wang, 2006] and [Wang and Pillay, 2003].

With the increasing attention on ship safety many improvements have been made to ships which can be seen in Lloyd's World Casualty Statistics. There is a decreasing rate of ship losses as shown in Figure 3.5. However the yearly average of gross tons lost is almost stable in the considered period [Soares and Teixeira, 2001] [Zhang et al., 2013]. This is due to the ever-larger ships and their cargo-carrying capacity. The cargo-carrying capacity has increased by 70% over the last decade. One container ship can now carry 1900+ containers and the loss of one of these mega-ships results in a huge gross tonnage lost in a single accident and with it a huge economic loss [Allianz, 2015].

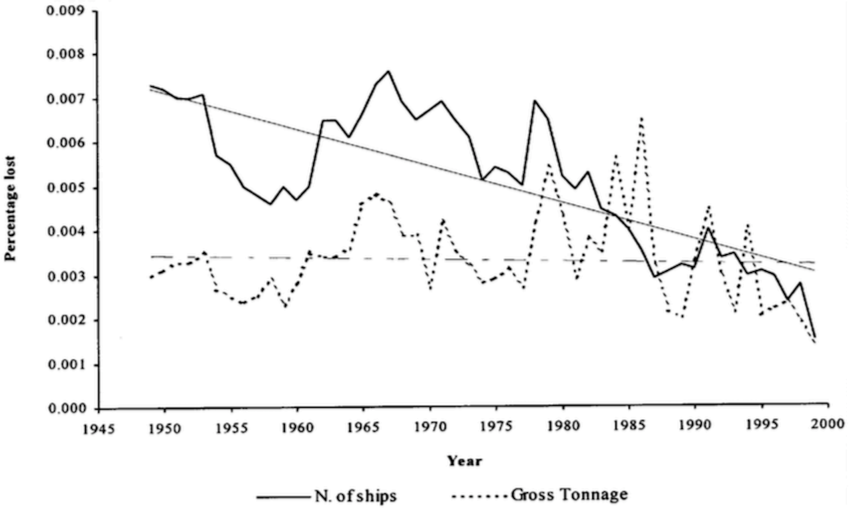


Figure 3.5: Annual rate of total losses [Soares and Teixeira, 2001]

3.2.2 Benefits of Risk Assessment

The first formal assessment for ship reliability was the Buships specification of July 31, 1960. This was done by the United states of America's Department of Defense and addressed the electronic equipment [Wang and Pillay, 2003]. Also the structure of the ship was the focus of one of the earliest probabilistic assessments of risk of failure. This resulted in a subdivision of ships in watertight compartments [Soares and Teixeira, 2001].

In recent years risk assessment has been regarded so important, also in other industries, that NEN standards have been developed. The NEN are norms which are applied as the standard that an engineering system has to fulfill. The NEN is a dutch standard but it complies with ISO (international standards). The NEN standards for risk assessment [NEN-ISO/IEC 31010, 2012] also mention the importance of risk assessment. With risk assessment the following benefits can be gained:

- Understanding the risk and the impact it might have on objectives.
- Information is provided to decision makers.
- Understanding the risk so that it can be used to select the effective controls for treatment.
- Identify the important risk factors and the weak links in the organization and / or system.
- Comparison with the risks in alternative systems, technologies and / or approaches to select the best one.
- Communicating the uncertainties and risks.
- Able to determine priorities.
- Incident prevention by investigating the incident.
- Different types of risk controls and treatments can be selected.
- Regulatory requirements are satisfied.
- Providing information for the risk evaluation phase - if the risk is negligible or intolerable.
- Assessing end of life disposal risks.

According to [Wang, 2006] risk assessment in MTS can lead to many benefits:

1. Improved performance of the current fleet by using the experience of the field.
2. Ensuring good design in new ships (incorporating the lessons learned).
3. Being able to predict and control the most likely accident scenarios.

Therefore it is of great importance to create an overview of the currently available risk assessment methods for maritime transportation systems and illustrate their advantages and disadvantages. Using this knowledge the challenges in this research field can be identified.

3.3 Risk Assessment Methods and Models

Following the risk assessment concept according to the NEN standards shown in Figure 3.2 the steps included in risk assessment are: risk identification, risk analysis and risk evaluation. The available methods are classified in terms of application in the three stages involved.

3.3.1 Risk Identification

In the risk identification phase, the risk is found, recognized and recorded. Methods that are used in this phase are [NEN-ISO/IEC 31010, 2012]:

- Evidence based methods such as checklists and reviews of historical data.
- Team of experts identify risks systematically.
- Reasoning techniques such as HAZOP (details of HAZOP can be found in Appendix A).

3.3.2 Risk Analysis

In the risk analysis phase, the consequences and probabilities of the risk are identified. The consequences and probabilities are combined to determine the level and type of risk. The causes and sources of the risk are discovered and more than one technique can be used for this phase. In short the sequence of risk analysis is:

1. Consequence analysis
2. Probability estimation
    (a) Quantitative-, semi-quantitative- or qualitative- techniques
    (b) Determining the effectiveness of already existing controls
3. Estimation of risk level

Methods used for risk analysis can be qualitative, semi-quantitative and /or quantitative [NEN-ISO/IEC 31010, 2012] and [Det Norske Veritas, 2001]. The choice depends on the degree of detail required. Qualitative risk assessments determines the consequences, probabilities and risk level as "high", "medium" or "low". Semi-quantitative methods use numerical rating scales such as linear of logarithmic scales. Quantitative analysis estimates values in specific units. Often quantitative analysis seems like the perfect option however it takes a lot of time and effort and this is not always required. In addition quantitative analysis is not always possible due to the lack of data and influence of human factors. It should be stated that the levels of risk, probabilities and consequences are in all cases estimates and the accuracy of the estimates depends on the information and methods available.

Sequence No. 1. Consequence Analysis

Consequence analysis as the term implies analyses the consequences if an event should occur. This involves analyzing the nature, type and magnitude of impact as well as the objectives / stakeholders influenced by the event. The consequence and probability of the impact are important for the selection of which risk is suitable for risk mitigation. The outcome of the analysis can differ significantly. Sometimes a simple description is the only outcome while some other methods produce an extensive vulnerability analysis [NEN-ISO/IEC 31010, 2012].

Consequence analysis can involve:

- Analyze the nature, type and magnitude of the impact.
- Analyze the objectives and stakeholders influenced by the event.
- Analyze the factors and controls that effect the consequences.
- Analyze the short-term and long-term consequences.
- Analyze secondary consequences.

Sequence No. 2a. Probability Estimation

Probability estimation can be done in three ways and these methods can be used individually but also jointly [NEN-ISO/IEC 31010, 2012] :

1. **Historical data**: Relevant historical data can be used to estimate the probability of a certain event occurrence in the future. It is important to only use data related to the situation and system.

2. **Forecasts**: Predictive techniques can be used to determine probability forecasts. Predictive techniques analyses failures and success states of the system, activities, equipment, organization etc. Numerical data or published databases can be used to estimate the probability. This method is often used when historical data is not available or not correct. Examples of this method are the ‘Fault tree analysis’ (FTA) and the ‘Event tree analysis’ (ETA) mentioned in Figure 3.7. More detailed information about the use of these methods, inputs, outputs, strengths and limitations can be found in Appendix A.

3. **Expert opinion**: The opinions of experts can be used to estimate probability on all aspects. However it is important to ensure that this is done in a systematic and structured manner. To ensure a systematic and structured manner several tools can be used such as the ‘Delphi approach’ mentioned in Figure 3.7. More detailed information about the use of these methods, inputs, outputs, strengths and limitations can be found in Appendix A.

Sequence No. 2b. Effectiveness of Existing Controls

The existing risk mitigation controls are important because with the known control effectiveness it can be determined whether the control has to be improved or a different risk treatment is needed [NEN-ISO/IEC 31010, 2012]. The existing control effectiveness can be expressed qualitatively, semi-quantitatively or quantitatively. Questions that may be asked are:

- What are the existing controls?

- Are the controls capable of adequately treating the risk?
- Are the controls in operating as intended?

Sequence No. 3. Estimation of Risk Levels

Using the qualitative, semi-quantitative and / or quantitative risk analysis methods and evaluating the consequence analysis, probability estimation and the effectiveness of existing controls the risk levels can be determined. Time and resource availability prevent all risks to be evaluated and therefore less significant or minor risks should be set aside. It is important to keep these assumptions in mind and not to set aside small risks that have a cumulative effect. Equally important is to communicate the uncertainties present in the risk levels. The risk levels are an estimation and when communicating the results the assumptions made and uncertainties present in the data, methods and models should be emphasized. Sensitivity analysis can be used to explore the range of possibilities in parameters with uncertainty and their size and influence on the risk [NEN-ISO/IEC 31010, 2012].

3.3.3 Risk Evaluation

The final part of the risk assessment is the risk evaluation. The risk evaluation consists of comparing the estimated risk levels to the risk criteria. This way the significance of the risk level and type can be determined [NEN-ISO/IEC 31010, 2012]. The risk evaluation serves as an input for whether and how to treat the risk for the decision makers.

The outcome of the comparison of the estimated risk levels to the risk criteria is the risk level. There are three levels of risk: intolerable, ALARP (As Low As Reasonably Practicable) and negligible [International Maritime Organization, 2002]. The various risk level criteria are shown in Figure 3.6 which divides the risks in three categories:

1. **Intolerable**: the risk level is regarded as intolerable, whatever benefits the activity may bring and risk treatment is essential whatever it costs.
2. **ALARP**: cost and benefits analysis is required to determine if the benefits of the risk outweigh the cost of the risk treatment measures.
3. **Negligible**: the risk level is so low that no risk treatment is required.

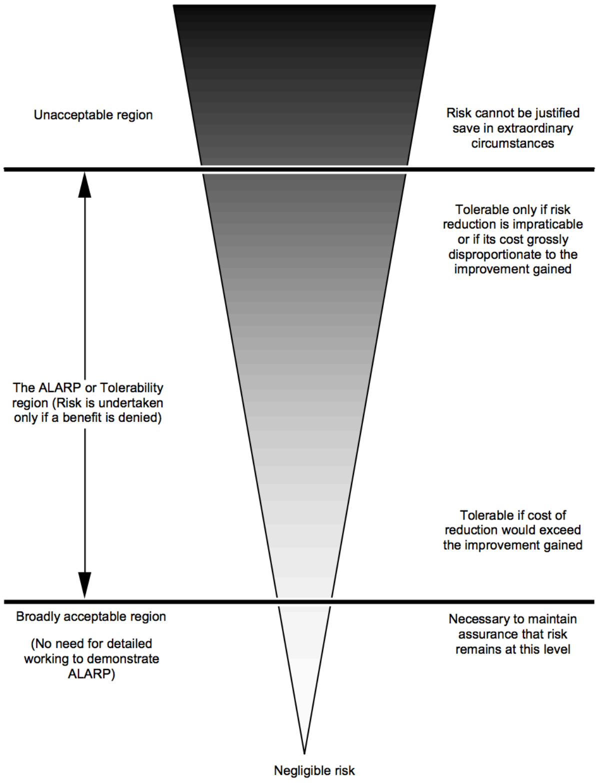
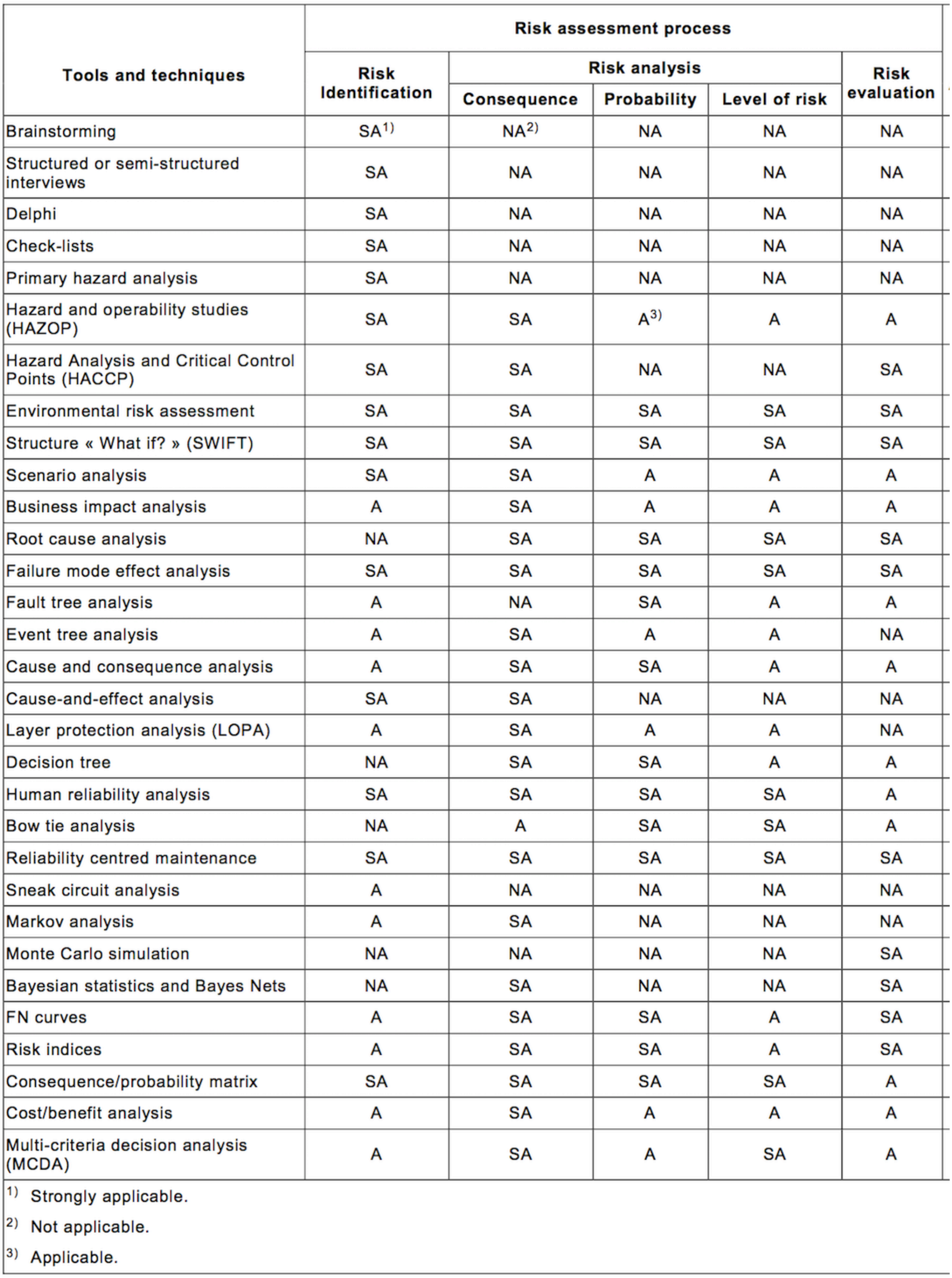


Figure 3.6: The risk levels [NEN-ISO/IEC 31010, 2012]

3.3.4 Methods and models

In Figure 3.7 the various risk assessment methods and models are shown. Risk assessment consists of three phases, first risk identification, discussed in Section 3.3.1, second risk analysis, discussed in Section 3.3.2 and third risk evaluation, discussed in Section 3.3.3. The second phase: risk analysis, consists of three phases; consequence analysis, probability estimation and determining the risk level. In Figure 3.7 the relevant risk methods used in each phase are shown. 'SA' stands for strongly applicable, 'A' for applicable and 'NA' for not applicable.

Figure 3.7 illustrates that brainstorming, interviews, the Delphi technique and checklists can only be used for risk identification while the Structured What If Technique (SWIFT) and Failure mode effect analysis (FMEA) can be used for all phases. Interesting methods are: Bayesian statistics and Bayesian nets which will be used for MTS risk assessment discussed in detail in Chapter 4 and Markov analysis and Monte Carlo simulation which are state-of-the-art methods. A detailed overview of each method including the advantages and disadvantages is provided in Appendix A.



Tools and techniques	Risk assessment process				
	Risk Identification	Risk analysis			Risk evaluation
		Consequence	Probability	Level of risk	
Brainstorming	SA[1]	NA[2]	NA	NA	NA
Structured or semi-structured interviews	SA	NA	NA	NA	NA
Delphi	SA	NA	NA	NA	NA
Check-lists	SA	NA	NA	NA	NA
Primary hazard analysis	SA	NA	NA	NA	NA
Hazard and operability studies (HAZOP)	SA	SA	A[3]	A	A
Hazard Analysis and Critical Control Points (HACCP)	SA	SA	NA	NA	SA
Environmental risk assessment	SA	SA	SA	SA	SA
Structure « What if? » (SWIFT)	SA	SA	SA	SA	SA
Scenario analysis	SA	SA	A	A	A
Business impact analysis	A	SA	A	A	A
Root cause analysis	NA	SA	SA	SA	SA
Failure mode effect analysis	SA	SA	SA	SA	SA
Fault tree analysis	A	NA	SA	A	A
Event tree analysis	A	SA	A	A	NA
Cause and consequence analysis	A	SA	SA	A	A
Cause-and-effect analysis	SA	SA	NA	NA	NA
Layer protection analysis (LOPA)	A	SA	A	A	NA
Decision tree	NA	SA	SA	A	A
Human reliability analysis	SA	SA	SA	SA	A
Bow tie analysis	NA	A	SA	SA	A
Reliability centred maintenance	SA	SA	SA	SA	SA
Sneak circuit analysis	A	NA	NA	NA	NA
Markov analysis	A	SA	NA	NA	NA
Monte Carlo simulation	NA	NA	NA	NA	SA
Bayesian statistics and Bayes Nets	NA	SA	NA	NA	SA
FN curves	A	SA	SA	A	SA
Risk indices	A	SA	SA	A	SA
Consequence/probability matrix	SA	SA	SA	SA	A
Cost/benefit analysis	A	SA	A	A	A
Multi-criteria decision analysis (MCDA)	A	SA	A	SA	A

[1] Strongly applicable.

[2] Not applicable.

[3] Applicable.

Figure 3.7: Applicability of tools used for risk assessment [NEN-ISO/IEC 31010, 2012]

[Marhavilas et al., 2011] has researched 6163 papers in six scientific journals from 2000-2009. From the 6163 papers 404 papers were selected which had as main research the risk assessment and risk analysis techniques. His research can be found in Appendix B. It should be noted that this research has been done for all type of fields not solely for the MTS. The main methods and models that have been used in various field are classified as shown in Figure 3.8. Qualitative technique is based on analytical estimation. Quantitative techniques involve estimation of the risk by a mathematical relation and hybrid techniques have the best of both worlds.

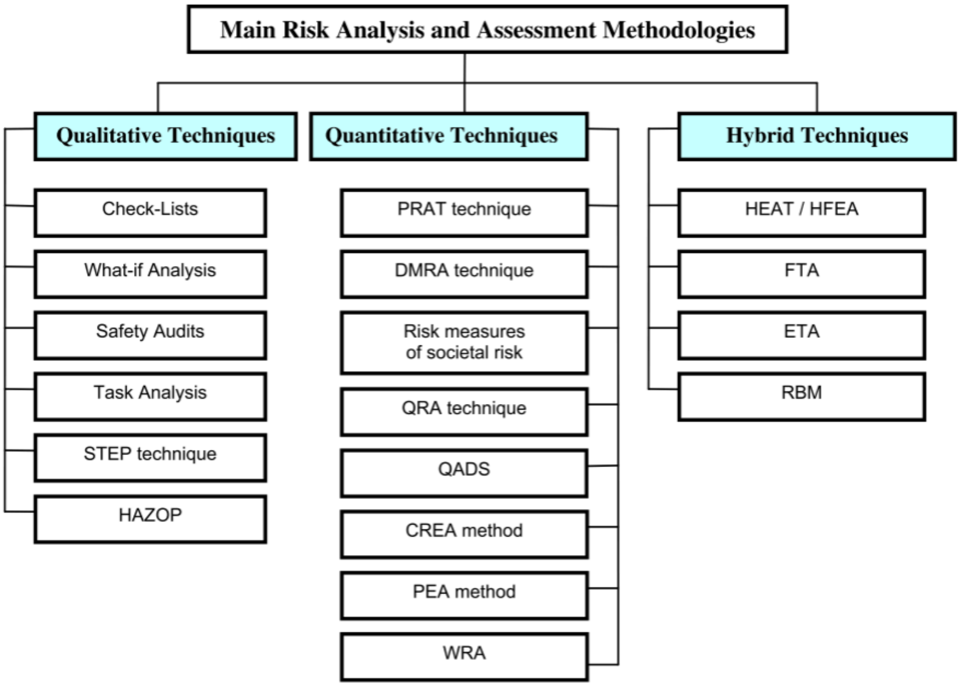


Figure 3.8: Classification of the main risk analysis and risk assessment models [Marhavilas et al., 2011]

Comparing Figure 3.7 with Figure 3.8 some overlapping methods and models can be found such as the check-lists, what-if analysis, Bowtie, HAZOP, FTA and ETA. However there are also numerous new methods and models presented which can be used for risk assessment. The new categories of the methods and models are:

- Safety audits
- Task analysis
- STEP technique (Sequentially Timed Event Plotting)
- PRAT technique (Proportional Risk Assessment)
- DMRA technique (Decision Matrix Risk Assessment)
- Risk measures of societal risk
- QRA technique (Quantitative Risk Assessment)
- QADS (Quantitative Assessment of Domino Scenarios)
- CREA method (Clinical Risk and Error Analysis)
- PEA method (Predictive, Epistemic Approach)
- WRA (Weighted Risk Analysis)
- HEAT / HFEA (Human Error Analysis Technique & Human Factor Event Analysis
- RBM (Risk Based Maintenance)

The advantages and disadvantages of the above named categories can be found in Appendix B. The methods and models that are part of these categories such as the: negative binomial regression, poisson-lognormal regression, GIS based approach and numerous more. The theory and background of the numerous methods and models will not be discussed in this literature review as there exist too many different models. The numerous methods are mentioned and the interested reader can turn to Appendix B. If more insight is required reading the original papers is recommended. This example is solely provided to illustrated that many methods and models have been developed for risk assessment.

3.4 Risk Assessment Methods and Models used in Maritime Transportation

Many risk methods and models have been developed by various authors and researchers as explained in the previous section. This section will provide a literature review of some of the risk assessment methods and models used in the MTS. Like the general risk assessment methods and models, also many methods and models are used in the risk assessment of the MTS. Many authors and researchers have different opinions on which method and / or models are more appropriate in certain situations. Therefore only a brief overview highlighting some of the main methods such as FSA will be elaborated below, for a more extensive research we refer to the in depth research of [Marhavilas et al., 2011], [Goerlandt and Montewka, 2015a] and [Ozbas, 2013].

3.4.1 Formal Safety Assessment

In 2002 the IMO introduced the Formal Safety Assessment (FSA). The “FSA is a sturctured and systematic methodology, aimed at enhancing maritime safety, including protection of life, health, the marine environment and property, by using risk analysis and cost benefit assessment [International Maritime Organization, 2002] and [International Maritime Organization, 2016b].” FSA is an example of proactive approach [Hassel et al., 2011]. FSA has been introduced by the IMO as many companies and researchers started to develop their own risk assessment method and there was no consensus on the used methods and models.

The FSA consists of 5 steps as shown in Figure 3.9.

1. **Identification of hazards**: similar to the risk identification phase in Section 3.3 listing the accident scenarios with potential causes and consequences. Identifying what can go wrong.

2. **Assessment of risks**: similar to the first part of the risk analysis phase in Section 3.3. Identifying what are the probabilities and the consequences.

3. **Risk control options**: similar to the second part of the risk analysis phase in Section 3.3. Here the existing controls are evaluated. Identifying if there are improvement options.

4. **Cost benefit assessment**: similar to the risk evaluation phase in Section 3.3. Determining the cost effectiveness of each risk control option. Identifying what it would cost and how much improvement would be gained.

5. **Recommendations for decision-making**: also part of the risk evaluation phase in Section 3.3. Identifying what actions should be taken.

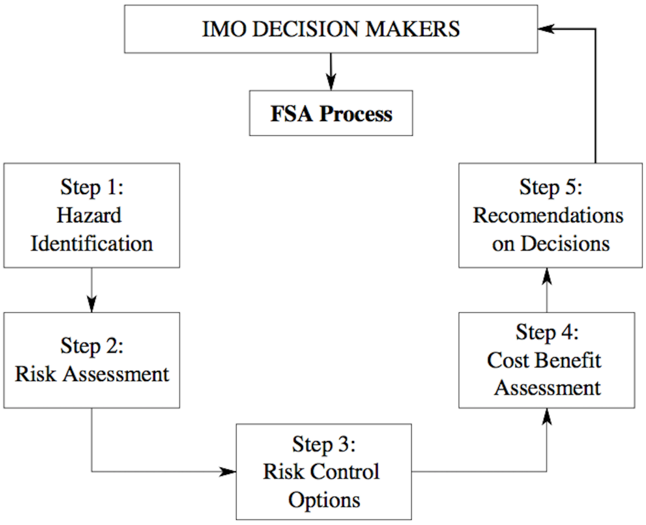


Figure 3.9: Flow chart of the FSA methodology [Soares and Teixeira, 2001]

The FSA was needed because many actors had an interest in improving the safety of maritime transportation as the costs of accidents are high. This resulted in many reactive (after the accident happened) risk assessments by various companies and other interested stakeholders. To ensure a transparent decision making process with the same rules and standards that would be pro-active (rather preventing accidents before they happened) the IMO introduced the FSA.

According to [Wang, 2006] the benefits of using FSA are:

1. A consistent method that addresses all aspects of safety.
2. Cost effectiveness: evaluating where the investment will achieve the greatest benefits.
3. Pro-active approach: preventing accidents rather than reducing risk after they already happened.
4. The regulatory requirements are in proportion to the severity of the risks.
5. A basis for risk analysis for new innovations with accompanying new risks in the continuously developing marine technology.

Several studies have already been performed using the FSA, for example on high-speed craft, bulk carriers, Ro-Ro vessels with dangerous goods, fishing vessels, offshore support vessels, cruising ships, ports, container ships and liner shipping [IACS, 2001], [Wang, 2006] and [Soares and Teixeira, 2001].

3.4.2 Other Methods and Models

On the 24th of March 1989 the Exxon Valdez grounded on the Bligh Reef spilling 11 million gallons in the Prince William Sound (PWS) in Alaska [Merrick et al., 2002]. The method used in the PWS is probabilistic risk assessment. First the series of events leading to the accident were identified, following the probability of these events were estimated and finally the consequences of the event were evaluated. This model was able to integrate system simulation, data analysis and expert judgment.

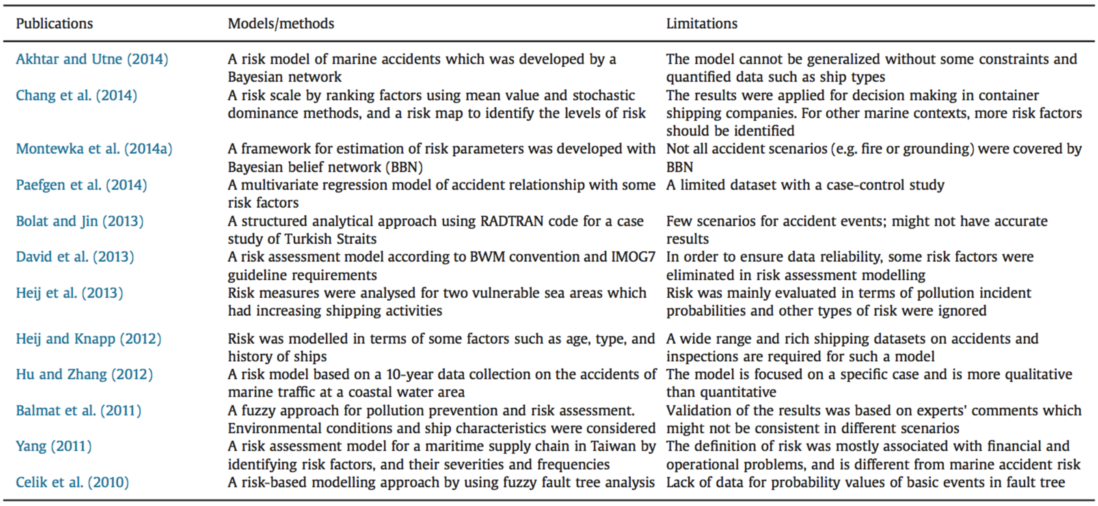
[Soares and Teixeira, 2001] examined ship loss by capsizing or by loss of floatability from a collision or grounding using phase plane analysis. Structural failure was also examined using reliability analysis and a probabilistic model.

[van Dorp et al., 2001] performed a risk management study for Washington state ferries. Using a dynamic simulation methodology the probability of ferry collision was modeled. First historical data was examined, following potential accident scenarios identified. A quantitative method was used to incorporate the risk factors. The modeling combined system simulation, expert judgment and available data.

[Akpan et al., 2002] has developed a risk assessment for the ultimate strength of an aging ship hull especially examining the impact of fatigue and corrosion. Time-dependent random variable model in combination with the second-order reliability method and a statistic and probabilistic description of corrosion are used in this risk assessment.

[Kaneko, 2002] examines a holistic method for risk evaluation, a method for estimating the probability of collision and a method of reducing the scenarios in fire. [Qu et al., 2011] performed a risk assessment of ship collision in the Singapore Strait. [Gasparotti and Rusu, 2012] aim to perform a risk assessment according to the guidelines of the FSA for oil pollution due to tanker accidents in the black sea.

[Faghih-Roohi et al., 2014] has analyzed several risk assessment models recently published. Many of the scientific literature focuses either on probabilistic risk assessment, simulation modeling or statistical data analysis. In Figure 3.10 the methods and limitations of various publications are shown. In this figure some authors have also used the Bayesian Belief Network as model. This model will be extensively discussed in Chapter 4.



Publications	Models/methods	Limitations
Akhtar and Utne (2014)	A risk model of marine accidents which was developed by a Bayesian network	The model cannot be generalized without some constraints and quantified data such as ship types
Chang et al. (2014)	A risk scale by ranking factors using mean value and stochastic dominance methods, and a risk map to identify the levels of risk	The results were applied for decision making in container shipping companies. For other marine contexts, more risk factors should be identified
Montewka et al. (2014a)	A framework for estimation of risk parameters was developed with Bayesian belief network (BBN)	Not all accident scenarios (e.g. fire or grounding) were covered by BBN
Paefgen et al. (2014)	A multivariate regression model of accident relationship with some risk factors	A limited dataset with a case-control study
Bolat and Jin (2013)	A structured analytical approach using RADTRAN code for a case study of Turkish Straits	Few scenarios for accident events; might not have accurate results
David et al. (2013)	A risk assessment model according to BWM convention and IMOG7 guideline requirements	In order to ensure data reliability, some risk factors were eliminated in risk assessment modelling
Heij et al. (2013)	Risk measures were analysed for two vulnerable sea areas which had increasing shipping activities	Risk was mainly evaluated in terms of pollution incident probabilities and other types of risk were ignored
Heij and Knapp (2012)	Risk was modelled in terms of some factors such as age, type, and history of ships	A wide range and rich shipping datasets on accidents and inspections are required for such a model
Hu and Zhang (2012)	A risk model based on a 10-year data collection on the accidents of marine traffic at a coastal water area	The model is focused on a specific case and is more qualitative than quantitative
Balmat et al. (2011)	A fuzzy approach for pollution prevention and risk assessment. Environmental conditions and ship characteristics were considered	Validation of the results was based on experts' comments which might not be consistent in different scenarios
Yang (2011)	A risk assessment model for a maritime supply chain in Taiwan by identifying risk factors, and their severities and frequencies	The definition of risk was mostly associated with financial and operational problems, and is different from marine accident risk
Celik et al. (2010)	A risk-based modelling approach by using fuzzy fault tree analysis	Lack of data for probability values of basic events in fault tree

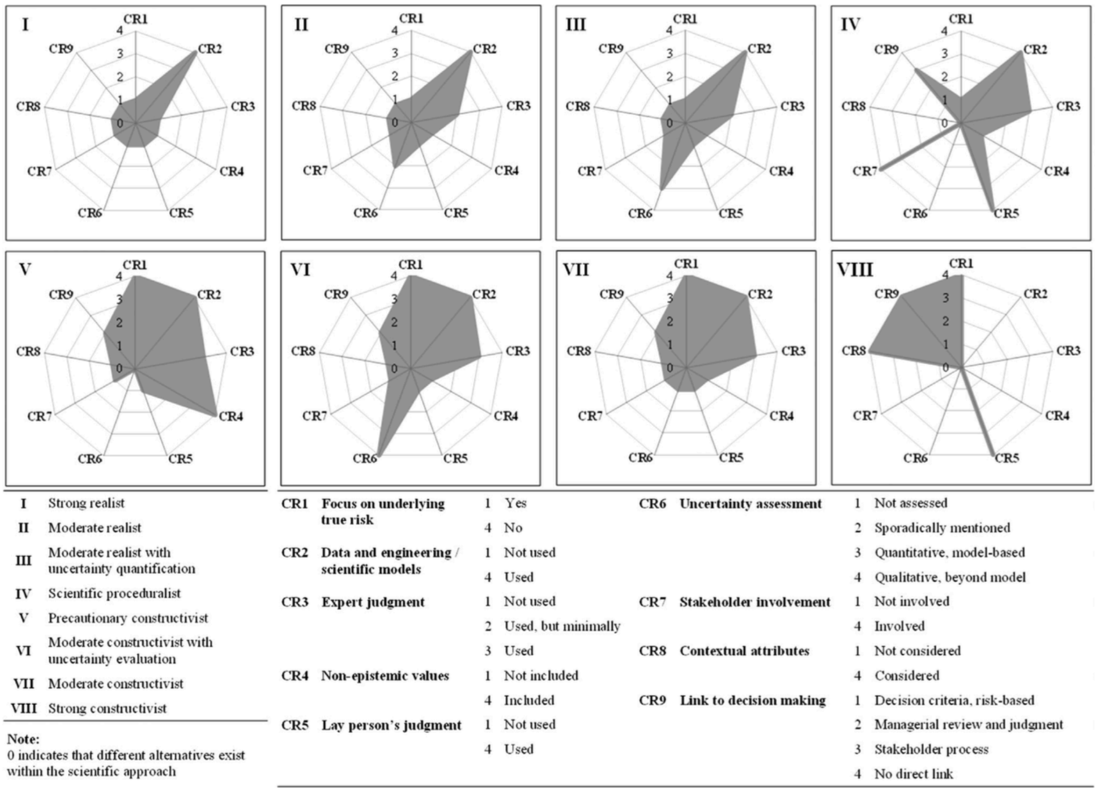
Figure 3.10: Risk assessment methods in Literature [Faghih-Roohi et al., 2014]

Many risk assessment studies on the MTS combine different techniques to estimate the risk. According to [Ozbas, 2013] most risk modeling studies use statistical data analysis to estimate inputs, parameters and analyze outputs. A data set is obtained using the distribution fitting technique, phase-type distributions and auto-regressive models. For the calibration of risk models historical accident data and statistical data analytics is used. Often quantitative risk assessment approaches are preferred over qualitative methodologies. Qualitative risk assessment don't require as much time but are limited and often subjective.

3.4.3 Comparison of Models

[Goerlandt and Montewka, 2015b] has analyzed 58 risk assessment and risk analysis methods applied to the MTS from 1974-2014 and compared them based on risk definition, risk perspective, approach to risk analysis science, data, model, judgment, non-epistemic values, contextual attributes etc. [Goerlandt and Montewka, 2015b] compared the various risk assessment and risk analysis methods and divided them in eight categories; strong realist, moderate realist, moderate realist with uncertainty quantification, scientific proceduralist, precautionary constructivist, moderate constructivist with uncertainty evaluation, moderate constructivist, strong constructivist. The characteristics of these risk analysis approaches are shown in Figure 3.12.

Using the characteristics of the classified risk analysis approaches, [Goerlandt and Montewka, 2015b] constructed a diagram showing which approach considers which aspects of risk analysis (e.g. models used, uncertainty assessment, stakeholders involved). This diagram can be found in Figure 3.11.

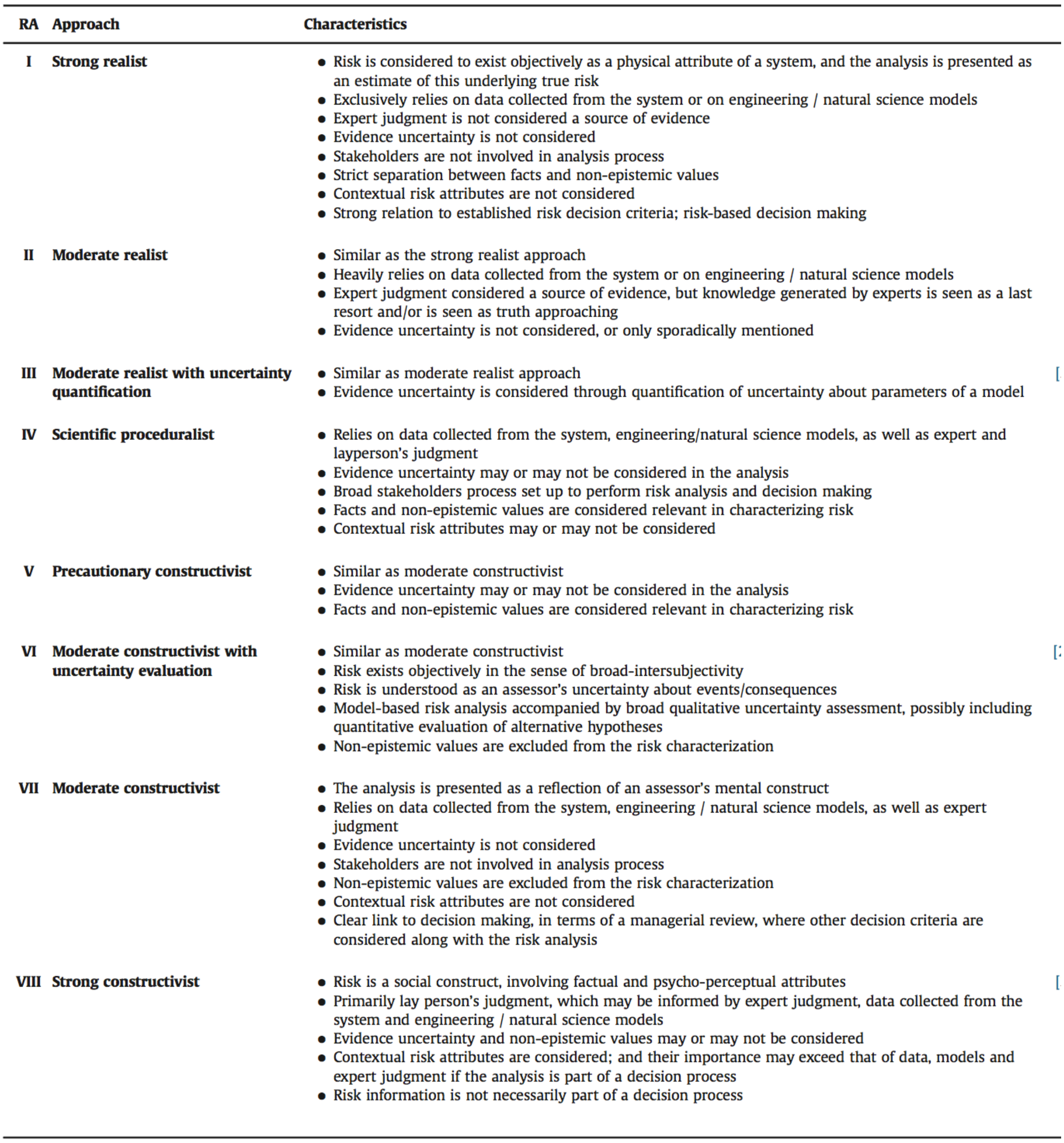


I	Strong realist
II	Moderate realist
III	Moderate realist with uncertainty quantification
IV	Scientific proceduralist
V	Precautionary constructivist
VI	Moderate constructivist with uncertainty evaluation
VII	Moderate constructivist
VIII	Strong constructivist

Note:
0 indicates that different alternatives exist within the scientific approach

CR1	**Focus on underlying true risk**	1	Yes
		4	No
CR2	**Data and engineering / scientific models**	1	Not used
		4	Used
CR3	**Expert judgment**	1	Not used
		2	Used, but minimally
		3	Used
CR4	**Non-epistemic values**	1	Not included
		4	Included
CR5	**Lay person's judgment**	1	Not used
		4	Used
CR6	**Uncertainty assessment**	1	Not assessed
		2	Sporadically mentioned
		3	Quantitative, model-based
		4	Qualitative, beyond model
CR7	**Stakeholder involvement**	1	Not involved
		4	Involved
CR8	**Contextual attributes**	1	Not considered
		4	Considered
CR9	**Link to decision making**	1	Decision criteria, risk-based
		2	Managerial review and judgment
		3	Stakeholder process
		4	No direct link

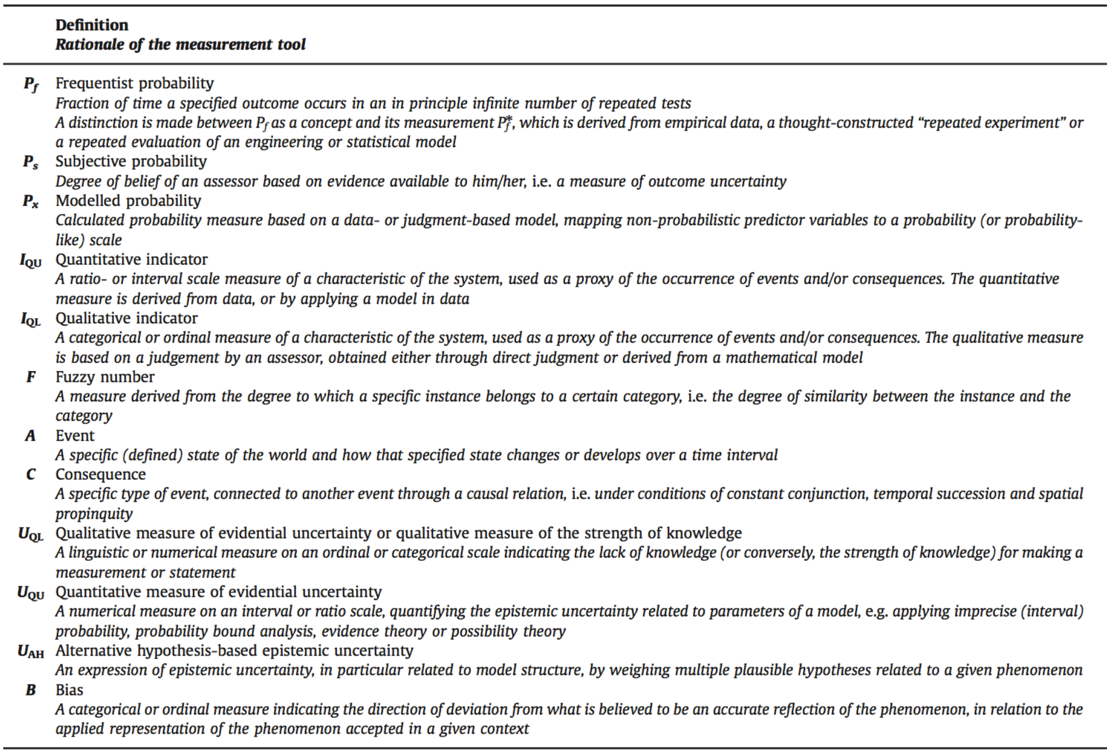
Figure 3.11: Risk analysis approaches diagram [Goerlandt and Montewka, 2015b]



RA	Approach	Characteristics
I	**Strong realist**	• Risk is considered to exist objectively as a physical attribute of a system, and the analysis is presented as an estimate of this underlying true risk • Exclusively relies on data collected from the system or on engineering / natural science models • Expert judgment is not considered a source of evidence • Evidence uncertainty is not considered • Stakeholders are not involved in analysis process • Strict separation between facts and non-epistemic values • Contextual risk attributes are not considered • Strong relation to established risk decision criteria; risk-based decision making
II	**Moderate realist**	• Similar as the strong realist approach • Heavily relies on data collected from the system or on engineering / natural science models • Expert judgment considered a source of evidence, but knowledge generated by experts is seen as a last resort and/or is seen as truth approaching • Evidence uncertainty is not considered, or only sporadically mentioned
III	**Moderate realist with uncertainty quantification**	• Similar as moderate realist approach • Evidence uncertainty is considered through quantification of uncertainty about parameters of a model
IV	**Scientific proceduralist**	• Relies on data collected from the system, engineering/natural science models, as well as expert and layperson's judgment • Evidence uncertainty may or may not be considered in the analysis • Broad stakeholders process set up to perform risk analysis and decision making • Facts and non-epistemic values are considered relevant in characterizing risk • Contextual risk attributes may or may not be considered
V	**Precautionary constructivist**	• Similar as moderate constructivist • Evidence uncertainty may or may not be considered in the analysis • Facts and non-epistemic values are considered relevant in characterizing risk
VI	**Moderate constructivist with uncertainty evaluation**	• Similar as moderate constructivist • Risk exists objectively in the sense of broad-intersubjectivity • Risk is understood as an assessor's uncertainty about events/consequences • Model-based risk analysis accompanied by broad qualitative uncertainty assessment, possibly including quantitative evaluation of alternative hypotheses • Non-epistemic values are excluded from the risk characterization
VII	**Moderate constructivist**	• The analysis is presented as a reflection of an assessor's mental construct • Relies on data collected from the system, engineering / natural science models, as well as expert judgment • Evidence uncertainty is not considered • Stakeholders are not involved in analysis process • Non-epistemic values are excluded from the risk characterization • Contextual risk attributes are not considered • Clear link to decision making, in terms of a managerial review, where other decision criteria are considered along with the risk analysis
VIII	**Strong constructivist**	• Risk is a social construct, involving factual and psycho-perceptual attributes • Primarily lay person's judgment, which may be informed by expert judgment, data collected from the system and engineering / natural science models • Evidence uncertainty and non-epistemic values may or may not be considered • Contextual risk attributes are considered; and their importance may exceed that of data, models and expert judgment if the analysis is part of a decision process • Risk information is not necessarily part of a decision process

Figure 3.12: Risk analysis approaches [Goerlandt and Montewka, 2015b]

In relation to the previous named methods and models that are available according to the NEN standard, this comparison graph is related. [Goerlandt and Montewka, 2015b] compared the measurement tool with the type of category (one of the 8 named above). As stated, there are numerous methods and models and as there is no consensus on their use, the measurement tool that is applied is used to compare the models. The measurement tool options are shown in Figure 3.13. The measurement tool can either consists of: Frequentist probability, subjective probability (e.g. expert judgment), modeled probability, quantitative indicator, qualitative indicator, fuzzy number, event, consequence, uncertainty and / or bias.



	Definition ***Rationale of the measurement tool***
P_f	Frequentist probability *Fraction of time a specified outcome occurs in an in principle infinite number of repeated tests* *A distinction is made between P_f as a concept and its measurement P_f^*, which is derived from empirical data, a thought-constructed "repeated experiment" or a repeated evaluation of an engineering or statistical model*
P_s	Subjective probability *Degree of belief of an assessor based on evidence available to him/her, i.e. a measure of outcome uncertainty*
P_x	Modelled probability *Calculated probability measure based on a data- or judgment-based model, mapping non-probabilistic predictor variables to a probability (or probability-like) scale*
I_{QU}	Quantitative indicator *A ratio- or interval scale measure of a characteristic of the system, used as a proxy of the occurrence of events and/or consequences. The quantitative measure is derived from data, or by applying a model in data*
I_{QL}	Qualitative indicator *A categorical or ordinal measure of a characteristic of the system, used as a proxy of the occurrence of events and/or consequences. The qualitative measure is based on a judgement by an assessor, obtained either through direct judgment or derived from a mathematical model*
F	Fuzzy number *A measure derived from the degree to which a specific instance belongs to a certain category, i.e. the degree of similarity between the instance and the category*
A	Event *A specific (defined) state of the world and how that specified state changes or develops over a time interval*
C	Consequence *A specific type of event, connected to another event through a causal relation, i.e. under conditions of constant conjunction, temporal succession and spatial propinquity*
U_{QL}	Qualitative measure of evidential uncertainty or qualitative measure of the strength of knowledge *A linguistic or numerical measure on an ordinal or categorical scale indicating the lack of knowledge (or conversely, the strength of knowledge) for making a measurement or statement*
U_{QU}	Quantitative measure of evidential uncertainty *A numerical measure on an interval or ratio scale, quantifying the epistemic uncertainty related to parameters of a model, e.g. applying imprecise (interval) probability, probability bound analysis, evidence theory or possibility theory*
U_{AH}	Alternative hypothesis-based epistemic uncertainty *An expression of epistemic uncertainty, in particular related to model structure, by weighing multiple plausible hypotheses related to a given phenomenon*
B	Bias *A categorical or ordinal measure indicating the direction of deviation from what is believed to be an accurate reflection of the phenomenon, in relation to the applied representation of the phenomenon accepted in a given context*

Figure 3.13: Rationale of the measurement tool [Goerlandt and Montewka, 2015b]

In Appendix C the detailed graph of the comparison can be found. Of the 58 scientific literature compared, 20 belong to the strong realist approach (Class I), 14 to the moderate realist approach (Class II), 13 to the strong constructivist approach (Class VII), 5 to the scientific proceduralist approach (Class IV), 3 to the moderate realist with uncertainty quantification (Class III), 2 to the precautionary constuctivist (Class V) and only 1 to the moderate constructivist with uncertainty evaluation (Class IV). Realist approaches are most dominant in the scientific literature.

[Ozbas, 2013] has also performed an analysis of many of the scientific literature on MTS. He came to the conclusion that there are many different methodologies to obtain an objective numeric value for risk contribution of system components. In conclusion it could be stated that many different models exist as there are many different applications and situations inside the MTS. There is a high chance that not one accident scenario is the same as the time, place and circumstances might be completely different.

3.4.4 Method Selection

The choice of using qualitative, semi-quantitative or quantitative model should always depend on what purpose the model is to serve. No model should be used as a fits-all solution [Hänninen, 2014]. It should be examined who will use the model and what type of information or background knowledge is available.

3.5 Current Challenges

Many methods and models have been proposed by various researchers to address risk assessment in the MTS. Scientific literature has criticized many of these methods and models and new methods and models have been developed. Below some of the main limitations of the methods and models can be found ranging from data limitations to difficulties with incorporating uncertainty.

Clarity on Fundamental Issues

[Ozbas, 2013] argues that in general in risk analysis and risk assessment there is no consensus over validity, practicality and applicability of approaches, definitions and methodologies. [Goerlandt and Montewka, 2015b] agrees that the clarity about fundamental issues should be improved (e.g. consensus on key terminology, perspectives and attention should be given to the scientific approach underlying the analysis) and adds that there is very little scientific research and discussion on the proposed methods and frameworks. [Wang, 2006] also states that the current techniques need to be further studied and the criteria for their effective use need to be determined. Currently it is unclear which different methods can be used individually or in combination and in which phase of the ship's life cycle as explained in Section 2.2.3 or in which accident scenario as explained in Section 2.4 they can be used. In addition new methods are needed to make effective en efficient design and operation decisions.

"All models are wrong, but some are useful" [Wikipedia, 2016a] is a quote from George E.P. Box, a british mathematicion and a pioneer in Bayesian inference. This quote refers to the fact that no single model is able to represent all systems. The fundamentals of each theory must be thoroughly analyzed to determine if they fit the complex phenomena and system that they are used for [Mullai and Paulsson, 2011]. 'The model is wrong' refers to that always some simplifications are made and the model never exactly represents reality but as long as the assumptions and uncertainties are communicated and applied correctly the model can be useful for decision-making.

Data

For all risk assessment methods and models the largest challenge is the gathering of data. Historical data is either incomplete, incorrect or non-existent due to the many changes in the history of rules and regulations and the inconsistency in reporting [Ozbas, 2013], [Montewka et al., 2014] and [Merrick and Van Dorp, 2006]. Furthermore the data in accident databases are not recorded in a consistent way and therefore are not ready-to use for modeling simulations. This results inadequate accidents models. According to [Hassel et al., 2011] 50% of the accidents are under-reported, [Psarros et al., 2010] also acknowledges this fact.

Many risk assessment models rely heavily on historical data [Mullai and Paulsson, 2011]. For the shortcoming of historical data often expert opinions are used, however this might introduce subjectivity. The improvements and determination of the effectiveness of controls are based on the data provided. To target the correct risk factors, actors and systems correct data is needed [Hassel et al., 2011]. Another problem is that models such as the Swiss analogy model, Bowtie model, FSA and ETA (all these models are discussed in detail in Appendix A) have no reference to or systematic analysis of the data [Mullai and Paulsson, 2011].

Reactive versus Proactive

Models are mainly based on historical data and therefore are considered reactive rather than proactive [Zhang et al., 2016] and [Montewka et al., 2014]. A reactive regulatory approach is when improvements and controls have been proposed to prevent the accident event or scenario of occurring again after the accident has already happened [Hassel et al., 2011]. To develop a proactive approach insight has to be gained into the way the accident develops. The most important variables have to be determined, how much they contribute to the risk and how sensitive they are.

Uncertainty

Communication of uncertainty in risk assessment methods and models is very important. Often decision-makers are incorrectly led to believe that the results are definitive without uncertainty. A large challenges in the above stated methods and models is how to communicate these uncertainties. Many authors acknowledge that uncertainty needs to be incorporated in risk assessment. However in practice assumptions are used to deal with uncertainty.

[Merrick et al., 2003], [Montewka et al., 2014] and [Merrick and Van Dorp, 2006] identify two types uncertainty. Aleatory uncertainty: uncertainty due to system randomness, and epistemic uncertainty: uncertainty due to lack of knowledge of the system or uncertainty in input variables. Bayesian simulation allows incorporation of aleatory and epistemic uncertainty and therefore allow the user to make decisions based on output uncertainty instead of point estimates. According to [Merrick et al., 2003] aleatory and epistemic uncertainty can be included in four steps:

1. Representation of uncertainty in simulation
2. Representation of uncertainty in expert judgment
3. Propagation of uncertainties through the entire model
4. Performing a trial uncertainty analysis

[Goerlandt and Montewka, 2015b] argues that in all the scientific literature that he compared in only a minority of the applications uncertainty and biases are systematically approached.

[Merrick and Van Dorp, 2006] argues that epistemic uncertainty can be reduced by further data collection but that epistemic uncertainty is irreducible as it is a property of the system. Epistemic uncertainty can be accounted for by using frequentist statistical techniques such as bootstrap or likelihood-based methods.

The remaining uncertainty can be addressed by using Bayesian modeling. Bayesian techniques can be used to analyze data and expert judgments and Monte Carlo simulation can be used to propagate uncertainty through the entire mode. Some of these methods and models have existed for quite some time, however the computational power was not sufficient enough to execute these models considering the large number of variables that have to be taken into account.

FSA

[Kristiansen, 2005] argues that although the FSA is a great initiative to achieve consensus on the risk assessment approach, this method can be criticized because they oversimplify the systems studied. In reality the systems are so large that by simplifying the systems many failure combinations are overlooked. In addition operator failures (human error) are not addressed. [Wang, 2006] agrees that there is improvement needed on FSA applications such as risk criteria acceptance, cost-benefit, uncertainty and expert judgment, life-saving equipment, human reliability and information availability etc. In addition, a great limitation of FSA is it's inability to assess individual ship safety cases [Wang, 2006]. Another limitation is that the reliability of FSA depends heavily on the reliability of the input data (often historical or expert judgments).

Fault Tree and Event Tree

[Montewka et al., 2014] argues that FT's and ET's discussed in detail in Appendix A are not representative for reality. The FT and ET may take more than just two states. In addition FT and ET only have a one-way interference. Therefore a hybrid combination of FT and ET with BN has been proposed.

Other

Most of the existing methods for risk assessment are defined in a spatio-temporal, stochastic framework. They do not consider the causal relations between the input variables such as the risk factors and output variables due to the fact that they are represented by single probabilities. Not taking into account the causality important elements of the risk assessment are missed, increasing the uncertainty of the model [Montewka et al., 2014].

Probabilistic methods and summary statistics can be used for risk assessment but are not sufficient for explaining and predicting accident phenomena. Other methods can be used complementary (if suitable in the case) for example: inferential statistics (canonical correlation analysis, multivariate analysis of variance, structural equation modeling) can result in a higher degree of confidence [Mullai and Paulsson, 2011]. [Mullai and Paulsson, 2011] concludes that new models have to be developed or that existing ones have to be improved. Literature also recognizes this fact and therefore it is of great importance to study other state-of-the art options.

Appendix A discussed the methods and models proposed in Figure 3.7. The challenges of all these methods and models are also discussed in this appendix. The additional models that have been proposed by [Marhavilas et al., 2011] are discussed in Appedix B. The advantages, disadvantages and future improvements are discussed.

4 Bayesian Belief Networks

With more large technological systems arising there is an increasing need for the quantification of the likelihood of rare accidental events [Aven and Kvaloy, 2002] and [Li et al., 2012]. To quantify this risk, risk assessment is needed. There are two schools of thought; the Frequentist theory and the Bayesian theory. The main difference between the two schools of thought is that the Frequentist approach assumes that the data is a random sample, while the Bayesian approach takes data from an observed sample. In addition the Frequentist approach has fixed parameters, meaning that the parameters remain constant. The Bayesian approach states that parameters are unknown and describe them probabilistically [Casella, 1998].

The large technological complex systems have problems that can not be solved using traditional, (Frequentist) statistics. Statistics describe the relation between characteristics and an accidents, but do not describe the influence degree of the risk factors [Li et al., 2012] and [Hanninen and Kujala, 2012]. Statistics are also limiting as they only describe the past and not the probability of the occurrence of a future accident. The historical performance can often be easily measured but the prediction of the future is difficult in an ever changing environment. An alternative is the Bayesian approach where the probability is determined by the analyst's measure of degree of belief [Aven and Kvaloy, 2002]. A technique for modeling complicated systems with uncertainty is Bayesian Belief Networks (BBN) [Hanninen and Kujala, 2012]. BBN's are also known as Bayesian Networks (BN), Bayesian nets or Probabilistic directed acyclic graphs [Hänninen, 2014].

4.1 Theory of Bayesian Belief Networks

This section discusses what a BBN is; who was the founder and how is it constructed. Following the mathematics behind the BBN is explained, this is done by deriving the equations used for the network. Fundamental probability, Bayes' rule, uncertainty in experiments, conditional probability and conditional independence are explained. Finally the theory is applied to the BBN. The network consists of variables and step by step is explained how the Conditional Probability Table (CPT) is constructed for each of the nodes and an example is provided.

4.1.1 What is a Bayesian Network?

Bayes' rule is known for describing the probability of an event based on conditions related to this event [Wikipedia, 2016b]. This theory is named after Thomas Bayes (1701-1761). The concept of BBN however is relatively new, first published by [Pearl et al., 1988] in *Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference.* [Pearl et al., 1988] stated that BBN is a modeling technique that can present relatively complex causal dependencies with uncertain variables. Although it is not a very new method, the use and impact of Bayesian modeling in the shipping industry is relatively new and in the early stages [Li et al., 2012].

As [Nielsen and Jensen, 2009] explain; a causal network consists of a set of variables and a set of directed links (also called arcs) between variables. This structure is called a directed graph. A directed graph is acyclic if there is no directed path $A_1 \rightarrow ... \rightarrow A_N$ so that $A_1 = A_N$. The relations between these variables can be explained as following: a link from A to B says that B is a child of A and that A is a parent of B. The states of a variable (outcomes) is finite and each variable is only one of its states. In BN's variables can be d-separated or d-connected. If variable A and B are d-separated (d for directed graph) if for all paths between A and B, there is an intermediate variable V such that either the connection is serial (shown in Figure 4.1) or diverging (shown in Figure 4.2) and V is instantiated or the connection is converging (shown in Figure 4.3) and neither V or any of V's descendants have received evidence.

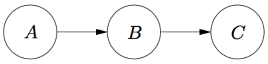


Figure 4.1: Serial connection [Nielsen and Jensen, 2009]

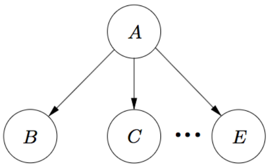


Figure 4.2: Diverging connection [Nielsen and Jensen, 2009]

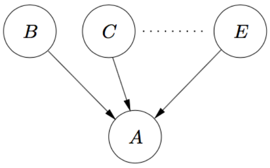


Figure 4.3: Converging connection [Nielsen and Jensen, 2009]

The structure of a BN model is a directed graph. The nodes in the model represent the variables, consisting of a finite number of mutually exclusive states (outcomes). Each state has a probability of occurrence found in the CPT. The links between nodes represent the variable dependencies. Each state therefore also depends on the state of the nodes it is linked to [Hanninen et al., 2014]. A BN is essentially a directed acyclic graph in combincation with a CPT [Eleye-Datubo et al., 2006].

A BBN is not allowed to contain cycles. [Nielsen and Jensen, 2009] state that a BBN consists of the following;

1. A set of variables and a set of directed edges between variables
2. The variables together with the directed edges form an acyclic directed graph.
3. To each variable A with parents $B_1, ..., B_N$ a conditional probability is attached.

A BN does not refer to causality, the links do not necessarily represent causal impact. Important is to analyze the model's d-separation properties and ensure that they correspond to the perception of the world's conditional independence properties [Nielsen and Jensen, 2009]. An example of a BN is given in Figure 4.4, shown for a ship collision application. It should be noted that this is a highly simplified version from one with more than 100 nodes.

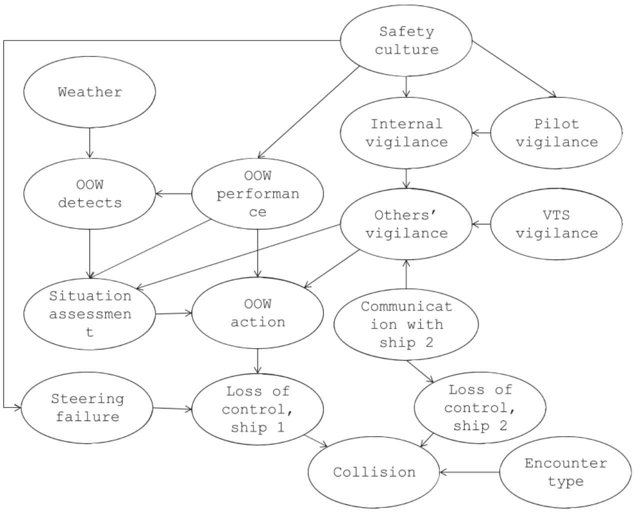


Figure 4.4: BBN of ship collision - simplified version [Hanninen and Kujala, 2012]

After the nodes and arcs are set up, a CPT can be developed for each node or event. The CPT can be developed using data or in absence of data, expert judgments, this is called the prior. A BN can then be used to estimate how the probabilities of each node are affected by the prior and posterior knowledge [Li et al., 2012].

4.1.2 Theory Behind the Bayesian Network

In this section the theory and mathematics behind the Bayesian Network are elaborated. The theory is based on [Kruschke, 2011] and [Nielsen and Jensen, 2009].

The outcome of an experiment (e.g. throw of a die) is called a sample space. A sample space contains all possible outcomes of the experiment (e.g. numbers 1 to 6) and each pair of outcomes is mutually exclusive (e.g. you can not throw and 1 and 6 in one turn). This is needed so that the experiment will result in exactly one of the specified outcomes in the sample space. A subset of the sample space is called an event (e.g. the sample space is all numbers 1 to 6, the event might be numbers 3 to 6). An event is true for an experiment if the outcome of the experiment is an element of that event (e.g. in case the event is 3 to 6; if you throw the element 4). If an event contains only one element, the event is also called the outcome.

Fundamental Probability

The fundamental rule for probability calculations is shown in Equation 4.1. This rule states that the probability when both A and B are seen is equivalent to the probability of A given B times the probability of B. More events can be conditioned as shown in Equation 4.2.

$$P(A|B)P(B) = P(A \bigcap B) \tag{4.1}$$

$$P(A|B \bigcap C)P(B|C) = P(A \bigcap B|C) \tag{4.2}$$

Bayes' Rule

From the fundamental equation shown in Equation 4.1 Bayes' rule can be derived. $P(A \bigcap B) = P(B \bigcap A)$ it can be stated that $P(A|B)P(B) = P(A \bigcap B) = P(B|A)P(A)$. This results in Bayes' rule shown in Equation 4.3.

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \tag{4.3}$$

The Bayesian method is a method for updating beliefs about event A given information about event B. P(A) is usually the prior; this is the probability that we believe event A to have without the data from event B taken into account. P(A|B) is called the posterior which is the probability of A with the data from event B taken into account. The probability P(B|A) is called the likelihood which represents how much more likely event A is to occur compared to event B.

Equation 4.3 can also be interpreted as: the posterior is equal to the likelihood times the prior divided by the evidence as shown in Equation 4.4. Where the evidence is the information that is given about event B.

$$Posterior = \frac{Likelihood \times Prior}{Evidence} \tag{4.4}$$

Uncertainty in Experiments

The terminology of an experiment (e.g. throw of a die) is explained in the beginning of this section. Each experiment has uncertainty involved, P(A) is the probability to each event $A \subseteq S$. A probability has three constraints:

1. P(S) = 1
   The event that is certain to occur will get probability 1.
2. For all $A \subseteq S$ it holds that P(A) $\geq$ 0.
   The event must have a non-negative probability.
3. If $A \subseteq S$, $B \subseteq S$ and $A \bigcap B = \emptyset$, then $P(A \bigcup B) = P(A) + P(B)$.
   If two events A and B are disjoint, the probability of the combined event is the sum of the probabilities for two individual events.

$A \bigcap B$ is the intersection between A and B and represents the event in which both A and B will occur. The equation in case A and B are not disjoint is shown in Equation 4.5.

$$P(A \bigcup B) = P(A) + P(B) - P(A \bigcap B) \tag{4.5}$$

Conditional Probability

Conditional probability is the probability of an event given known conditions. Equation 4.6 shows the conditional probability (p) for event A given event B. For two events A and B the conditional probability for A given B is shown in Equation 4.7. For more than two events the conditional probability is shown in Equation 4.8.

$$P(A|B) = p \tag{4.6}$$

$$P(A|B) = \frac{P(A \bigcap B)}{P(B)} \tag{4.7}$$

$$P(A|B \bigcap C) = \frac{P(A \bigcap B \bigcap C)}{P(B \bigcap C)} \tag{4.8}$$

Conditional Independence

Event A and event B are said to be independent if information about event B does not change the belief about event A. This is illustrated by Equation 4.9. If event A and event B are independent the fundamental rule shown in Equation 4.1 can be rewritten to Equation 4.10. Equation 4.10 states that the probability that both event A and event B will occur can be calculated by multiplying the probabilities of the individual events. Conditional independence can also be applied to more than two events as shown in Equation 4.11. In this situation A is conditionally independent of B given C and B is conditionally independent of A given C.

$$P(A|B) = P(A) \tag{4.9}$$

$$P(A \bigcap B) = P(A|B)P(B) = P(A) \cdot P(B) \tag{4.10}$$

$$P(A \bigcap B|C) = P(A|C) \cdot P(B|C) \tag{4.11}$$

4.1.3 Theory Applied to Bayesian Networks

For a BBN more than one sample space will be used. A collection of sample spaces are called variables. A variable can be considered an experiment; explained in Section 4.1.2. Just as an experiment the variables have a corresponding state. For example the states of variable A are $sp(A) = (a_1, a_2, ..., a_n)$. The assumption is made that these states are mutually exclusive, ensuring that with a coin not both heads and tails can be thrown at the same time and exhaustive, ensuring that the variable is in one of its states. A variable has a finite number of states. The probability distribution P(A) represents the uncertainty associated with variable A as shown in Equation 4.12 with the conditions shown in Equation 4.13 and Equation 4.14. x_i Is the probability of A being in state a_i.

$$P(A) = (x_1, x_2, ..., x_n) \tag{4.12}$$

$$x_i \geq 0 \tag{4.13}$$

$$\sum_{i=1}^{n} x_i = x_1 + ... + x_n = 1 \tag{4.14}$$

First we calculate the conditional probability P(A|B), secondly the joint probability P(A,B) is determined. Using the fundamental rule and marginalization the probability distribution P(A) and P(B) can be calculated. Finally Bayes' rule P(B|A) is calculated and conditional independence for variables can be used to construct the conditional probability table (CPT). Below these steps are explained.

Conditional Probability

There exist many conditional probabilities for variables as each variable can have many states. If variable B has states $b_1, ..., b_n$ then P(A|B) contains $n \cdot m$ conditional probabilities $P(a_j|b_j)$. This results in an $n \times m$ table with one probability for each configuration of the states of the variables involved. The probabilities over variable A should sum to 1 for each state of variable B as shown in Equation 4.15.

$$\sum_{i=1}^{n} P(A = a_i | B = b_j) = 1 \qquad for \quad each \quad b_j \tag{4.15}$$

Joint Probability

Joint probability is the probability of seeing joint outcomes for different experiments. The probability of seeing both variable A with state a_i and variable B with state b_j is P(A,B) with configuration (a_i, b_j). The probability of seeing both P(A,B) is a table of $n \cdot m$. All combinations of the states are mutually exclusive and exhaustive, hence have to sum up to 1 as shown in Equation 4.16.

$$P(A,B) = \sum_{i=1}^{n} \sum_{j=1}^{m} P(A = a_i, B = b_j) = 1 \tag{4.16}$$

Fundamental Rule

The conditional probability P(A|B) and the joint probability P(A,B) are known. Using Equation 4.1, Equation 4.17 and 4.18 are constructed. The probability distribution P(A) can now be calculated using Equation 4.19. This equation illustrates that there are m different outcomes for A in state $a_i; (a_i, b_1)...(a_i, b_m)$. This is called marginalization, shown in Equation 4.20.

$$P(a_i|b_j)P(b_j) = P(a_i, b_j) \tag{4.17}$$

$$P(A,B) = P(A|B)P(B) \tag{4.18}$$

$$P(a_i) = \sum_{j=1}^{m} P(a_i, b_j) \tag{4.19}$$

$$P(A) = \sum_{B} P(A,B) \tag{4.20}$$

Bayes' Rule

Bayes' rule for variables results in Equation 4.21. The probabilities over B for each state of A sum to 1.

$$P(B|A) = \frac{P(A|B)P(B)}{P(A)} = \frac{P(A,B)}{\sum_B P(A,B)} \tag{4.21}$$

Conditional Independence of Variables

Variable A and variable C are conditionally independent given variable B if

$$P(a_i|c_k,b_j) = P(a_i|b_j) \tag{4.22}$$

If variable A and variable C are conditionally independent the fundamental rule can be simplified to:

$$P(A,C|B) = P(A|B,C)P(C,B) = P(A|B)P(C|B) \tag{4.23}$$

The above equations show how to construct the CPT for the other nodes of the BBN. However the initial nodes must also have some input. The CPT for these nodes are determined using historical data or expert opinions [Li et al., 2012]. As shown in Figure 4.6 to determine the posterior, Bayes' theorem is used with input data in the form of actual data or expert opinions and/or the prior.

Figure 4.5 shows a directed acyclic graph. In this graph the properties that have to be specified are P(A), P(B), P(C|A,B), P(E|C), P(D|C), P(F|E) and P(G|D,E,F).

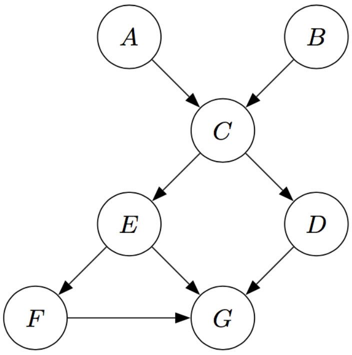


Figure 4.5: A directed acyclic graph Nielsen and Jensen [2009]

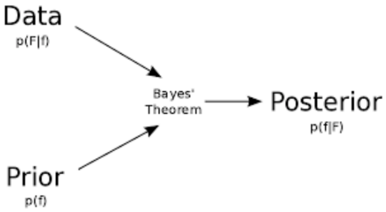


Figure 4.6: Posterior calculation [Keenan, 2011]

4.2 Using BBN for Risk Assessment of the MTS

Over the last decade BBN's have been used as a quantitative modeling approach in maritime traffic safety related issues. As the computational power of computer has increased, programs have been developed to construct and calculate with BBNs such as HUGIN [Madsen et al., 2005] and GeNIe [Druzdzel, 1999]. Many authors have applied BBN to the MTS or related aspects of the MTS. A short summary of several researches is presented below.

[Hanninen et al., 2014] have analyzed maritime safety management using the BN's. [Hanninen and Kujala, 2012] looked at the influences of the variables in a BBN for estimating the role of human factors on ship collision probability. [Shenping et al., 2007] studied the risk assessment of ship navigation, estimating the traffic accidents using the BBN

[Li et al., 2012] has combined the use of BBN's with the logistic regression method. BBN is chosen as it is increasingly used in the maritime industry. However a BBN requires too much information to determine the probability of the prior. To use other information sources such as expert opinions would induce too much uncertainty. The logistic regression method is used as an input for the BBN.

[Eleye-Datubo et al., 2006] examined a typical ship evacuation in an accidental risk contribution scenario using the BBN. In addition they examined an authorized vessel to floating, production, storage and offloading (FPSO) installation collision scenario. A flow chart of a proposed BBN reasoning framework is developed.

[Merrick et al., 2003] has analyzed the uncertainty in simulation using the Bayesian technique to model input and output uncertainty. The characterization of uncertainty in simulation-based analysis provides the user with a greater insight which can be used for decision-making. The Bayesian technique is applied to the case of San Francisco Bay ferry expansion.

[Zhang et al., 2013] estimates the navigational risk of the Yangtze river in China using the FSA concept and the BBN technique. [Zhang et al., 2013] argues that the input of many risk analysis studies are based on expert opinions or questionnaires. In addition there are few researchers who have used the combination of a quantitative method and FSA together and finally the risk probability and consequences are not often considered simultaneously. [Zhang et al., 2013] identifies that it would be too difficult to collect sufficient data for all factors using historical data and expert judgments. Therefore the BBN technique is used as shown in Figure 4.7. The procedure starts with data gathering from historical data and/or expert judgment, following the nodes, dependencies and CPTs are constructed, next a parameter sensitivity analysis is performed to justify the dependencies of the nodes. The BBN is shown in Figure 4.8. The risk factors identified in Section 2.3 are used by Zhang to establish the BBN. The results of the BNB, the probabilities and the consequences are then further evaluated using a traditional risk assessment method the risk matrix (explained in Section 3.3.4).

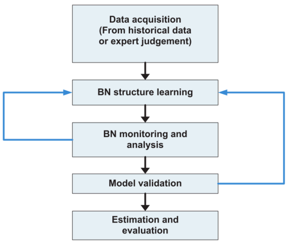


Figure 4.7: A data based B/bN procedure [Zhang et al., 2013]

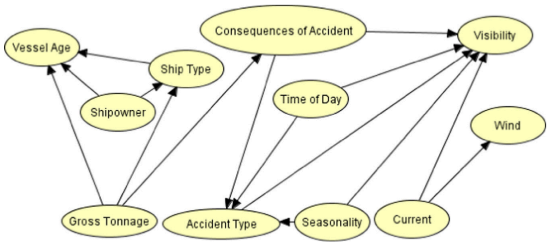


Figure 4.8: Bayesian Belief Network [Zhang et al., 2013]

[Zhang et al., 2016] also performed a risk assessment for the Tianjin Port in China using BBN. Statistics and expert knowledge are used to construct the BBN to generate the probability distribution and consequences of accidents. In Figure 4.9 a simplified version of the constructed BBN can be found. It can be seen that the nodes used are similar to the risk factors identified in Section 2.3. Next the CPT for each combination is determined. Figure 4.10 illustrates the areas that are examined. For the different areas and the accident types a CPT is constructed, shown in Figure 4.11. Each column adds up to 1.

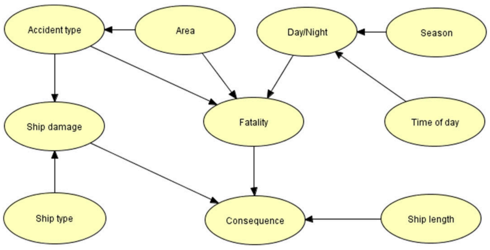


Figure 4.9: BN Network for Tianjin [Zhang et al., 2016]

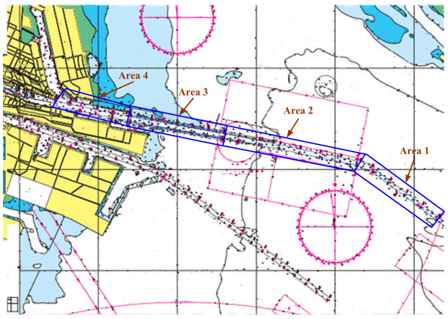
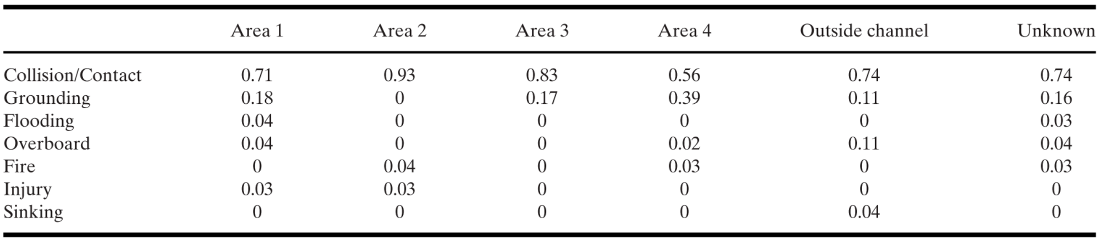


Figure 4.10: Area 1-4 considered for Tianjin [Zhang et al., 2016]



	Area 1	Area 2	Area 3	Area 4	Outside channel	Unknown
Collision/Contact	0.71	0.93	0.83	0.56	0.74	0.74
Grounding	0.18	0	0.17	0.39	0.11	0.16
Flooding	0.04	0	0	0	0	0.03
Overboard	0.04	0	0	0.02	0.11	0.04
Fire	0	0.04	0	0.03	0	0.03
Injury	0.03	0.03	0	0	0	0
Sinking	0	0	0	0	0.04	0

Figure 4.11: CPT between area and accident type [Zhang et al., 2016]

[Trucco et al., 2008] has developed a BBN for the MTS. Often researchers analyze the mechanical or environmental influences of the accident. However the human factor is accountable for 80% of the accident. The Human and Organizational Factor (HOF) is incorporated. The model that is proposed is a hybrid combination between a BBN and a FT analysis. The initial values of the BBN are taken from expert estimations, the BBN only modifies the prior of the event and does not generate them. The examples of BBN shown in Figure 4.8 and Figure 4.9 are a simplified version of the real BBN. Some BBN's can extend up to more than 200 nodes; see Figure 4.12 for a simplified version of [Trucco et al., 2008] model. Interesting is to see that many of the risk factors identified return in this model (speed, climate, training etc.).

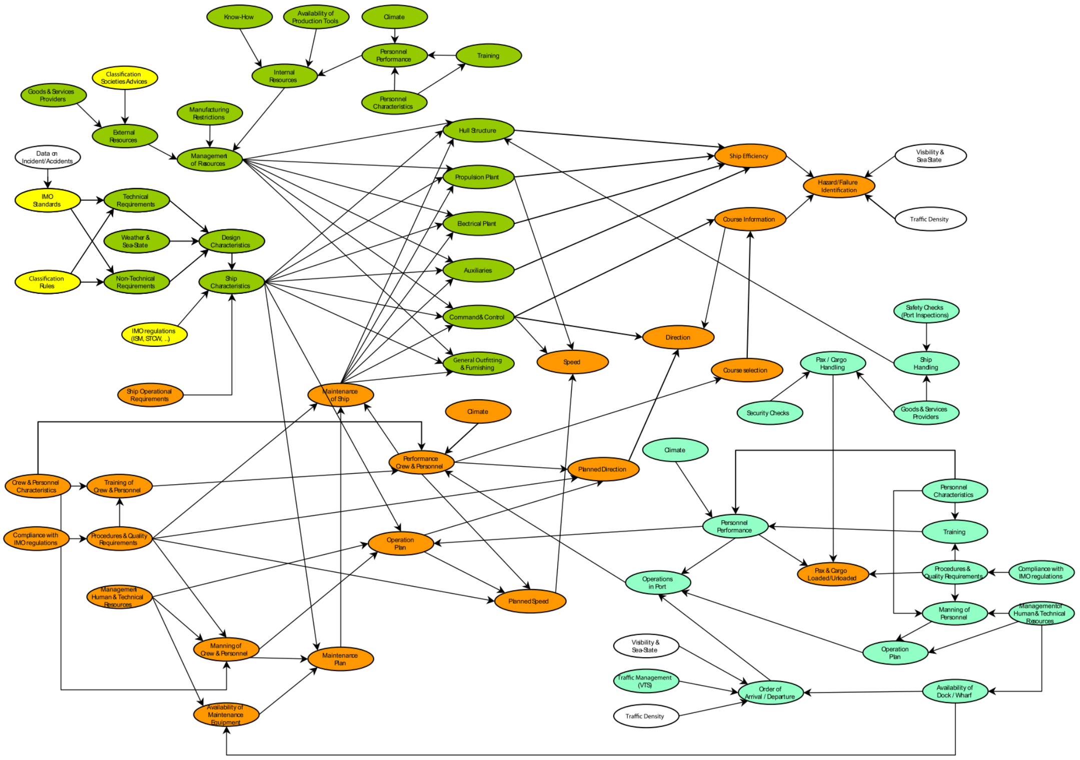


Figure 4.12: BBN of MTS according to [Trucco et al., 2008]

[Goerlandt and Montewka, 2015a] have also developed a framework for the MTS. First a BBN is developed using expert judgment followed by a subjective probability assessment. For the latter various tools are introduced to highlight uncertainties and biases. This is applied to a case study on oil-spills.

[Montewka et al., 2014] developed a framework to address the ship-to-ship collision in the open sea with a Ro-Ro/Passenger (RoPax) ship. Their choice for using a BBN is because it allows for reasoning under uncertainty and with limited data, in addition to to finding the most essential parameters which have the largest influence on the outcome of the model.

5 Challenges in Maritime Risk Assessment

The main objective of risk assessment is learn about the risks, to be able to prevent future accidents. In order to identify the risk factors, high risk areas and risk level inputs are needed. One of the challenges of risk assessment is to understand complex safety systems, especially in the case of rare events [Li et al., 2012]. The problem with rare events is that there is no accident data available. Often expert judgment is used in developing frequency data for risk analysis but this should be used with care. Biases and heuristics are introduced when expert judgment is used. In this section the advantages and challenges in the state-of-the-art Bayesian Belief Network technique are illustrated. In combination with the limitations of the existing risk assessment techniques presented in Section 3.5 they provide input for further research.

5.1 Advantages of BBN

According to [Eleye-Datubo et al., 2006] using a BBN has several advantages compared to using alternative modeling approaches:

1. Good visual representation of cause and effect relationship
2. Strong mathematical basis in Bayesian probability
3. Meaningful communication of uncertainty
4. Consistent with the risk assessment paradigm
5. Combining diverse data; e.g. expert judgment and empirical data
6. Method not paralyzed by lack of observational data by use of expert judgment
7. Easy updating of prediction
8. No entire new network has to be made when adding or deleting information

Especially incorporating uncertainty is a great advantage compared to alternative modeling approaches. This method can therefore be used in many fields in which until now modeling was not possible.

[Montewka et al., 2014] state as advantages of using BBN that they allow multi-scenario thinking enabling analyzing the causality of the event instead of limiting to the probability of an accident. As well as handling uncertainty in variables and links between variables.

[Hänninen, 2014] extensively researched the advantages and disadvantages of BBNs, the advantages are:

1. **Suitability for complex system modeling**:
    (a) Able to model accidents that are a result of complex, partially unknown interactions between systems.
    (b) Able to incorporate many nodes and dependencies.
2. **Coping with uncertainty**: A model is always a simplification of reality, the model will always include uncertainty due to lack of data, incomplete knowledge, variability, the chosen modeling technique and the applied assumptions on the system boundaries. Still BBN allows for:

   (a) Modeling when not all data is available.
   (b) Modeling with expert opinions (incomplete information).
   (c) Uncertainty in safety performance of ships.
   (d) Uncertainty due to simplification of reality.
   (e) Able to update the model when more data / information is available: biases in data and expert opinions can be minimized by relying on more than one data source.

3. **Relaxation of causality**

   (a) The nodes can represent any kind of factor relevant to the problem. In previous risk assessment methods such as FT and ET were limited to describing events.
   (b) The directed links between nodes do not necessarily have to be direct causal connections.
   (c) Include common causes as hidden nodes in a BBN.

4. **Versatility**:

   - The same model can be used in may ways.
   - Once the network structure and the probability parameters have been defined the model can be applied to several types of system investigations and reasoning.
   - Analyzed with sensitivity and mutual information.

5. **Capability of dynamic modeling**:

   (a) BBNs can be used to describe uncertain dynamic systems.
   (b) Model includes multiple copies of the same variable which state changes over time.

6. **Extendable to a decision problem model**

   (a) A decision problem model (influence diagram (ID)) can be constructed from the BBN by adding decision (decisions or interventions) and utility (cost benefit) variables.
   (b) ID's provide a more compact representation compared to other risk assessment methods such as decision trees.
   (c) Can be combined with FSA.

5.2 Limitations of BBN

Some limitations involving BBN's are that it is impossible to violate the distribution of probabilities on which the system is built. The system is designed to update the goals and objectives based on prior distributions of the goals and objectives in the same sample space. However, the system can not respond to previously unforeseen events, events that it is not expecting. The second limitation is the computational difficulty in exploring a previously unknown network. To calculate the probability of one branch of a network, the entire network needs to be calculated, which might either be very costly or timely because of the large number of variables or might not be possible at all. The final limitation is that the quality of the BBN is only as good as the quality of the prior belief. A very optimistic or pessimistic value can affect the quality of the prior belief which is propagated through the entire network [Holmes and Jain, 2008].

[Aven and Kvaloy, 2002] discusses how the Bayesian approach is not commonly accepted as some risk analysts show skepticism involving subjective probabilities. In addition the theoretical and technical aspects of the Bayesian approach are often described in literature, the practical challenges are seldom addressed. It is challenging to apply the Bayesian approach because of the interpretation problems; the risk numbers that are generated contain uncertainty. However also a fictitious population is used, therefore there are problems with model uncertainty. [Aven and Kvaloy, 2002] also argue that to apply the full Bayesian approach there are limitations due to the complexity of the calculations. The calculations sometimes require a Markov chain Monte Carlo (McMC) simulations and especially in complex problem they can be very time consuming, therefore often assumptions and simplifications are made.

[Merrick and Van Dorp, 2006] point out that in the Bayesian approach there is no argument that separates the aleatory uncertainty and the epistemic uncertainty.

[Li et al., 2012] combines BBN with logistic regression and databases. This is done as the Bayesian approach requires too much information in the form of prior probabilities and that this information is often difficult, sometimes impossible to get [Yang et al., 2008]. A solution for the lack of information is the use of expert judgments, however these judgments are often subjective and therefore error-prone. Experts might fail to take in consideration all of the possibilities and/or are easily affected by operational experience [Li et al., 2012]. [Eleye-Datubo et al., 2006] identify that the CPT increases significantly as more nodes are added and increasing the complexity and the computation time. As the computers still are not fast enough often this is a limiting factor for researching large complex problems as not all nodes can be taken into account.

[Eleye-Datubo et al., 2006] and [Zhang et al., 2013] state several limitations of using BBN's:

1. Unobserved variables are difficult to incorporate due to the fact that the internal CPT grows very large.
2. There is a computational limitation. This computational complexity grows exponentially with the number of nodes.
3. Likelihood functions are not always analytically solvable introducing heuristics.

[Hänninen, 2014] extensively researched the advantages and disadvantages of BBNs, the limitations are:

1. **Incomplete understanding of safety and accident occurrence**
    (a) It is not clear how and why accidents occur.
    (b) The initiating event in root cause modeling is arbitrary and can always go further.
    (c) The controversies in the theoretical understanding are a challenge, however a BN can incorporate this uncertainty.
2. **Scarce data**
    (a) Maritime traffic accidents are a rare event (only 0.7 accidents per 1000 port ship calls [Hänninen and Kujala, 2014]).

  - (b) Rules and regulations have often been changed so data can not be gathered from a long time ago.
  - (c) Data is limited due to under-reporting (accidents that are not reported are around 50% of all occurred accidents [Hassel et al., 2011]).
  - (d) The accidents that have been reported often have missing data.
  - (e) Data is subjective by underlying views on how accidents occur.
  - (f) Data might not be available for the analyst.

3. **Problems with data quality**
   - (a) Maritime accident databases have errors in their contents.
   - (b) Often accidents are written in text format - would take hours to put in right context plus it might introduce subjectivity from the interpreter.
   - (c) Land and air safety has improved significantly over the last decades by performing numerous studies on under-reporting and data quality. This is missing in maritime safety [Hassel et al., 2011].
   - (d) Most accident reports are not complete and only look for someone to blame.

4. **Relying on expert judgment**
   - (a) Often the only way to work with new risk control options.
   - (b) People tend to rely on heuristics resulting in baised quantitative information.
   - (c) Information is always subjective (background, experience, interpretation of the problem)
   - (d) Can also be seen as an advantage: several expert judgments may be more valuable than one single data source.
   - (e) Experts might only have experience on local scale, not on system scale.
   - (f) Experts are often very busy, it is hard to find enough time to get a long information session.

5. **Validation**
   - (a) A way to validate a statistical model is to see how well it performs on data. However for a BBN it is difficult to validate on expert judgment.
   - (b) [Pitchforth and Mengersen, 2013] have constructed a framework for BBN validation including seven types of validation: nonlogical, face, content, concurrent, convergent, discriminant and predictive validity.

BBN might not be the best modeling tool in some cases. BBN represents the joint probability over its variables as shown in Equation 4.16. Sometimes a model which estimates a single variable based on the other variables might be needed. When the variables are probabilistic this equals estimating the conditional probability. However the BBN is learned from data, the model is a result of finding a BBN which best describes the joint probability. This model then might not be best for assessing the conditional probability. It might be better to use decision trees of logistic regression [Hänninen, 2014].

[Faghih-Roohi et al., 2014] has proposed another state-of-the-art method, namely the McMC simulation. This simulation is also able to incorporate uncertainty. As shown in Figure 3.10 [Faghih-Roohi et al., 2014] have criticized researchers that have used BBN in their analysis. The limitations are that the model can not be generalized without some constraints and quantified data and that not all accidents scenarios have been covered by the BBN analysis. The McMC method can also perform a BBN. [Faghih-Roohi et al.,

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2014] has performed the McMC method on a maritime application. They argue that the advantages of using a McMC model is that this model can consider any accident or marine system and that it is a simple approach with no need for large scale data collection.

6 Conclusion & Recommendation

In this chapter the conclusion and recommendation will be given. The conclusion will consists of answering the main research question and key questions stated in the Introduction in Chapter 1. The recommendation will provide insights into further research that can be performed.

6.1 Conclusion

Maritime transportation is expected to grow significantly in the coming years (19-24 billion by 2030 [Lloyd's Register et al., 2013]) due to the increasing demand for the transportation of goods. With the occurrence of several tragic accidents the focus on maritime safety has increased with the maritime authorities. The forecast of increasing demand for sea transportation also increases the risk of a maritime accident. For effective risk mitigation an insight is needed in the risk calculation. This report has provided an overview of the existing and state-of-the-art methodologies for risk assessment in the maritime transportation industry.

The first key question: *"What are maritime transportation systems and the inter-relationship between its parties and components"* has been answered with the definition of [Swales and Feak, 1996]: A maritime transportation system is the entire value chain related to the transportation of cargo and passengers over water. The parties and system components involved in the MTS were addressed such as; the actors, the marine activities that are performed in the MTS and the systems and functions involved were mentioned. Risk assessment is very important to mitigate risks for future accidents. Until now mostly reactive risk assessment has taken place, relying on historical data. However to avoid future accidents resulting in human casualties, environmental damage or property damage, a proactive system is needed. With the ever increasing complexity and size of engineering projects it is important to have a proactive system because although the number of shipping accidents have decreased the consequences have been very stable due to the increasing sizes of individual ships.

The second key question: *"What are the available risk assessment methods / models in maritime transportation systems"* has been answered using various techniques. First the concept of risk assessment is explained, focusing on key definitions and risk assessment frameworks. Following using the framework of the NEN standards the steps in risk assessment are addressed and several standard risk assessment methods and models are illustrated. Following an overview of the risk assessment methods and models used in the maritime transportation industry is given. It can be concluded that many different approaches to risk assessment have been developed by various researchers. The IMO has aimed to structure the risk assessment by developing the Formal Safety Assessment approach often used shipping companies. An overview of various other models, a comparison between the different approaches is provided and the steps of how to select a method or model are explained. Finally an overview of the limitations of the currently available models is presented. It is clear that one of the main limitations is the uncertainty of data. Many databases do not have enough data on maritime accidents as they are rare. In addition data is often incomplete, incorrect, not in the correct format or non-existent. In light of this problem an alternative approach is suggested: the Bayesian Belief Networks.

The third key question: *"How can Bayesian Belief Networks be used for risk assessment in maritime transportation systems"* is answered by an explanation of this method. Most of the existing methods and models are limited by the incorporation of (aleatory and epistemic) uncertainty. Often the existing models make assumptions, however with risk assessment this leaves out may risk options. A state-of-the-art method is the Bayesian Belief Networks. The Bayesian Belief Networks can present relatively complex causal dependencies with uncertain variables. The theory behind Bayesian Belief Networks is presented and an overview of researchers having applied the Bayesian Belief Network to risk assessment is provided.

The final key question: *"What are the remaining challenges in risk assessment in maritime transportation systems and how can they be approached"* is answered by providing an overview of the advantages and limitations of Bayesian Belief Networks. In combination with the advantages and limitations of the currently existing methodologies for risk assessment they provide an input for further exploration.

Concluding we can state that the main research question *"What are the existing and state-of-the-art approaches for risk assessment of maritime transportation systems with a focus on Bayesian Belief Networks"* has been answered. Many authors have provided many methods and models to address risk assessment in the maritime industry. There are also a number of researchers that have applied the state-of-the-art Bayesian Belief Network as a methodology for risk assessment, but mostly in combination with another technique. It is therefore unclear if BN's are the optimal approach to solving these complex problems [Hänninen, 2014].

6.2 Recommendation

Many methods and models have been proposed by various authors. Scientific literature has criticized many method and models and new methods and models have been developed. Examining the current models there are many limitations. In Appendix B the future improvements for nearly all methods identified by the NEN standards can be found [NEN-ISO/IEC 31010, 2012]. Other limitations regarding methods and models that need further research are the clarification of fundamental issues, guidelines to work with data that is incomplete, incorrect, non-existent and introducing a lot of uncertainty in models and how to deal with this uncertainty.

Consensus on fundamental issues is of great importance. Clarity on key terminology and perspectives is something that is still lacking and research can be conducted on this. In addition more scientific research should be done to the underlying approach to determine if a method or model is suitable or not to be applied to a certain problem. Also more scientific research and discussion among researchers and authors of scientific literature should take place on the current proposed methods and frameworks to increase it's credibility, as is done in road and air safety.

The lack of clarification of fundamental issues, guidelines to work with data that is incomplete, incorrect, non-existent data induces a lot of uncertainty in models. It is therefore recommended that more research is conduced into the data bases, the collection of information and how to cope with this uncertainty. Although Bayesian Belief Networks are able to cope partly with this uncertainty, there are still many variations in the outcomes and this should be communicated with the user of the risk assessment. In this light, more research can be done on how to determine the uncertainty level that will be tolerated in risk assessment studies.

6.2.1 Exploration for Breakthrough

A suggestion for the use of another model was proposed by [Faghih-Roohi et al., 2014]. This method is able to perform a more generalized model; the Markov Chain Monte Carlo. As indicated the advantages of McMC modeling according to the authors is that their model can consider any accident or marine system and that MCMC simulation is a simple approach with no need for large scale data collection. MCMC modeling is also mentioned in Figure 3.7. A small introduction to the use of Markov analysis and Monte Carlo simulation is given in Appendix A with the description of methods and models. Additional research can be done on the performance, requirements and limitations of MCMC simulation. MCMC simulation is also able to perform a BBN therefore it would be interesting to research how this exactly works.

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A NEN Standard Risk Assessment Methods

This appendix describes the NEN standard for risk assessment methods and models according to NEN-ISO/IEC 31010 [2012]. The NEN is the official dutch standard which adapts from the international standard ISO. There are many methods and models which can be used in risk assessment. The table in this appendix shows the type of risk assessment technique, it's description, the relevance of the influencing factors and if it can provide a quantitative output (a numerical output with units). If the method can not provide a numerical output with units it is called a qualitative method and the output is indicated by “High", “Medium" or “Low".

Following all the risk assessment techniques are discussed according to the NEN standard. Per technique an overview of the method or model is given, it's use, required inputs, the process, the produced outputs and finally it's strengths and limitations are discussed. This is done for all techniques shown in Figure 3.7.

1. Brainstroming
2. Structured or semi-structured interviews
3. Delphi technique
4. Check-lists
5. Preliminary hazard analysis (PHA)
6. HAZOP
7. Hazard analysis and critical control points (HACCP)
8. Toxicity assessment
9. Structured “What-if" Technique (SWIFT)
10. Scenario Analysis
11. Business impact analysis (BIA)
12. Root cause analysis (RCA)
13. Failure modes and effects analysis (FMEA) and Failure modes and effects and criticality analysis (FMECA)
14. Fault tree analysis (FTA)
15. Event tree analysis (ETA)
16. Cause-consequence analysis
17. Cause-and-effect analysis
18. Layers of protection analysis (LOPA)
19. Decision tree analysis
20. Human reliability assessment (HRA)
21. Bow tie analysis
22. Reliability centered maintenance
23. Sneak analysis and sneak circuit analysis (SCI)
24. Markov analysis
25. Monte Carlo simulation
26. Bayesian statistics and Bayesian Nets
27. FN curves
28. Risk indices
29. Consequence / probability matrix
30. Cost / benefit analysis (CBA)
31. Multi-criteria decision analysis (MCDA)

Table A.2 – Attributes of a selection of risk assessment tools

Type of risk assessment technique	**Description**	**Relevance of influencing factors**			**Can provide Quantitative output**
		Resources and capability	**Nature and degree of uncertainty**	**Complexity**	
LOOK-UP METHODS					
Check-lists	A simple form of risk identification. A technique which provides a listing of typical uncertainties which need to be considered. Users refer to a previously developed list, codes or standards	Low	Low	Low	No
Preliminary hazard analysis	A simple inductive method of analysis whose objective is to identify the hazards and hazardous situations and events that can cause harm for a given activity, facility or system	Low	High	Medium	No
SUPPORTING METHODS					
Structured Interview and brainstorming	A means of collecting a broad set of ideas and evaluation, ranking them by a team. Brainstorming may be stimulated by prompts or by one-on-one and one-on-many interview techniques	Low	Low	Low	No
Delphi technique	A means of combining expert opinions that may support the source and influence identification, probability and consequence estimation and risk evaluation. It is a collaborative technique for building consensus among experts. Involving independent analysis and voting by experts	Medium	Medium	Medium	No
SWIFT Structured “what-if”)	A system for prompting a team to identify risks. Normally used within a facilitated workshop. Normally linked to a risk analysis and evaluation technique	Medium	Medium	Any	No
Human reliability analysis (HRA)	Human reliability assessment (HRA) deals with the impact of humans on system performance and can be used to evaluate human error influences on the system	Medium	Medium	Medium	Yes
SCENARIO ANALYSIS					
Root cause analysis (single loss analysis)	A single loss that has occurred is analysed in order to understand contributory causes and how the system or process can be improved to avoid such future losses. The analysis shall consider what controls were in place at the time the loss occurred and how controls might be improved	Medium	Low	Medium	No

Type of risk assessment technique	Description	Relevance of influencing factors			Can provide Quantitative output
		Resources and capability	Nature and degree of uncertainty	Complexity	
Scenario analysis	Possible future scenarios are identified through imagination or extrapolation from the present and different risks considered assuming each of these scenarios might occur. This can be done formally or informally qualitatively or quantitatively	Medium	High	Medium	No
Toxicological risk assessment	Hazards are identified and analysed and possible pathways by which a specified target might be exposed to the hazard are identified. Information on the level of exposure and the nature of harm caused by a given level of exposure are combined to give a measure of the probability that the specified harm will occur	High	High	Medium	Yes
Business impact analysis	Provides an analysis of how key disruption risks could affect an organization's operations and identifies and quantifies the capabilities that would be required to manage it	Medium	Medium	Medium	No
Fault tree analysis	A technique which starts with the undesired event (top event) and determines all the ways in which it could occur. These are displayed graphically in a logical tree diagram. Once the fault tree has been developed, consideration should be given to ways of reducing or eliminating potential causes / sources	High	High	Medium	Yes
Event tree analysis	Using inductive reasoning to translate probabilities of different initiating events into possible outcomes	Medium	Medium	Medium	Yes
Cause/ consequence analysis	A combination of fault and event tree analysis that allows inclusion of time delays. Both causes and consequences of an initiating event are considered	High	Medium	High	Yes
Cause-and-effect analysis	An effect can have a number of contributory factors which may be grouped into different categories. Contributory factors are identified often through brainstorming and displayed in a tree structure or fishbone diagram	Low	Low	Medium	No

Example type of risk assessment method and technique	Description	Relevance of influencing factors			Quantitative output possible?
FUNCTION ANALYSIS					
FMEA and FMECA	FMEA (Failure Mode and Effect Analysis) is a technique which identifies failure modes and mechanisms, and their effects. There are several types of FMEA: Design (or product) FMEA which is used for components and products, System FMEA which is used for systems, Process FMEA which is used for manufacturing and assembly processes, Service FMEA and Software FMEA. FMEA may be followed by a criticality analysis which defines the significance of each failure mode, qualitatively, semi-qualitatively, or quantitatively (FMECA). The criticality analysis may be based on the probability that the failure mode will result in system failure, or the level of risk associated with the failure mode, or a risk priority number	Medium	Medium	Medium	Yes
Reliability-centred maintenance	A method to identify the policies that should be implemented to manage failures so as to efficiently and effectively achieve the required safety, availability and economy of operation for all types of equipment	Medium	Medium	Medium	Yes
Sneak analysis (Sneak circuit analysis)	A methodology for identifying design errors. A sneak condition is a latent hardware, software, or integrated condition that may cause an unwanted event to occur or may inhibit a desired event and is not caused by component failure. These conditions are characterized by their random nature and ability to escape detection during the most rigorous of standardized system tests. Sneak conditions can cause improper operation, loss of system availability, program delays, or even death or injury to personnel	Medium	Medium	Medium	No
HAZOP Hazard and operability studies	A general process of risk identification to define possible deviations from the expected or intended performance. It uses a guideword based system. The criticalities of the deviations are assessed	Medium	High	High	No
HACCP Hazard analysis and critical control points	A systematic, proactive, and preventive system for assuring product quality, reliability and safety of processes by measuring and monitoring specific characteristics which are required to be within defined limits	Medium	Medium	Medium	No

Example type of risk assessment method and technique	Description	Relevance of influencing factors			Quantitative output possible?
CONTROLS ASSESSMENT					
LOPA (Layers of protection analysis	(May also be called barrier analysis). It allows controls and their effectiveness to be evaluated	Medium	Medium	Medium	Yes
Bow tie analysis	A simple diagrammatic way of describing and analysing the pathways of a risk from hazards to outcomes and reviewing controls. It can be considered to be a combination of the logic of a fault tree analysing the cause of an event (represented by the knot of a bow tie) and an event tree analysing the consequences	Medium	High	Medium	Yes
STATISTICAL METHODS					
Markov analysis	Markov analysis, sometimes called *State-space* analysis, is commonly used in the analysis of repairable complex systems that can exist in multiple states, including various degraded states	High	Low	High	Yes
Monte-Carlo analysis	Monte Carlo simulation is used to establish the aggregate variation in a system resulting from variations in the system, for a number of inputs, where each input has a defined distribution and the inputs are related to the output via defined relationships. The analysis can be used for a specific model where the interactions of the various inputs can be mathematically defined. The inputs can be based upon a variety of distribution types according to the nature of the uncertainty they are intended to represent. For risk assessment, triangular distributions or beta distributions are commonly used	High	Low	High	Yes
Bayesian analysis	A statistical procedure which utilizes prior distribution data to assess the probability of the result. Bayesian analysis depends upon the accuracy of the prior distribution to deduce an accurate result. Bayesian belief networks model cause-and-effect in a variety of domains by capturing probabilistic relationships of variable inputs to derive a result	High	Low	High	Yes

Annex B
(informative)

Risk assessment techniques

B.1 Brainstorming

B.1.1 Overview

Brainstorming involves stimulating and encouraging free-flowing conversation amongst a group of knowledgeable people to identify potential failure modes and associated hazards, risks, criteria for decisions and/or options for treatment. The term “brainstorming” is often used very loosely to mean any type of group discussion. However true brainstorming involves particular techniques to try to ensure that people's imagination is triggered by the thoughts and statements of others in the group.

Effective facilitation is very important in this technique and includes stimulation of the discussion at kick-off, periodic prompting of the group into other relevant areas and capture of the issues arising from the discussion (which is usually quite lively).

B.1.2 Use

Brainstorming can be used in conjunction with other risk assessment methods described below or may stand alone as a technique to encourage imaginative thinking at any stage of the risk management process and any stage of the life cycle of a system. It may be used for high-level discussions where issues are identified, for more detailed review or at a detailed level for particular problems.

Brainstorming places a heavy emphasis on imagination. It is therefore particularly useful when identifying risks of new technology, where there is no data or where novel solutions to problems are needed.

B.1.3 Inputs

A team of people with knowledge of the organization, system, process or application being assessed.

B.1.4 Process

Brainstorming may be formal or informal. Formal brainstorming is more structured with participants prepared in advance and the session has a defined purpose and outcome with a means of evaluating ideas put forward. Informal brainstorming is less structured and often more ad-hoc.

In a formal process:

- the facilitator prepares thinking prompts and triggers appropriate to the context prior to the session;
- objectives of the session are defined and rules explained;
- the facilitator starts off a train of thought and everyone explores ideas identifying as many issues as possible There is no discussion at this point about whether things should or should not be in a list or what is meant by particular statements because this tends to inhibit free-flowing thought. All input is accepted and none is criticized and the group moves on quickly to allow ideas to trigger lateral thinking;

- the facilitator may set people off on a new track when one direction of thought is exhausted or discussion deviates too far. The idea however, is to collect as many diverse ideas as possible for later analysis.

B.1.5 Outputs

Outputs depend on the stage of the risk management process at which it is applied, for example at the identification stage, outputs might be a list of risks and current controls.

B.1.6 Strengths and limitations

Strengths of brainstorming include:

- it encourages imagination which helps identify new risks and novel solutions;
- it involves key stakeholders and hence aids communication overall;
- it is relatively quick and easy to set up.

Limitations include:

- participants may lack the skill and knowledge to be effective contributors;
- since it is relatively unstructured, it is difficult to demonstrate that the process has been comprehensive, e.g. that all potential risks have been identified;
- there may be particular group dynamics where some people with valuable ideas stay quiet while others dominate the discussion. This can be overcome by computer brainstorming, using a chat forum or nominal group technique. Computer brainstorming can be set up to be anonymous, thus avoiding personal and political issues which may impede free flow of ideas. In nominal group technique ideas are submitted anonymously to a moderator and are then discussed by the group.

B.2 Structured or semi-structured interviews

B.2.1 Overview

In a structured interview, individual interviewees are asked a set of prepared questions from a prompting sheet which encourages the interviewee to view a situation from a different perspective and thus identify risks from that perspective. A semi-structured interview is similar, but allows more freedom for a conversation to explore issues which arise.

B.2.2 Use

Structured and semi-structured interviews are useful where it is difficult to get people together for a brainstorming session or where free-flowing discussion in a group is not appropriate for the situation or people involved. They are most often used to identify risks or to assess effectiveness of existing controls as part of risk analysis. They may be applied at any stage of a project or process. They are a means of providing stakeholder input to risk assessment.

B.2.3 Inputs

Inputs include:

- a clear definition of the objectives of the interviews;
- a list of interviewees selected from relevant stakeholders;
- a prepared set of questions.

B.2.4 Process

A relevant question set, is created to guide the interviewer. Questions should be open-ended where possible, should be simple, in appropriate language for the interviewee and cover one issue only. Possible follow-up questions to seek clarification are also prepared.

Questions are then posed to the person being interviewed. When seeking elaboration, questions should be open-ended. Care should be taken not to "lead" the interviewee.

Responses should be considered with a degree of flexibility in order to provide the opportunity of exploring areas into which the interviewee may wish to go.

B.2.5 Outputs

The outputs are the stakeholder's views on the issues which are the subject of the interviews.

B.2.6 Strengths and limitations

The strengths of structured interviews are as follows :

- structured interviews allow people time for considered thought about an issue;
- one-to-one communication may allow more in-depth consideration of issues;
- structured interviews enable involvement of a larger number of stakeholders than brainstorming which uses a relatively small group.

Limitations are as follows:

- it is time-consuming for the facilitator to obtain multiple opinions in this way;
- bias is tolerated and not removed through group discussion;
- the triggering of imagination which is a feature of brainstorming may not be achieved.

B.3 Delphi technique

B.3.1 Overview

The Delphi technique is a procedure to obtain a reliable consensus of opinion from a group of experts. Although the term is often now broadly used to mean any form of brainstorming, an essential feature of the Delphi technique, as originally formulated, was that experts expressed their opinions individually and anonymously while having access to the other expert's views as the process progresses.

B.3.2 Use

The Delphi technique can be applied at any stage of the risk management process or at any phase of a system life cycle, wherever a consensus of views of experts is needed.

B.3.3 Inputs

A set of options for which consensus is needed.

B.3.4 Process

A group of experts are questioned using a semi-structured questionnaire. The experts do not meet so their opinions are independent.

The procedure is as follows:

- formation of a team to undertake and monitor the Delphi process;

- selection of a group of experts (may be one or more panels of experts);
- development of round 1 questionnaire;
- testing the questionnaire;
- sending the questionnaire to panellists individually;
- information from the first round of responses is analysed and combined and re-circulated to panellists;
- panellists respond and the process is repeated until consensus is reached.

B.3.5 Outputs

Convergence toward consensus on the matter in hand.

B.3.6 Strengths and limitations

Strengths include:

- as views are anonymous, unpopular opinions are more likely to be expressed;
- all views have equal weight, which avoids the problem of dominating personalities;
- achieves ownership of outcomes;
- people do not need to be brought together in one place at one time.

Limitations include:

- it is labour intensive and time consuming;
- participants need to be able to express themselves clearly in writing.

B.4 Check-lists

B.4.1 Overview

Check-lists are lists of hazards, risks or control failures that have been developed usually from experience, either as a result of a previous risk assessment or as a result of past failures.

B.4.2 Use

A check-list can be used to identify hazards and risks or to assess the effectiveness of controls. They can be used at any stage of the life cycle of a product, process or system. They may be used as part of other risk assessment techniques but are most useful when applied to check that everything has been covered after a more imaginative technique that identifies new problems has been applied.

B.4.3 Inputs

Prior information and expertise on the issue, such that a relevant and preferably validated check-list can be selected or developed.

B.4.4 Process

The procedure is as follows:

- the scope of the activity is defined;
- a check-list is selected which adequately covers the scope. Check-lists need to be carefully selected for the purpose. For example a check-list of standard controls cannot be used to identify new hazards or risks;

- the person or team using the check-list steps through each element of the process or system and reviews whether items on the check-list are present.

B.4.5 Outputs

Outputs depend on the stage of the risk management process at which they are applied. For example output may be a list of controls which are inadequate or a list of risks.

B.4.6 Strengths and limitations

Strengths of check-lists include:

- they may be used by non experts;
- when well designed, they combine wide ranging expertise into an easy to use system;
- they can help ensure common problems are not forgotten.

Limitations include:

- they tend to inhibit imagination in the identification of risks;
- they address the ‘known known’s’, not the ‘known unknown’s or the ‘unknown unknowns’.
- they encourage ‘tick the box’ type behaviour;
- they tend to be observation based, so miss problems that are not readily seen.

B.5 Preliminary hazard analysis (PHA)

B.5.1 Overview

PHA is a simple, inductive method of analysis whose objective is to identify the hazards and hazardous situations and events that can cause harm for a given activity, facility or system.

B.5.2 Use

It is most commonly carried out early in the development of a project when there is little information on design details or operating procedures and can often be a precursor to further studies or to provide information for specification of the design of a system. It can also be useful when analysing existing systems for prioritizing hazards and risks for further analysis or where circumstances prevent a more extensive technique from being used.

B.5.3 Inputs

Inputs include:

- information on the system to be assessed;
- such details of the design of the system as are available and relevant.

B.5.4 Process

A list of hazards and generic hazardous situations and risks is formulated by considering characteristics such as:

- materials used or produced and their reactivity;
- equipment employed;
- operating environment;
- layout;
- interfaces among system components, etc.

Qualitative analysis of consequences of an unwanted event and their probabilities may be carried out to identify risks for further assessment.

PHA should be updated during the phases of design, construction and testing in order to detect any new hazards and make corrections, if necessary. The results obtained may be presented in different ways such as tables and trees.

B.5.5 Outputs

Outputs include:

- a list of hazards and risks;
- recommendations in the form of acceptance, recommended controls, design specification or requests for more detailed assessment.

B.5.6 Strengths and limitations

Strengths include:

- that it is able to be used when there is limited information;
- it allows risks to be considered very early in the system lifecycle.

Limitations include:

- a PHA provides only preliminary information; it is not comprehensive, neither does it provide detailed information on risks and how they can best be prevented.

B.6 HAZOP

B.6.1 Overview

HAZOP is the acronym for **HA**Zard and **OP**erability study and, is a structured and systematic examination of a planned or existing product, process, procedure or system. It is a technique to identify risks to people, equipment, environment and/or organizational objectives. The study team is also expected, where possible, to provide a solution for treating the risk.

The HAZOP process is a qualitative technique based on use of guide words which question how the design intention or operating conditions might not be achieved at each step in the design, process, procedure or system. It is generally carried out by a multi-disciplinary team during a set of meetings.

HAZOP is similar to FMEA in that it identifies failure modes of a process, system or procedure their causes and consequences. It differs in that the team considers unwanted outcomes and deviations from intended outcomes and conditions and works back to possible causes and failure modes, whereas FMEA starts by identifying failure modes.

B.6.2 Use

The HAZOP technique was initially developed to analyse chemical process systems, but has been extended to other types of systems and complex operations. These include mechanical and electronic systems, procedures, and software systems, and even to organizational changes and to legal contract design and review.

The HAZOP process can deal with all forms of deviation from design intent due to deficiencies in the design, component(s), planned procedures and human actions.

It is widely used for software design review. When applied to safety critical instrument control and computer systems it may be known as CHAZOP (**C**ontrol **HA**zards and **OP**erability Analysis or computer hazard and operability analysis).

A HAZOP study is usually undertaken at the detail design stage, when a full diagram of the intended process is available, but while design changes are still practicable. It may however, be carried out in a phased approach with different guidewords for each stage as a design develops in detail. A HAZOP study may also be carried out during operation but required changes can be costly at that stage.

B.6.3 Inputs

Essential inputs to a HAZOP study include current information about the system, the process or procedure to be reviewed and the intention and performance specifications of the design. The inputs may include: drawings, specification sheets, flow sheets, process control and logic diagrams, layout drawings, operating and maintenance procedures, and emergency response procedures. For non-hardware related HAZOP the inputs can be any document that describes functions and elements of the system or procedure under study. For example, inputs can be organizational diagrams and role descriptions, a draft contract or even a draft procedure.

B.6.4 Process

HAZOP takes the “design” and specification of the process, procedure or system being studied and reviews each part of it to discover what deviations from the intended performance can occur, what are the potential causes and what are the likely consequences of a deviation. This is achieved by systematically examining how each part of the system, process or procedure will respond to changes in key parameters by using suitable guidewords. Guidewords can be customized to a particular system, process or procedure or generic words can be used that encompass all types of deviation. Table B.1 provides examples of commonly used guidewords for technical systems. Similar guidewords such as ‘too early’, ‘too late’, ‘too much’, ‘too little’, ‘too long’, ‘too short’, ‘wrong direction’, on ‘wrong object’, ‘wrong action’ can be used to identify human error modes.

The normal steps in a HAZOP study include:

- nomination of a person with the necessary responsibility and authority to conduct the HAZOP study and to ensure that any actions arising from the study are completed;
- definition of the objectives and scope of the study;
- establishing a set of key or guidewords for the study;
- defining a HAZOP study team; this team is usually multidisciplinary and should include design and operations personnel with appropriate technical expertise to evaluate the effects of deviations from intended or current design. It is recommended that the team include persons not directly involved in the design or the system, process or procedure under review;
- collection of the required documentation.

Within a facilitated workshop with the study team:

- splitting the system, process or procedure into smaller elements or sub-systems or sub-processes or sub-elements to make the review tangible;
- agreeing the design intent for each subsystem, sub-process or sub-element and then for each item in that subsystem or element applying the guidewords one after the other to postulate possible deviations which will have undesirable outcomes;
- where an undesirable outcome is identified, agreeing the cause and consequences in each case and suggesting how they might be treated to prevent them occurring or mitigate the consequences if they do;
- documenting the discussion and agreeing specific actions to treat the risks identified.

Table B.1 – Example of possible HAZOP guidewords

Terms	Definitions
No or not	No part of the intended result is achieved or the intended condition is absent
More (higher)	Quantitative increase in output or in the operating condition
Less (lower)	Quantitative decrease
As well as	Quantitative increase (e.g. additional material)
Part of	Quantitative decrease (e.g. only one or two components in a mixture)
Reverse /opposite	Opposite (e.g. backflow)
Other than	No part of the intention is achieved, something completely different happens (e.g. flow or wrong material)
Compatibility	Material; environment
Guide words are applied to parameters such as	
	Physical properties of a material or process
	Physical conditions such as temperature, speed
	A specified intention of a component of a system or design (e.g. information transfer)
	Operational aspects

B.6.5 Outputs

Minutes of the HAZOP meeting(s) with items for each review point recorded. This should include: the guide word used, the deviation(s), possible causes, actions to address the identified problems and person responsible for the action.

For any deviation that cannot be corrected, then the risk for the deviation should be assessed.

B.6.6 Strengths and limitations

A HAZOP analysis offers the following advantages:

- it provides the means to systematically and thoroughly examine a system, process or procedure;
- it involves a multidisciplinary team including those with real-life operational experience and those who may have to carry out treatment actions;
- it generates solutions and risk treatment actions;
- it is applicable to a wide range of systems, processes and procedures;
- it allows explicit consideration of the causes and consequences of human error;
- it creates a written record of the process which can be used to demonstrate due diligence.

The limitations include:

- a detailed analysis can be very time-consuming and therefore expensive;
- a detailed analysis requires a high level of documentation or system/process and procedure specification;
- it can focus on finding detailed solutions rather than on challenging fundamental assumptions (however, this can be mitigated by a phased approach);
- the discussion can be focused on detail issues of design, and not on wider or external issues;

- it is constrained by the (draft) design and design intent, and the scope and objectives given to the team;
- the process relies heavily on the expertise of the designers who may find it difficult to be sufficiently objective to seek problems in their designs.

B.6.7 Reference document

IEC 61882, *Hazard and operability studies (HAZOP studies) – Application guide*

B.7 Hazard analysis and critical control points (HACCP)

B.7.1 Overview

Hazard analysis and critical control point (HACCP) provides a structure for identifying hazards and putting controls in place at all relevant parts of a process to protect against the hazards and to maintain the quality reliability and safety of a product. HACCP aims to ensure that risks are minimized by controls throughout the process rather than through inspection of the end product.

B.7.2 Use

HACCP was developed to ensure food quality for the NASA space program. It is now used by organizations operating anywhere within the food chain to control risks from physical, chemical or biological contaminants of food. It has also been extended for use in manufacture of pharmaceuticals and to medical devices. The principle of identifying things which can influence product quality, and defining points in a process where critical parameters can be monitored and hazards controlled, can be generalized to other technical systems.

B.7.3 Inputs

HACCP starts from a basic flow diagram or process diagram and information on hazards which might affect the quality, safety or reliability of the product or process output. Information on the hazards and their risks and ways in which they can be controlled is an input to HACCP.

B.7.4 Process

HACCP consists of the following seven principles:

- identifies hazards and preventive measures related to such hazards;
- determines the points in the process where the hazards can be controlled or eliminated (the critical control points or CCPs);
- establishes critical limits needed to control the hazards, i.e. each CCP should operate within specific parameters to ensure the hazard is controlled;
- monitors the critical limits for each CCP at defined intervals;
- establishes corrective actions if the process falls outside established limits;
- establishes verification procedures;
- implements record keeping and documentation procedures for each step.

B.7.5 Outputs

Documented records including a hazard analysis worksheet and a HACCP **plan**.

The hazard analysis worksheet lists for each step of the process:

- hazards which could be introduced, controlled or exacerbated at this step;

- whether the hazards present a significant risk (based on consideration of consequence and probability from a combination of experience, data and technical literature);
- a justification for the significance;
- possible preventative measures for each hazard;
- whether monitoring or control measures can be applied at this step (i.e. is it a CCP?).

The HACCP plan delineates the procedures to be followed to assure the control of a specific design, product, process or procedure. The plan includes a list of all CCPs and for each CCP:

- the critical limits for preventative measures;
- monitoring and continuing control activities (including what, how, and when monitoring will be carried out and by whom);
- corrective actions required if deviations from critical limits are detected;
- verification and record-keeping activities.

B.7.6 Strengths and limitations

Strengths include:

- a structured process that provides documented evidence for quality control as well as identifying and reducing risks;
- a focus on the practicalities of how and where, in a process, hazards can be prevented and risks controlled;
- better risk control throughout the process rather than relying on final product inspection;
- an ability to identify hazards introduced through human actions and how these can be controlled at the point of introduction or subsequently.

Limitations include:

- HACCP requires that hazards are identified, the risks they represent defined, and their significance understood as inputs to the process. Appropriate controls also need to be defined. These are required in order to specify critical control points and control parameters during HACCP and may need to be combined with other tools to achieve this;
- taking action when control parameters exceed defined limits may miss gradual changes in control parameters which are statistically significant and hence should be actioned.

B.7.7 Reference document

ISO 22000, *Food safety management systems – Requirements for any organization in the food chain*

B.8 Toxicity assessment

B.8.1 Overview

Environmental risk assessment is used here to cover the process followed in assessing risks to plants, animals and humans as a result of exposure to a range of environmental hazards. Risk management refers to decision-making steps including risk evaluation and risk treatment.

The method involves analysing the hazard or source of harm and how it affects the target population, and the pathways by which the hazard can reach a susceptible target population. This information is then combined to give an estimate of the likely extent and nature of harm.

B.8.2 Use

The process is used to assess risks to plants, animals and humans as a result of exposure to hazards such as chemicals, micro-organisms or other species.

Aspects of the methodology, such as pathway analysis which explore different routes by which a target might be exposed to a source of risk, can be adapted and used across a very wide range of different risk areas, outside human health and the environment, and is useful in identifying treatments to reduce risk.

B.8.3 Inputs

The method requires good data on the nature and properties of hazards, the susceptibilities of the target population (or populations) and the way in which the two interact. This data is normally based on research which may be laboratory based or epidemiological.

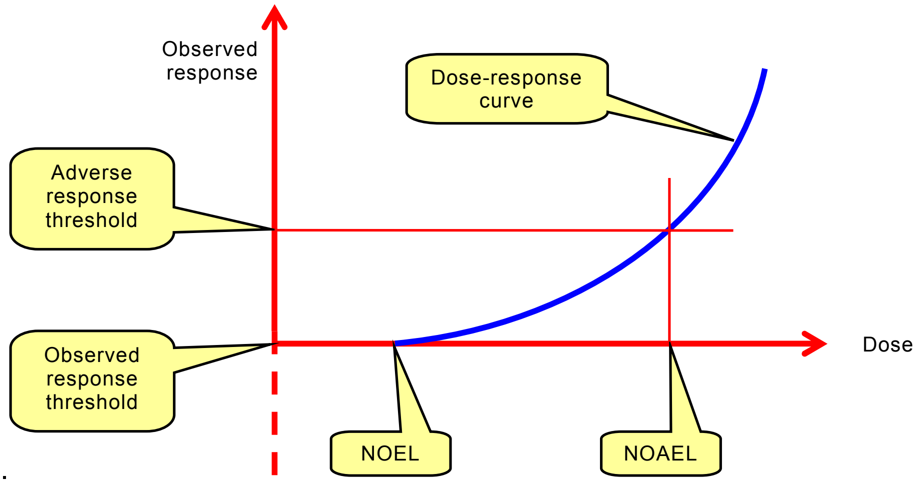
B.8.4 Process

The procedure is as follows:

a) Problem formulation – this includes setting the scope of the assessment by defining the range of target populations and hazard types of interest;

b) Hazard identification – this involves identifying all possible sources of harm to the target population from hazards within the scope of the study. Hazard identification normally relies on expert knowledge and a review of literature;

c) Hazard analysis – this involves understanding the nature of the hazard and how it interacts with the target. For example, in considering human exposure to chemical effects, the hazard might include acute and chronic toxicity, the potential to damage DNA, or the potential to cause cancer or birth defects. For each hazardous effect, the magnitude of the effect (the response) is compared to the amount of hazard to which the target is exposed (the dose) and, wherever possible, the mechanism by which the effect is produced is determined. The levels at which there is No Observable Effect (NOEL) and no Observable Adverse Effect (NOAEL) are noted. These are sometimes used as criteria for acceptability of the risk.



IEC 2062/09

Figure B.1 – Dose-response curve

For chemical exposure, test results are used to derive dose-response curves such as that shown schematically in Figure B.1. These are usually derived from tests on animals or from experimental systems such as cultured tissues or cells.

Effects of other hazards such as micro-organisms or introduced species may be determined from field data and epidemiological studies. The nature of the interaction of diseases or pests with the target is determined and the probability that a particular level of harm from a particular exposure to the hazard is estimated.

d) Exposure analysis – this step examines how a hazardous substance or its residues might reach a susceptible target population and in what amount. It often involves a pathway analysis which considers the different routes the hazard might take, the barriers which might prevent it from reaching the target and the factors that might influence the level of exposure. For example, in considering the risk from chemical spraying the exposure analysis would consider how much chemical was sprayed, in what way and under what conditions, whether there was any direct exposure of humans or animals, how much might be left as residue on plant life, the environmental fate of pesticides reaching the ground, whether it can accumulate in animals or whether it enters groundwater. In bio security, the pathway analysis might consider how any pests entering the country might enter the environment, become established and spread.

e) Risk characterization – in this step, the information from the hazard analysis and the exposure analysis are brought together to estimate the probabilities of particular consequences when effects from all pathways are combined. Where there are large numbers of hazards or pathways, an initial screening may be carried out and the detailed hazard and exposure analysis and risk characterization carried out on the higher risk scenarios.

B.8.5 Outputs

The output is normally an indication of the level of risk from exposure of a particular target to a particular hazard in the context concerned. The risk may be expressed quantitatively semi-quantitatively or qualitatively. For example, the risk of cancer is often expressed quantitatively as the probability, that a person will develop cancer over a specified period given a specified exposure to a contaminant. Semi-quantitative analysis may be used to derive a risk index for a particular contaminant or pest and qualitative output may be a level of risk (e.g. high, medium, low) or a description with practical data of likely effects.

B.8.6 Strengths and limitations

The strength of this analysis is that it provides a very detailed understanding of the nature of the problem and the factors which increase risk.

Pathway analysis is a useful tool, generally, for all areas of risk and permits the identification of how and where it may be possible to improve controls or introduce new ones.

It does, however, need good data which is often not available or has a high level of uncertainty associated with it. For example, dose response curves derived from exposing animals to high levels of a hazard should be extrapolated to estimate the effects of very low levels of the contaminants to humans and there are multiple models by which this is achieved. Where the target is the environment rather than humans and the hazard is not chemical, data which is directly relevant to the particular conditions of the study may be limited.

B.9 Structured “What-if” Technique (SWIFT)

B.9.1 Overview

SWIFT was originally developed as a simpler alternative to HAZOP. It is a systematic, team-based study, utilizing a set of ‘prompt’ words or phrases that is used by the facilitator within a workshop to stimulate participants to identify risks. The facilitator and team use standard ‘what-if’ type phrases in combination with the prompts to investigate how a system, plant item, organization or procedure will be affected by deviations from normal operations and behaviour. SWIFT is normally applied at more of a systems level with a lower level of detail than HAZOP.

B.9.2 Use

While SWIFT was originally designed for chemical and petrochemical plant hazard study, the technique is now widely applied to systems, plant items, procedures, organizations generally. In particular it is used to examine the consequences of changes and the risks thereby altered or created.

B.9.3 Inputs

The system, procedure, plant item and/or change has to be carefully defined before the study can commence. Both the external and internal contexts are established through interviews and through the study of documents, plans and drawings by the facilitator. Normally, the item, situation or system for study is split into nodes or key elements to facilitate the analysis process but this rarely occurs at the level of definition required for HAZOP.

Another key input is the expertise and experience present in the study team which should be carefully selected. All stakeholders should be represented if possible together with those with experience of similar items, systems, changes or situations.

B.9.4 Process

The general process is as follows:

a) Before the study commences, the facilitator prepares a suitable prompt list of words or phrases that may be based on a standard set or be created to enable a comprehensive review of hazards or risks.
b) At the workshop the external and internal context of the item, system, change or situation and the scope of the study are discussed and agreed.
c) The facilitator asks the participants to raise and discuss:
   - known risks and hazards;
   - previous experience and incidents;
   - known and existing controls and safeguards;
   - regulatory requirements and constraints.
d) Discussion is facilitated by creating a question using a ‘what-if’ phrase and a prompt word or subject. The ‘what-if’ phrases to be used are “what if…”, “what would happen if…”, “could someone or something…”, “has anyone or anything ever….” The intent is to stimulate the study team into exploring potential scenarios, their causes and consequences and impacts.
e) Risks are summarized and the team considers controls in place.
f) The description of the risk, its causes, consequences and expected controls are confirmed with the team and recorded.
g) The team considers whether the controls are adequate and effective and agree a statement of risk control effectiveness. If this is less than satisfactory, the team further considers risk treatment tasks and potential controls are defined.
h) During this discussion further ‘what-if’ questions are posed to identify further risks.
i) The facilitator uses the prompt list to monitor the discussion and to suggest additional issues and scenarios for the team to discuss.
j) It is normal to use a qualitative or semi-quantitative risk assessment method to rank the actions created in terms of priority. This risk assessment is normally conducted by taking into account the existing controls and their effectiveness.

B.9.5 Outputs

Outputs include a risk register with risk-ranked actions or tasks. These tasks can then become the basis for a treatment plan.

B.9.6 Strengths and limitations

Strengths of SWIFT:

- it is widely applicable to all forms of physical plant or system, situation or circumstance, organization or activity;
- it needs minimal preparation by the team;
- it is relatively rapid and the major hazards and risks quickly become apparent within the workshop session;
- the study is 'systems orientated' and allows participants to look at the system response to deviations rather than just examining the consequences of component failure;
- it can be used to identify opportunities for improvement of processes and systems and generally can be used to identify actions that lead to and enhance their probabilities of success;
- involvement in the workshop by those who are accountable for existing controls and for further risk treatment actions, reinforces their responsibility;
- it creates a risk register and risk treatment plan with little more effort;
- while often a qualitative or semi-quantitative form of risk rating is used for risk assessment and to prioritize attention on the resulting actions, SWIFT can be used to identify risks and hazards that can be taken forward into a quantitative study.

Limitations of SWIFT:

- it needs an experienced and capable facilitator to be efficient;
- careful preparation is needed so that the workshop team's time is not wasted;
- if the workshop team does not have a wide enough experience base or if the prompt system is not comprehensive, some risks or hazards may not be identified;
- the high-level application of the technique may not reveal complex, detailed or correlated causes.

B.10 Scenario analysis

B.10.1 Overview

Scenario analysis is a name given to the development of descriptive models of how the future might turn out. It can be used to identify risks by considering possible future developments and exploring their implications. Sets of scenarios reflecting (for example) 'best case', 'worst case' and 'expected case' may be used to analyse potential consequences and their probabilities for each scenario as a form of sensitivity analysis when analysing risk.

The power of scenario analysis is illustrated by considering major shifts over the past 50 years in technology, consumer preferences, social attitudes, etc. Scenario analysis cannot predict the probabilities of such changes but can consider consequences and help organizations develop strengths and the resilience needed to adapt to foreseeable changes.

B.10.2 Use

Scenario analysis can be used to assist in making policy decisions and planning future strategies as well as to consider existing activities. It can play a part in all three components of risk assessment. For identification and analysis, sets of scenarios reflecting (for example) best case, worst case and 'expected' case may be used to identify what might happen under particular circumstances and analyse potential consequences and their probabilities for each scenario.

Scenario analysis may be used to anticipate how both threats and opportunities might develop and may be used for all types of risk with both short and long term time frames. With short time frames and good data, likely scenarios may be extrapolated from the present. For longer time frames or with weak data, scenario analysis becomes more imaginative and may be referred to as futures analysis.

Scenario analysis may be useful where there are strong distributional differences between positive outcomes and negative outcomes in space, time and groups in the community or an organization.

B.10.3 Inputs

The prerequisite for a scenario analysis is a team of people who between them have an understanding of the nature of relevant changes (for example possible advances in technology) and imagination to think into the future without necessarily extrapolating from the past. Access to literature and data about changes already occurring is also useful.

B.10.4 Process

The structure for scenario analysis may be informal or formal.

Having established a team and relevant communication channels, and defined the context of the problem and issues to be considered, the next step is to identify the nature of changes that might occur. This will need research into the major trends and the probable timing of changes in trends as well as imaginative thinking about the future.

Changes to be considered may include:

- external changes (such as technological changes);
- decisions that need to be made in the near future but which may have a variety of outcomes;
- stakeholder needs and how they might change;
- changes in the macro environment (regulatory, demographics, etc). Some will be inevitable and some will be uncertain.

Sometimes, a change may be due to the consequences of another risk. For example, the risk of climate change is resulting in changes in consumer demand related to food miles. This will influence which foods can be profitably exported as well as which foods can be grown locally.

The local and macro factors or trends can now be listed and ranked for (1) importance (2) uncertainty. Special attention is paid to the factors that are most important and most uncertain. Key factors or trends are mapped against each other to show areas where scenarios can be developed.

A series of scenarios is proposed with each one focussing on a plausible change in parameters.

A “story” is then written for each scenario that tells how you might move from here towards the subject scenario. The stories may include plausible details that add value to the scenarios.

The scenarios can then be used to test or evaluate the original question. The test takes into account any significant but predictable factors (e.g. use patterns), and then explores how ‘successful’ the policy (activity) would be in this new scenario, and ‘pre-tests’ outcomes by using ‘what if’ questions based on model assumptions.

When the question or proposal has been evaluated with respect to each scenario, it may be obvious that it needs to be modified to make it more robust or less risky. It should also be possible to identify some leading indicators that show when change is occurring. Monitoring and responding to leading indicators can provide opportunity for change in planned strategies.

Since scenarios are only defined ‘slices’ of possible futures, it is important to make sure that account is taken of the probability of a particular outcome (scenario) occurring, i.e. to adopt a risk framework. For example, where best case, worst case and expected case scenarios are used, some attempt should be made to qualify, or express the probability of each scenario occurring.

B.10.5 Outputs

There may be no best-fit scenario but one should end with a clearer perception of the range of options and how to modify the chosen course of action as indicators move.

B.10.6 Strengths and limitations

Scenario analysis takes account of a range of possible futures which may be preferable to the traditional approach of relying on high-medium-low forecasts that assume, through the use of historical data, that future events will probably continue to follow past trends. This is important for situations where there is little current knowledge on which to base predictions or where risks are being considered in the longer term future.

This strength however has an associated weakness which is that where there is high uncertainty some of the scenarios may be unrealistic.

The main difficulties in using scenario analysis are associated with the availability of data, and the ability of the analysts and decision makers to be able to develop realistic scenarios that are amenable to probing of possible outcomes.

The dangers of using scenario analysis as a decision-making tool are that the scenarios used may not have an adequate foundation; that data may be speculative; and that unrealistic results may not be recognized as such.

B.11 Business impact analysis (BIA)

B.11.1 Overview

Business impact analysis, also known as business impact assessment, analyses how key disruption risks could affect an organization’s operations and identifies and quantifies the capabilities that would be needed to manage it. Specifically, a BIA provides an agreed understanding of:

- the identification and criticality of key business processes, functions and associated resources and the key interdependencies that exist for an organization;
- how disruptive events will affect the capacity and capability of achieving critical business objectives;
- the capacity and capability needed to manage the impact of a disruption and recover the organization to agreed levels of operation.

B.11.2 Use

BIA is used to determine the criticality and recovery timeframes of processes and associated resources (people, equipment, information technology) to ensure the continued achievement of objectives. Additionally, the BIA assists in determining interdependencies and interrelationships between processes, internal and external parties and any supply chain linkages.

B.11.3 Inputs

Inputs include:

- a team to undertake the analysis and develop a plan;
- information concerning the objectives, environment, operations and interdependencies of the organization;
- details on the activities and operations of the organization, including processes, supporting resources, relationships with other organizations, outsourced arrangements, stakeholders;
- financial and operational consequences of loss of critical processes;
- prepared questionnaire;
- list of interviewees from relevant areas of the organization and/or stakeholders that will be contacted.

B.11.4 Process

A BIA can be undertaken using questionnaires, interviews, structured workshops or combinations of all three, to obtain an understanding of the critical processes, the effects of the loss of those processes and the required recovery timeframes and supporting resources.

The key steps include:

- based on the risk and vulnerability assessment, confirmation of the key processes and outputs of the organization to determine the criticality of the processes;
- determination of the consequences of a disruption on the identified critical processes in financial and/or operational terms, over defined periods;
- identification of the interdependencies with key internal and external stakeholders. This could include mapping the nature of the interdependencies through the supply chain;
- determination of the current available resources and the essential level of resources needed to continue to operate at a minimum acceptable level following a disruption;
- identification of alternate workarounds and processes currently in use or planned to be developed. Alternate workarounds and processes may need to be developed where resources or capability are inaccessible or insufficient during the disruption;
- determination of the maximum acceptable outage time (MAO) for each process based on the identified consequences and the critical success factors for the function. The MAO represents the maximum period of time the organization can tolerate the loss of capability;
- determination of the recovery time objective(s) (RTO) for any specialized equipment or information technology. The RTO represents the time within which the organization aims to recover the specialized equipment or information technology capability;
- confirmation of the current level of preparedness of the critical processes to manage a disruption. This may include evaluating the level of redundancy within the process (e.g. spare equipment) or the existence of alternate suppliers.

B.11.5 Outputs

The outputs are as follows:

- a priority list of critical processes and associated interdependencies;
- documented financial and operational impacts from a loss of the critical processes;
- supporting resources needed for the identified critical processes;
- outage time frames for the critical process and the associated information technology recovery time frames.

B.11.6 Strengths and limitations

Strengths of the BIA include:

- an understanding of the critical processes that provide the organization with the ability to continue to achieve their stated objectives;
- an understanding of the required resources;
- an opportunity to redefine the operational process of an organization to assist in the resilience of the organization.

Limitations include:

- lack of knowledge by the participants involved in completing questionnaires, undertaking interviews or workshops;
- group dynamics may affect the complete analysis of a critical process;
- simplistic or over-optimistic expectations of recovery requirements;
- difficulty in obtaining an adequate level of understanding of the organization’s operations and activities.

B.12 Root cause analysis (RCA)

B.12.1 Overview

The analysis of a major loss to prevent its reoccurrence is commonly referred to as Root Cause Analysis (RCA), Root Cause Failure Analysis (RCFA) or loss analysis. RCA is focused on asset losses due to various types of failures while loss analysis is mainly concerned with financial or economic losses due to external factors or catastrophes. It attempts to identify the root or original causes instead of dealing only with the immediately obvious symptoms. It is recognized that corrective action may not always be entirely effective and that continuous improvement may be required. RCA is most often applied to the evaluation of a major loss but may also be used to analyse losses on a more global basis to determine where improvements can be made.

B.12.2 Use

RCA is applied in various contexts with the following broad areas of usage:

- safety-based RCA is used for accident investigations and occupational health and safety;
- failure analysis is used in technological systems related to reliability and maintenance;
- production-based RCA is applied in the field of quality control for industrial manufacturing;
- process-based RCA is focused on business processes;
- system-based RCA has developed as a combination of the previous areas to deal with complex systems with application in change management, risk management and systems analysis.

B.12.3 Inputs

The basic input to an RCA is all of the evidence gathered from the failure or loss. Data from other similar failures may also be considered in the analysis. Other inputs may be results that are carried out to test specific hypotheses.

B.12.4 Process

When the need for an RCA is identified, a group of experts is appointed to carry out the analysis and make recommendations. The type of expert will mostly be dependent on the specific expertise needed to analyse the failure.

Even though different methods can be used to perform the analysis, the basic steps in executing an RCA are similar and include:

- forming the team;
- establishing the scope and objectives of the RCA;
- gathering data and evidence from the failure or loss;
- performing a structured analysis to determine the root cause;
- developing solutions and make recommendations;
- implementing the recommendations;
- verifying the success of the implemented recommendations.

Structured analysis techniques may consist of one of the following:

- “5 whys” technique, i.e. repeatedly asking ‘why?’ to peel away layers of cause and sub cause);
- failure mode and effects analysis;
- fault tree analysis;
- Fishbone or Ishikawa diagrams;
- Pareto analysis;
- root cause mapping.

The evaluation of causes often progresses from initially evident physical causes to human-related causes and finally to underlying management or fundamental causes. Causal factors have to be able to be controlled or eliminated by involved parties in order for corrective action to be effective and worthwhile.

B.12.5 Outputs

The outputs from an RCA include:

- documentation of data and evidence gathered;
- hypotheses considered;
- conclusion about the most likely root causes for the failure or loss;
- recommendations for corrective action.

B.12.6 Strengths and limitations

Strengths include:

- involvement of applicable experts working in a team environment;
- structured analysis;
- consideration of all likely hypotheses;
- documentation of results;
- need to produce final recommendations.

Limitations of an RCA:

- required experts may not be available;
- critical evidence may be destroyed in the failure or removed during clean-up;
- the team may not be allowed enough time or resources to fully evaluate the situation;
- it may not be possible to adequately implement recommendations.

B.13 Failure modes and effects analysis (FMEA) and failure modes and effects and criticality analysis (FMECA)

B.13.1 Overview

Failure modes and effects analysis (FMEA) is a technique used to identify the ways in which components, systems or processes can fail to fulfil their design intent.

FMEA identifies:

- all potential failure modes of the various parts of a system (a failure mode is what is observed to fail or to perform incorrectly);
- the effects these failures may have on the system;
- the mechanisms of failure;
- how to avoid the failures, and/or mitigate the effects of the failures on the system.

FMECA extends an FMEA so that each fault mode identified is ranked according to its importance or criticality

This criticality analysis is usually qualitative or semi-quantitative but may be quantified using actual failure rates.

B.13.2 Use

There are several applications of FMEA: Design (or product) FMEA which is used for components and products, System FMEA which is used for systems, Process FMEA which is used for manufacturing and assembly processes, Service FMEA and Software FMEA.

FMEA/FMECA may be applied during the design, manufacture or operation of a physical system.

To improve dependability, however, changes are usually more easily implemented at the design stage. FMEA AND FMECA may also be applied to processes and procedures. For example, it is used to identify potential for medical error in healthcare systems and failures in maintenance procedures.

FMEA/FMECA can be used to

- assist in selecting design alternatives with high dependability,
- ensure that all failure modes of systems and processes, and their effects on operational success have been considered,
- identify human error modes and effects,
- provide a basis for planning testing and maintenance of physical systems,
- improve the design of procedures and processes,
- provide qualitative or quantitative information for analysis techniques such as fault tree analysis.

FMEA and FMECA can provide input to other analyses techniques such as fault tree analysis at either a qualitative or quantitative level.

B.13.3 Inputs

FMEA and FMECA need information about the elements of the system in sufficient detail for meaningful analysis of the ways in which each element can fail. For a detailed Design FMEA the element may be at the detailed individual component level, while for higher level Systems FMEA, elements may be defined at a higher level.

Information may include:

- drawings or a flow chart of the system being analysed and its components, or the steps of a process;
- an understanding of the function of each step of a process or component of a system;
- details of environmental and other parameters, which may affect operation;
- an understanding of the results of particular failures;
- historical information on failures including failure rate data where available.

B.13.4 Process

The FMEA process is as follows:

a) define the scope and objectives of the study;
b) assemble the team;
c) understand the system/process to be subjected to the FMECA;
d) breakdown of the system into its components or steps;
e) define the function of each step or component;
f) for every component or step listed identify:
  - how can each part conceivably fail?
  - what mechanisms might produce these modes of failure?
  - what could the effects be if the failures did occur?
  - is the failure harmless or damaging?
  - how is the failure detected?

g) identify inherent provisions in the design to compensate for the failure.

For FMECA, the study team goes on to classify each of the identified failure modes according to its criticality

There are several ways this may be done. Common methods include

- the mode criticality index,
- the level of risk,
- the risk priority number.

The model criticality is a measure of the probability that the mode being considered will result in failure of the system as a whole; it is defined as:

Failure effect probability * Mode failure rate * Operating time of the system

It is most often applied to equipment failures where each of these terms can be defined quantitatively and failure modes all have the same consequence.

The risk level is obtained by combining the consequences of a failure mode occurring with the probability of failure. It is used when consequences of different failure modes differ and can be applied to equipment systems or processes. Risk level can be expressed qualitatively, semi-quantitatively or quantitatively.

The risk priority number (RPN) is a semi-quantitative measure of criticality obtained by multiplying numbers from rating scales (usually between 1 and 10) for consequence of failure, likelihood of failure and ability to detect the problem. (A failure is given a higher priority if it is difficult to detect.) This method is used most often in quality assurance applications

Once failure modes and mechanisms are identified, corrective actions can be defined and implemented for the more significant failure modes.

FMEA is documented in a report that contains:

- details of the system that was analysed;
- the way the exercise was carried out;
- assumptions made in the analysis;
- sources of data;
- the results, including the completed worksheets;
- the criticality (if completed) and the methodology used to define it;
- any recommendations for further analyses, design changes or features to be incorporated in test plans, etc.

The system may be reassessed by another cycle of FMEA after the actions have been completed.

B.13.5 Outputs

The primary output of FMEA is a list of failure modes, the failure mechanisms and effects for each component or step of a system or process (which may include information on the likelihood of failure). Information is also given on the causes of failure and the consequences to the system as a whole. The output from FMECA includes a rating of importance based on the likelihood that the system will fail, the level of risk resulting from the failure mode or a combination of the level of risk and the ‘detectability’ of the failure mode.

FMECA can give a quantitative output if suitable failure rate data and quantitative consequences are used.

B.13.6 Strengths and limitations

The strengths of FMEA/FMECA are as follows:

- widely applicable to human, equipment and system failure modes and to hardware, software and procedures;
- identify component failure modes, their causes and their effects on the system, and present them in an easily readable format;
- avoid the need for costly equipment modifications in service by identifying problems early in the design process;
- identify single point failure modes and requirements for redundancy or safety systems;
- provide input to the development monitoring programmes by highlighting key features to be monitored.

Limitations include:

- they can only be used to identify single failure modes, not combinations of failure modes;
- unless adequately controlled and focussed, the studies can be time consuming and costly;
- they can be difficult and tedious for complex multi-layered systems.

B.13.7 Reference document

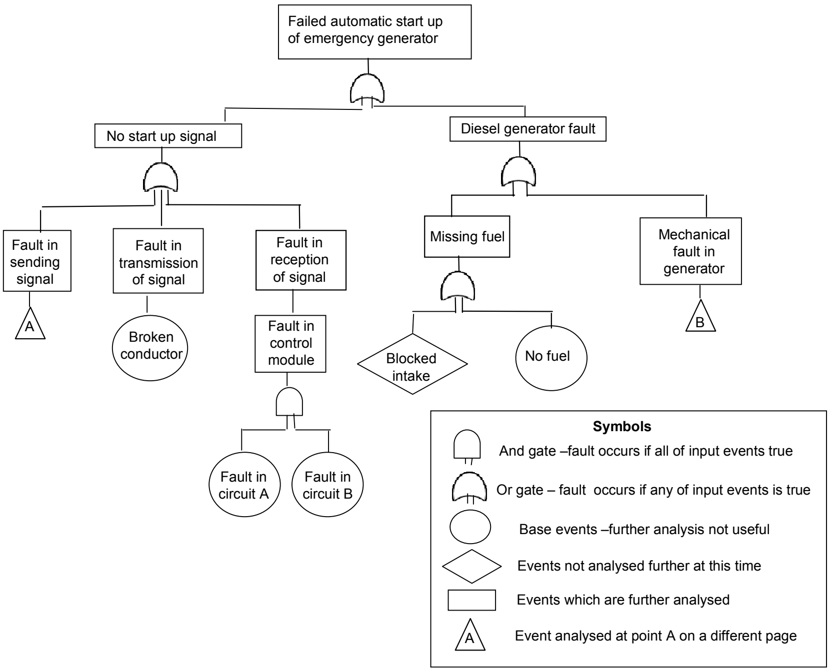
IEC 60812, *Analysis techniques for system reliability – Procedures for failure mode and effect analysis (FMEA)*

B.14 Fault tree analysis (FTA)

B.14.1 Overview

FTA is a technique for identifying and analysing factors that can contribute to a specified undesired event (called the “top event”). Causal factors are deductively identified, organized in a logical manner and represented pictorially in a tree diagram which depicts causal factors and their logical relationship to the top event.

The factors identified in the tree can be events that are associated with component hardware failures, human errors or any other pertinent events which lead to the undesired event.



IEC 2063/09

Figure B.2 – Example of an FTA from IEC 60300-3-9

B.14.2 Use

A fault tree may be used qualitatively to identify potential causes and pathways to a failure (the top event) or quantitatively to calculate the probability of the top event, given knowledge of the probabilities of causal events.

It may be used at the design stage of a system to identify potential causes of failure and hence to select between different design options. It may be used at the operating phase to identify how major failures can occur and the relative importance of different pathways to the head event. A fault tree may also be used to analyse a failure which has occurred to display diagrammatically how different events came together to cause the failure.

B.14.3 Inputs

For qualitative analysis, an understanding of the system and the causes of failure is required, as well as a technical understanding of how the system can fail. Detailed diagrams are useful to aid the analysis.

For quantitative analysis, data on failure rates or the probability of being in a failed state for all basic events in the fault tree are required.

B.14.4 Process

The steps for developing a fault tree are as follows:

- The top event to be analysed is defined. This may be a failure or maybe a broader outcome of that failure. Where the outcome is analysed, the tree may contain a section relating to mitigation of the actual failure.
- Starting with the top event, the possible immediate causes or failure modes leading to the top event are identified.
- Each of these causes/fault modes is analysed to identify how their failure could be caused.
- Stepwise identification of undesirable system operation is followed to successively lower system levels until further analysis becomes unproductive. In a hardware system this may be the component failure level. Events and causal factors at the lowest system level analysed are known as base events.
- Where probabilities can be assigned to base events the probability of the top event may be calculated. For quantification to be valid it must be able to be shown that, for each gate, all inputs are both necessary and sufficient to produce the output event. If this is not the case, the fault tree is not valid for probability analysis but may be a useful tool for displaying causal relationships.

As part of quantification the fault tree may need to be simplified using Boolean algebra to account for duplicate failure modes.

As well as providing an estimate of the probability of the head event, minimal cut sets, which form individual separate pathways to the head event, can be identified and their influence on the top event calculated.

Except for simple fault trees, a software package is needed to properly handle the calculations when repeated events are present at several places in the fault tree, and to calculate minimal cut sets. Software tools help ensure consistency, correctness and verifiability.

B.14.5 Outputs

The outputs from fault tree analysis are as follows:

- a pictorial representation of how the top event can occur which shows interacting pathways where two or more simultaneous events must occur;
- a list of minimal cut sets (individual pathways to failure) with (where data is available) the probability that each will occur;
- the probability of the top event.

B.14.6 Strengths and limitations

Strengths of FTA:

- It affords a disciplined approach which is highly systematic, but at the same time sufficiently flexible to allow analysis of a variety of factors, including human interactions and physical phenomena.
- The application of the "top-down" approach, implicit in the technique, focuses attention on those effects of failure which are directly related to the top event.
- FTA is especially useful for analysing systems with many interfaces and interactions.
- The pictorial representation leads to an easy understanding of the system behaviour and the factors included, but as the trees are often large, processing of fault trees may require computer systems. This feature enables more complex logical relationships to be included (e.g. NAND and NOR) but also makes the verification of the fault tree difficult.

- Logic analysis of the fault trees and the identification of cut sets is useful in identifying simple failure pathways in a very complex system where particular combinations of events which lead to the top event could be overlooked.

Limitations include:

- Uncertainties in the probabilities of base events are included in calculations of the probability of the top event. This can result in high levels of uncertainty where base event failure probabilities are not known accurately; however, a high degree of confidence is possible in a well understood system.
- In some situations, causal events are not bound together and it can be difficult to ascertain whether all important pathways to the top event are included. For example, including all ignition sources in an analysis of a fire as a top event. In this situation probability analysis is not possible.
- Fault tree is a static model; time interdependencies are not addressed.
- Fault trees can only deal with binary states (failed/not failed) only.
- While human error modes can be included in a qualitative fault tree, in general failures of degree or quality which often characterize human error cannot easily be included;
- A fault tree does not enable domino effects or conditional failures to be included easily.

B.14.7 Reference document

IEC 61025, *Fault tree analysis (FTA)*

IEC 60300-3-9, *Dependability management — Part 3: Application guide — Section 9: Risk analysis of technological systems*

B.15 Event tree analysis (ETA)

B.15.1 Overview

ETA is a graphical technique for representing the mutually exclusive sequences of events following an initiating event according to the functioning/not functioning of the various systems designed to mitigate its consequences (see Figure B.3). It can be applied both qualitatively and quantitatively.

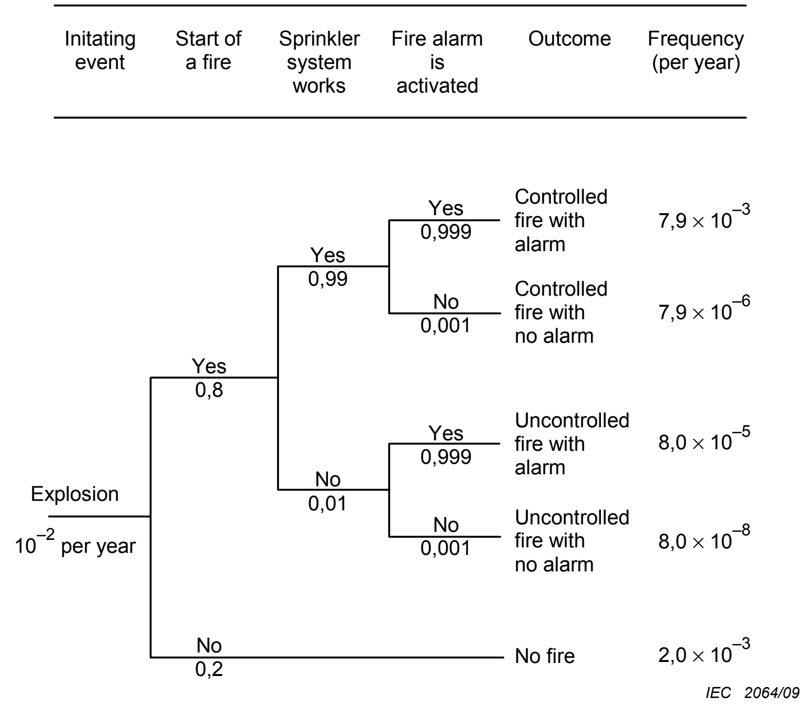


Figure B.3 – Example of an event tree

Figure B.3 shows simple calculations for a sample event tree, when branches are fully independent.

By fanning out like a tree, ETA is able to represent the aggravating or mitigating events in response to the initiating event, taking into account additional systems, functions or barriers.

B.15.2 Use

ETA can be used for modelling, calculating and ranking (from a risk point of view) different accident scenarios following the initiating event

ETA can be used at any stage in the life cycle of a product or process. It may be used qualitatively to help brainstorm potential scenarios and sequences of events following an initiating event and how outcomes are affected by various treatments, barriers or controls intended to mitigate unwanted outcomes.

The quantitative analysis lends itself to consider the acceptability of controls. It is most often used to model failures where there are multiple safeguards.

ETA can be used to model initiating events which might bring loss or gain. However, circumstances where pathways to optimize gain are sought are more often modelled using a decision tree.

B.15.3 Inputs

Inputs include:

- a list of appropriate initiating events;
- information on treatments, barriers and controls, and their failure probabilities (for quantitative analyses);
- understanding of the processes whereby an initial failure escalates.

B.15.4 Process

An event tree starts by selecting an initiating event. This may be an incident such as a dust explosion or a causal event such as a power failure. Functions or systems which are in place to mitigate outcomes are then listed in sequence. For each function or system, a line is drawn to represent their success or failure. A particular probability of failure can be assigned to each line, with this conditional probability estimated e.g. by expert judgement or a fault tree analysis. In this way, different pathways from the initiating event are modelled.

Note that the probabilities on the event tree are conditional probabilities, for example the probability of a sprinkler functioning is not the probability obtained from tests under normal conditions, but the probability of functioning under conditions of fire caused by an explosion.

Each path through the tree represents the probability that all of the events in that path will occur. Therefore, the frequency of the outcome is represented by the product of the individual conditional probabilities and the frequency of the initiation event, given that the various events are independent.

B.15.5 Outputs

Outputs from ETA include the following:

- qualitative descriptions of potential problems as combinations of events producing various types of problems (range of outcomes) from initiating events;
- quantitative estimates of event frequencies or probabilities and relative importance of various failure sequences and contributing events;
- lists of recommendations for reducing risks;
- quantitative evaluations of recommendation effectiveness.

B.15.6 Strengths and limitations

Strengths of ETA include the following:

- ETA displays potential scenarios following an initiating event, are analysed and the influence of the success or failure of mitigating systems or functions in a clear diagrammatic way;
- it accounts for timing, dependence and domino effects that are cumbersome to model in fault trees;
- it graphically represent sequences of events which are not possible to represent when using fault trees.

Limitations include:

- in order to use ETA as part of a comprehensive assessment, all potential initiating events need to be identified. This may be done by using another analysis method (e.g. HAZOP, PHA), however, there is always a potential for missing some important initiating events;
- with event trees, only success and failure states of a system are dealt with, and it is difficult to incorporate delayed success or recovery events;
- any path is conditional on the events that occurred at previous branch points along the path. Many dependencies along the possible paths are therefore addressed. However, some dependencies, such as common components, utility systems and operators, may be overlooked if not handled carefully, may lead to optimistic estimations of risk.

B.16 Cause-consequence analysis

B.16.1 General

Cause-consequence analysis is a combination of fault tree and event tree analysis. It starts from a critical event and analyses consequences by means of a combination of YES/NO logic gates which represent conditions that may occur or failures of systems designed to mitigate the consequences of the initiating event. The causes of the conditions or failures are analysed by means of fault trees (see Clause B.15)

B.16.2 Use

Cause-consequence analysis was originally developed as a reliability tool for safety critical systems to give a more complete understanding of system failures. Like fault tree analysis, it is used to represent the failure logic leading to a critical event but it adds to the functionality of a fault tree by allowing time sequential failures to be analysed. The method also allows time delays to be incorporated into the consequence analysis which is not possible with event trees.

The method is used to analyse the various paths a system could take following a critical event and depending on the behaviour of particular subsystems (such as emergency response systems). If quantified they will give an estimate of the probability of different possible consequences following a critical event.

As each sequence in a cause-consequence diagram is a combination of sub-fault trees, the cause-consequence analysis can be used as a tool to build big fault trees.

Diagrams are complex to produce and use and tend to be used when the magnitude of the potential consequence of failure justifies intensive effort.

B.16.3 Inputs

An understanding of the system and its failure modes and failure scenarios is required.

B.16.4 Process

Figure B.4 shows a conceptual diagram of a typical cause-consequence analysis.

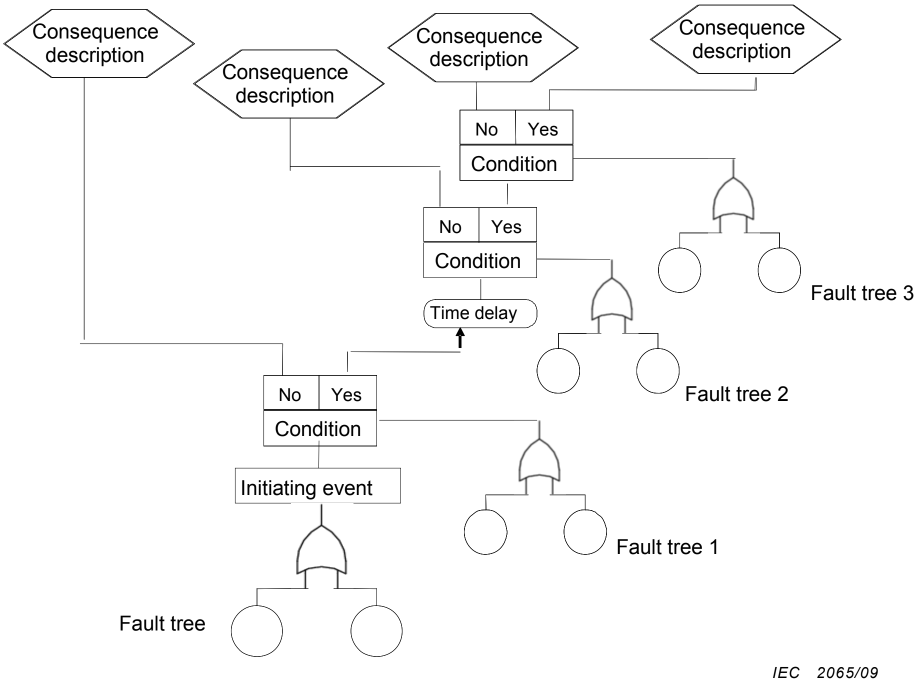


Figure B.4 – Example of cause-consequence analysis

The procedure is as follows:

a) Identify the critical (or initiating) event (equivalent to the top event of a fault tree and the initiating event of an event tree).

b) Develop and validate the fault tree for causes of the initiating event as described in Clause B.14. The same symbols are used as in conventional fault tree analysis.

c) Decide the order in which conditions are to be considered. This should be a logical sequence such as the time sequence in which they occur.

d) Construct the pathways for consequences depending on the different conditions. This is similar to an event tree but the split in pathways of the event tree is shown as a box labelled with the particular condition that applies.

e) Provided the failures for each condition box are independent, the probability of each consequence can be calculated. This is achieved by first assigning probabilities to each output of the condition box (using the relevant fault trees as appropriate) The probability of any one sequence leading to a particular consequence is obtained by multiplying the probabilities of each sequence of conditions which terminates in that particular consequence. If more than one sequence ends up with the same consequence, the probabilities from each sequence are added. If there are dependencies between failures of conditions in a sequence (for example a power failure may cause several conditions to fail) then the dependencies should be dealt with prior to calculation.

B.16.5 Output

The output of cause-consequence analysis is a diagrammatic representation of how a system may fail showing both causes and consequences. An estimation of the probability of occurrence of each potential consequence based on analysis of probabilities of occurrence of particular conditions following the critical event.

B.16.6 Strengths and limitations

The advantages of cause-consequence analysis are the same as those of event trees and fault trees combined. In addition, it overcomes some of the limitations of those techniques by being able to analyse events that develop over time. Cause-consequence analysis provides a comprehensive view of the system.

Limitations are that it is more complex than fault tree and event tree analysis, both to construct and in the manner in which dependencies are dealt with during quantification.

B.17 Cause-and-effect analysis

B.17.1 Overview

Cause-and-effect analysis is a structured method to identify possible causes of an undesirable event or problem. It organizes the possible contributory factors into broad categories so that all possible hypotheses can be considered. It does not, however, by itself point to the actual causes, since these can only be determined by real evidence and empirical testing of hypotheses. The information is organized in either a Fishbone (also called Ishikawa) or sometimes a tree diagram (see B.17.4).

B.17.2 Use

Cause-and-effect analysis provides a structured pictorial display of a list of causes of a specific effect. The effect may be positive (an objective) or negative (a problem) depending on context.

It is used to enable consideration of all possible scenarios and causes generated by a team of experts and allows consensus to be established as to the most likely causes which can then be tested empirically or by evaluation of available data. It is most valuable at the beginning of an analysis to broaden thinking about possible causes and then to establish potential hypotheses that can be considered more formally.

Constructing a cause-and-effect diagram can be undertaken when there is need to:

- identify the possible root causes, the basic reasons, for a specific effect, problem or condition;
- sort out and relate some of the interactions among the factors affecting a particular process;
- analyse existing problems so that corrective action can be taken.

Benefits from constructing a cause-and-effect diagram include:

- concentrates review members' attention on a specific problem;
- to help determine the root causes of a problem using a structured approach;
- encourages group participation and utilizes group knowledge for the product or process;
- uses an orderly, easy-to-read format to diagram cause-and-effect relationships;
- indicates possible causes of variation in a process;
- identifies areas where data should be collected for further study.

Cause-and-effect analysis can be used as a method in performing root cause analysis (see Clause B.12).

B.17.3 Input

The input to a cause-and-effect analysis may come from expertise and experience from participants or a previously developed model that has been used in the past.

B.17.4 Process

The cause-and-effect analysis should be carried out by a team of experts knowledgeable with the problem requiring resolution.

The basic steps in performing a cause-and-effect analysis are as follows:

- establish the effect to be analysed and place it in a box. The effect may be positive (an objective) or negative (a problem) depending on the circumstances;
- determine the main categories of causes represented by boxes in the Fishbone diagram. Typically, for a system problem, the categories might be people, equipment, environment, processes, etc. However, these are chosen to fit the particular context;
- fill in the possible causes for each major category with branches and sub-branches to describe the relationship between them;
- keep asking "why?" or "what caused that?" to connect the causes;
- review all branches to verify consistency and completeness and ensure that the causes apply to the main effect;
- identify the most likely causes based on the opinion of the team and available evidence.

The results are normally displayed as either a Fishbone or Ishikawa diagram or tree diagram. The Fishbone diagram is structured by separating causes into major categories (represented by the lines off the fish backbone) with branches and sub-branches that describe more specific causes in those categories.

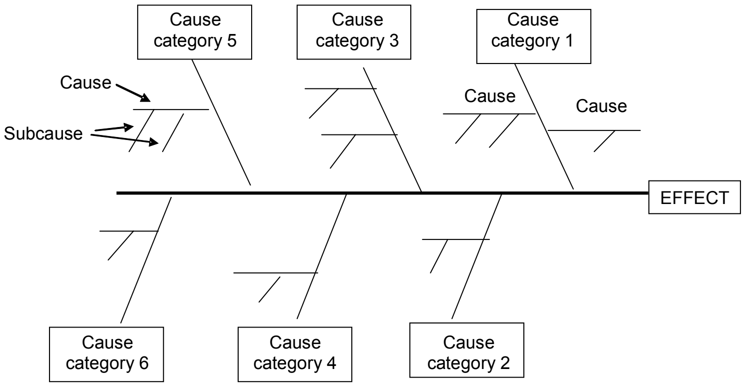


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Figure B.5 – Example of Ishikawa or Fishbone diagram

The tree representation is similar to a fault tree in appearance, although it is often displayed with the tree developing from left to right rather than down the page. However, it cannot be quantified to produce a probability of the head event as the causes are possible contributory factors rather than failures with a known probability of occurrence

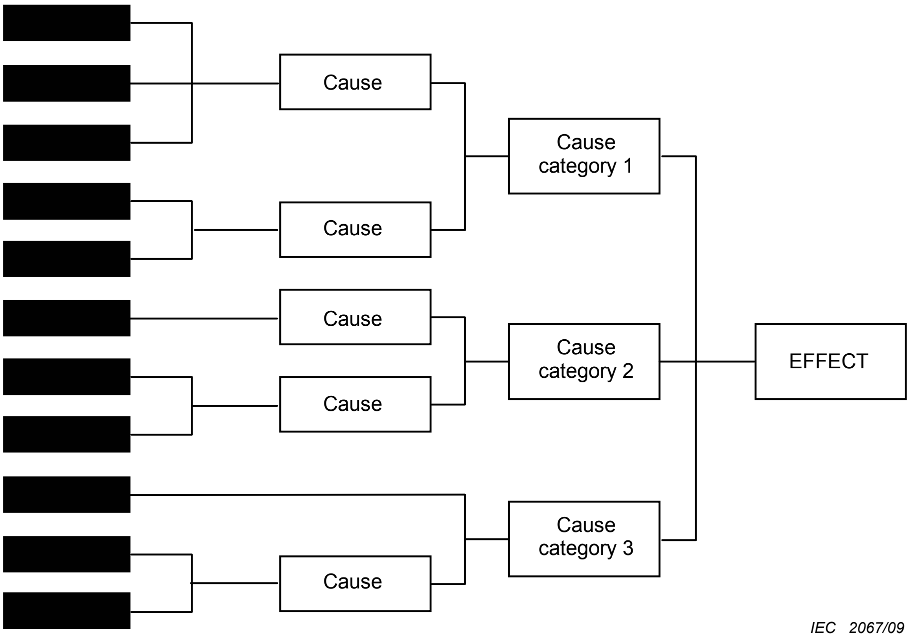

Figure B.6 – Example of tree formulation of cause-and-effect analysis

Cause-and-effect diagrams are generally used qualitatively. It is possible to assume the probability of the problem is 1 and assign probabilities to generic causes, and subsequently to the sub-causes, on the basis of the degree of belief about their relevance. However, contributory factors often interact and contribute to the effect in complex ways which make quantification invalid

B.17.5 Output

The output from a cause-and-effect analysis is a Fishbone or tree diagram that shows the possible and likely causes. This has then to be verified and tested empirically before recommendations can be made.

B.17.6 Strengths and limitations

Strengths include:

- involvement of applicable experts working in a team environment;
- structured analysis;
- consideration of all likely hypotheses;
- graphical easy-to-read illustration of results;
- areas identified where further data is needed;
- can be used to identify contributory factors to wanted as well as unwanted effects. Taking a positive focus on an issue can encourage greater ownership and participation.

Limitations include:

- the team may not have the necessary expertise;
- it is not a complete process in itself and needs to be a part of a root cause analysis to produce recommendations;
- it is a display technique for brainstorming rather than a separate analysis technique;
- the separation of causal factors into major categories at the start of the analysis means that interactions between the categories may not be considered adequately, e.g. where

equipment failure is caused by human error, or human problems are caused by poor design.

B.18 Layers of protection analysis (LOPA)

B.18.1 Overview

LOPA is a semi-quantitative method for estimating the risks associated with an undesired event or scenario. It analyses whether there are sufficient measures to control or mitigate the risk.

A cause-consequence pair is selected and the layers of protection which prevent the cause leading to the undesired consequence are identified. An order of magnitude calculation is carried out to determine whether the protection is adequate to reduce risk to a tolerable level.

B.18.2 Uses

LOPA may be used qualitatively simply to review the layers of protection between a hazard or causal event and an outcome. Normally a semi-quantitative approach would be applied to add more rigour to screening processes for example following HAZOP or PHA.

LOPA provides a basis for the specification of independent protection layers (IPLs) and safety integrity levels (SIL levels) for instrumented systems, as described in the IEC 61508 series and in IEC 61511, in the determination of safety integrity level (SIL) requirements for safety instrumented systems. LOPA can be used to help allocate risk reduction resources effectively by analysing the risk reduction produced by each layer of protection.

B.18.3 Inputs

Inputs to LOPA include

- basic information on risks including hazards, causes and consequences such as provided by a PHA;
- information on controls in place or proposed;
- causal event frequencies, and protection layer failure probabilities, measures of consequence and a definition of tolerable risk;
- initiating cause frequencies, protection layer failure probabilities, measures of consequence and a definition of tolerable risk.

B.18.4 Process

LOPA is carried out using a team of experts who apply the following procedure:

- identify initiating causes for an undesired outcome and seek data on their frequencies and consequences;
- select a single cause-consequence pair;
- layers of protection which prevent the cause proceeding to the undesired consequence are identified and analysed for their effectiveness;
- identify independent protection layers (IPLs) (not all layers of protection are IPLs);
- estimate the probability of failure of each IPL;
- the frequency initiating cause is combined with the probabilities of failure of each IPL and the probabilities of any conditional modifiers (a conditional modifier is for example whether a person will be present to be impacted) to determine the frequency of occurrence of the undesired consequence. Orders of magnitude are used for frequencies and probabilities;

- the calculated level of risk is compared with risk tolerance levels to determine whether further protection is required.

An IPL is a device system or action that is capable of preventing a scenario proceeding to its undesired consequence, independent of the causal event or any other layer of protection associated with the scenario.

IPLs include:

- design features;
- physical protection devices;
- interlocks and shutdown systems;
- critical alarms and manual intervention;
- post event physical protection;
- emergency response systems (procedures and inspections are not IPLs).

B.18.5 Output

Recommendations for any further controls and the effectiveness of these controls in reducing risk shall be given.

LOPA is one of the techniques used for SIL assessment when dealing with safety related/instrumented systems

B.18.6 Strengths and limitations

Strengths include:

- it requires less time and resources than a fault tree analysis or fully quantitative risk assessment but is more rigorous than qualitative subjective judgments;
- it helps identify and focus resources on the most critical layers of protection;
- it identifies operations, systems and processes for which there are insufficient safeguards;
- it focuses on the most serious consequences.

Limitations include:

- LOPA focuses on one cause-consequence pair and one scenario at a time. Complex interactions between risks or between controls are not covered;
- quantified risks may not account for common mode failures;
- LOPA does not apply to very complex scenarios where there are many cause-consequence pairs or where there are a variety of consequences affecting different stakeholders.

B.18.7 Reference documents

IEC 61508 (all parts)*, Functional safety of electrical/electronic/programmable electronic safety-related systems*

IEC 61511, *Functional safety – Safety instrumented systems for the process industry sector*

B.19 Decision tree analysis

B.19.1 Overview

A decision tree represents decision alternatives and outcomes in a sequential manner which takes account of uncertain outcomes. It is similar to an event tree in that it starts from an initiating event or an initial decision and models different pathways and outcomes as a result of events that may occur and different decisions that may be made.

B.19.2 Use

A decision tree is used in managing project risks and in other circumstances to help select the best course of action where there is uncertainty. The graphical display can also help communicate reasons for decisions.

B.19.3 Input

A project plan with decision points. Information on possible outcomes of decisions and on chance events which might affect decisions.

B.19.4 Process

A decision tree starts with an initial decision, for example to proceed with project A rather than project B. As the two hypothetical projects proceed, different events will occur and different predictable decisions will need to be made. These are represented in tree format, similar to an event tree. The probability of the events can be estimated together with the cost or utility of the final outcome of the pathway.

Information concerning the best decision pathway is logically that which produces the highest expected value calculated as the product of all the conditional probabilities along the pathway and the outcome value.

B.19.5 Outputs

Outputs include:

- a logical analysis of the risk displaying different options that may be taken
- a calculation of the expected value for each possible path

B.19.6 Strengths and limitations

Strengths include:

- they provide a clear graphical representation of the details of a decision problem;
- they enable a calculation of the best pathway through a situation.

Limitations include:

- large decisions trees may become too complex for easy communication with others;
- there may be a tendency to oversimplify the situation so as to be able to represent it as a tree diagram.

B.20 Human reliability assessment (HRA)

B.20.1 Overview

Human reliability assessment (HRA) deals with the impact of humans on system performance and can be used to evaluate human error influences on the system.

Many processes contain potential for human error, especially when the time available to the operator to make decisions is short. The probability that problems will develop sufficiently to become serious can be small. Sometimes, however, human action will be the only defence to prevent an initial failure progressing towards an accident.

The importance of HRA has been illustrated by various accidents in which critical human errors contributed to a catastrophic sequence of events. Such accidents are warnings against risk assessments that focus solely on the hardware and software in a system. They illustrate the dangers of ignoring the possibility of human error contribution. Moreover, HRAs are useful in highlighting errors that can impede productivity and in revealing ways in which these errors and other failures (hardware and software) can be "recovered" by the human operators and maintenance personnel.

B.20.2 Use

HRA can be used qualitatively or quantitatively. Qualitatively, it is used to identify the potential for human error and its causes so the probability of error can be reduced. Quantitative HRA is used to provide data on human failures into FTA or other techniques.

B.20.3 Input

Inputs to HRA include:

- information to define tasks that people should perform;
- experience of the types of error that occur in practice and potential for error;
- expertise on human error and its quantification.

B.20.4 Process

The HRA process is as follows:

- **Problem definition**, what types of human involvements are to be investigated/assessed?
- **Task analysis,** how will the task be performed and what type of aids will be needed to support performance?
- **Human error analysis**, how can task performance fail: what errors can occur and how can they be recovered?
- **Representation**, how can these errors or task performance failures be integrated with other hardware, software, and environmental events to enable overall system failure probabilities to be calculated?
- **Screening**, are there any errors or tasks that do not require detailed quantification?
- **Quantification**, how likely are individual errors and failures of tasks?
- **Impact assessment**, which errors or tasks are most important, i.e. which ones have the highest contribution to reliability or risk?
- **Error reduction**, how can higher human reliability be achieved?
- **Documentation**, what details of the HRA need to be documented?

In practice, the HRA process proceeds step-wise although sometimes with parts (e.g. tasks analysis and error identification) proceeding in parallel with one another.

B.20.5 Output

Outputs include:

- a list of errors that may occur and methods by which they can be reduced – preferably through redesign of the system;
- error modes, error types causes and consequences;

- a qualitative or quantitative assessment of the risk posed by the errors.

B.20.6 Strengths and limitations

Strengths of HRA include:

- HRA provides a formal mechanism to include human error in consideration of risks associated with systems where humans often play an important role;
- formal consideration of human error modes and mechanisms can help reduce the probability of failure due to error.

Limitations include:

- the complexity and variability of humans, which make defining simple failure modes and probabilities difficult;
- many activities of humans do not have a simple pass/fail mode. HRA has difficulty dealing with partial failures or failure in quality or poor decision-making.

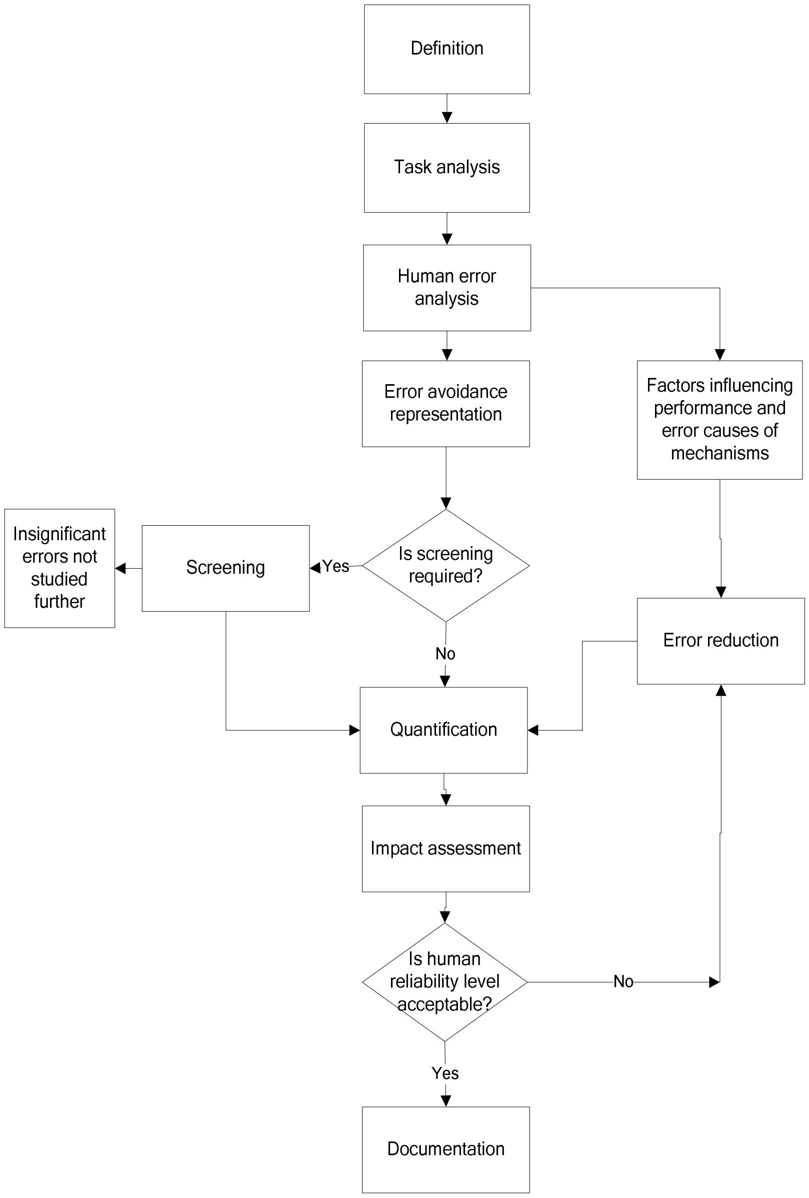

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Figure B.7 – Example of human reliability assessment

B.21 Bow tie analysis

B.21.1 Overview

Bow tie analysis is a simple diagrammatic way of describing and analysing the pathways of a risk from causes to consequences. It can be considered to be a combination of the thinking of a fault tree analysing the cause of an event (represented by the knot of a bow tie) and an event tree analysing the consequences. However the focus of the bow tie is on the barriers between the causes and the risk, and the risk and consequences. Bow tie diagrams can be constructed starting from fault and event trees, but are more often drawn directly from a brainstorming session.

B.21.2 Use

Bow tie analysis is used to display a risk showing a range of possible causes and consequences. It is used when the situation does not warrant the complexity of a full fault tree analysis or when the focus is more on ensuring that there is a barrier or control for each failure pathway. It is useful where there are clear independent pathways leading to failure.

Bow tie analysis is often easier to understand than fault and event trees, and hence can be a useful communication tool where analysis is achieved using more complex techniques.

B.21.3 Input

An understanding is required of information on the causes and consequences of a risk and the barriers and controls which may prevent, mitigate or stimulate it.

B.21.4 Process

The bow tie is drawn as follows:

a) A particular risk is identified for analysis and represented as the central knot of a bow tie.

b) Causes of the event are listed considering sources of risk (or hazards in a safety context).

c) The mechanism by which the source of risk leads to the critical event is identified.

d) Lines are drawn between each cause and the event forming the left-hand side of the bow tie. Factors which might lead to escalation can be identified and included in the diagram.

e) Barriers which should prevent each cause leading to the unwanted consequences can be shown as vertical bars across the line. Where there were factors which might cause escalation, barriers to escalation can also be represented. The approach can be used for positive consequences where the bars reflect ‘controls’ that stimulate the generation of the event.

f) On the right-hand side of the bow tie different potential consequences of the risk are identified and lines drawn to radiate out from the risk event to each potential consequence.

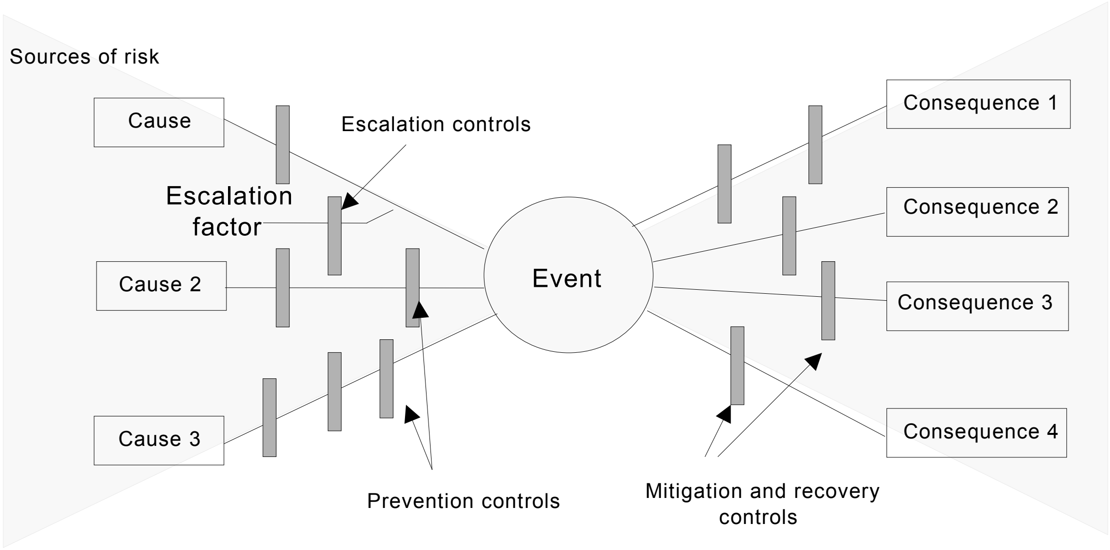
g) Barriers to the consequence are depicted as bars across the radial lines. The approach can be used for positive consequences where the bars reflect ‘controls’ that support the generation of consequences.

h) Management functions which support controls (such as training and inspection) can be shown under the bow tie and linked to the respective control.

Some level of quantification of a bow tie diagram may be possible where pathways are independent, the probability of a particular consequence or outcome is known and a figure can be estimated for the effectiveness of a control. However, in many situations, pathways and barriers are not independent and controls may be procedural and hence the effectiveness unclear. Quantification is often more appropriately carried out using FTA and ETA.

B.21.5 Output

The output is a simple diagram showing main risk pathways and the barriers in place to prevent or mitigate the undesired consequences or stimulate and promote desired consequences.



IEC 2069/09

Figure B.8 – Example bow tie diagram for unwanted consequences

B.21.6 Strengths and limitations

Strengths of bow tie analysis:

- it is simple to understand and gives a clear pictorial representation of the problem;
- it focuses attention on controls which are supposed to be in place for both prevention and mitigation and their effectiveness;
- it can be used for desirable consequences;
- it does not need a high level of expertise to use.

Limitations include:

- it cannot depict where multiple causes occur simultaneously to cause the consequences (i.e. where there are AND gates in a fault tree depicting the left-hand side of the bow);
- it may over-simplify complex situations, particularly where quantification is attempted.

B.22 Reliability centred maintenance

B.22.1 Overview

Reliability centred maintenance (RCM) is a method to identify the policies that should be implemented to manage failures so as to efficiently and effectively achieve the required safety, availability and economy of operation for all types of equipment.

RCM is now a proven and accepted methodology used in a wide range of industries.

RCM provides a decision process to identify applicable and effective preventive maintenance requirements for equipment in accordance with the safety, operational and economic consequences of identifiable failures, and the degradation mechanism responsible for those failures. The end result of working through the process is a judgment as to the necessity of performing a maintenance task or other action such as operational changes. Details regarding the use and application of RCM are provided in IEC 60300-3-11.

B.22.2 Use

All tasks are based on safety in respect of personnel and environment, and on operational or economic concerns. However, it should be noted that the criteria considered will depend on the nature of the product and its application. For example, a production process will need to be economically viable, and may be sensitive to strict environmental considerations, whereas an item of defence equipment should be operationally successful, but may have less stringent safety, economic and environmental criteria. Greatest benefit can be achieved through targeting of the analysis to where failures would have serious safety, environmental, economic or operational effects.

RCM is used to ensure that applicable and effective maintenance is performed, and is generally applied during the design and development phase and then implemented during operation and maintenance.

B.22.3 Input

Successful application of RCM needs a good understanding of the equipment and structure, the operational environment and the associated systems, subsystems and items of equipment, together with the possible failures, and the consequences of those failures.

B.22.4 Process

The basic steps of an RCM programme are as follows:

- initiation and planning;
- functional failure analysis;
- task selection;
- implementation;
- continuous improvement.

RCM is risk based since it follows the basic steps in risk assessment. The type of risk assessment is a failure mode, effect and criticality analysis (FMECA) but requires a specific approach to analysis when used in this context.

Risk identification focuses on situations where potential failures may be eliminated or reduced in frequency and/or consequence by carrying out maintenance tasks. It is performed by identifying required functions and performance standards and failures of equipment and components that can interrupt those functions

Risk analysis consists of estimating the frequency of each failure without maintenance being carried out. Consequences are established by defining failure effects. A risk matrix that combines failure frequency and consequences allows categories for levels of risk to be established.

Risk evaluation is then performed by selecting the appropriate failure management policy for each failure mode.

The entire RCM process is extensively documented for future reference and review. Collection of failure and maintenance-related data enables monitoring of results and implementation of improvements.

B.22.5 Output

RCM provides a definition of maintenance tasks such as condition monitoring, scheduled restoration, scheduled replacement, failure-finding or non preventive maintenance. Other possible actions that can result from the analysismay include redesign, changes to operating or maintenance procedures or additional training. Task intervals and required resources are then identified.

B.22.6 Reference documents

IEC 60300-3-11, *Dependability management – Part 3-11: Application guide – Reliability centred maintenance*

B.23 Sneak analysis (SA)and sneak circuit analysis (SCI)

B.23.1 Overview

Sneak analysis (SA) is a methodology for identifying design errors. A sneak condition is a latent hardware, software or integrated condition that may cause an unwanted event to occur or may inhibit a desired event and is not caused by component failure. These conditions are characterized by their random nature and ability to escape detection during the most rigorous of standardized system tests. Sneak conditions can cause improper operation, loss of system availability, program delays, or even death or injury to personnel.

B.23.2 Use

Sneak circuit analysis (SCA) was developed in the late 1960s for NASA to verify the integrity and functionality of their designs. It served as a useful tool for discovering unintentional electrical circuit paths, and assisted in devising solutions to isolate each function. However, as technology advanced, the tools for sneak circuit analysis also had to advance. Sneak analysis includes and far exceeds the coverage of sneak circuit analysis. It can locate problems in both hardware and software using any technology. The sneak analysis tools can integrate several analyses such as fault trees, failure mode and effects analysis (FMEA), reliability estimates, etc. into a single analysis saving time and project expenses.

B.23.3 Input

Sneak analysis is unique from the design process in that it uses different tools (network trees, forests, and clues or questions to help the analyst identify sneak conditions) to find a specific type of problem. The network trees and forests are topological groupings of the actual system. Each network tree represents a sub-function and shows all inputs that may affect the sub-function output. Forests are constructed by combining the network trees that contribute to a particular system output. A proper forest shows a system output in terms of all of its related inputs. These, along with others, become the input to the analysis.

B.23.4 Process

The basic steps in performing a sneak analysis consist of:

- data preparation;
- construction of the network tree;
- evaluation of network paths;
- final recommendations and report.

B.23.5 Output

A sneak circuit is an unexpected path or logic flow within a system which, under certain conditions, can initiate an undesired function or inhibit a desired function. The path may consist of hardware, software, operator actions, or combinations of these elements. Sneak circuits are not the result of hardware failure but are latent conditions, inadvertently designed into the system, coded into the software program, or triggered by human error. There are four categories of sneak circuits:

a) sneak paths: unexpected paths along which current, energy, or logical sequence flows in an unintended direction;
b) sneak timing: events occurring in an unexpected or conflicting sequence;
c) sneak indications: ambiguous or false displays of system operating conditions that may cause the system or an operator to take an undesired action;
d) sneak labels: incorrect or imprecise labelling of system functions, e.g. system inputs, controls, display buses that may cause an operator to apply an incorrect stimulus to the system.

B.23.6 Strengths and limitations

Strengths include:

- sneak analysis is good for identifying design errors;
- it works best when applied in conjunction with HAZOP;
- it is very good for dealing with systems which have multiple states such as batch and semi-batch plant.

Limitations may include:

- the process is somewhat different depending on whether it is applied to electrical circuits, process plants, mechanical equipment or software;
- the method is dependent on establishing correct network trees.

B.24 Markov analysis

B.24.1 Overview

Markov analysis is used where the future state of a system depends only upon its present state. It is commonly used for the analysis of repairable systems that can exist in multiple states and the use of a reliability block analysis would be unsuitable to adequately analyse the system. The method can be extended to more complex systems by employing higher order Markov processes and is only restricted by the model, mathematical computations and the assumptions.

The Markov analysis process is a quantitative technique and can be discrete (using probabilities of change between the states) or continuous (using rates of change across the states).

While a Markov analysis can be performed by hand, the nature of the techniques lends itself to the use of computer programmes, many of which exist in the market.

B.24.2 Use

The Markov analysis technique can be used on various system structures, with or without repair, including:

- independent components in parallel;
- independent components in series;
- load-sharing system;
- stand-by system, including the case where switching failure can occur;
- degraded systems.

The Markov analysis technique can also be used for calculating availability, including taking into account the spares components for repairs.

B.24.3 Input

The inputs essential to a Markov analysis are as follows:

- list of various states that the system, sub-system or component can be in (e.g. fully operational, partially operation (i.e. a degraded state), failed state, etc);
- a clear understanding of the possible transitions that are necessary to be modelled. For example, failure of a car tyre needs to consider the state of the spare wheel and hence the frequency of inspection;
- rate of change from one state to another, typically represented by either a probability of change between states for discrete events, or failure rate (λ) and/or repair rate (μ) for continuous events.

B.24.4 Process

The Markov analysis technique is centred around the concept of "states", e.g. "available" and "failed", and the transition between these two states over time based on a constant probability of change. A stochastic transitional probability matrix is used to describe the transition between each of the states to allow the calculation of the various outputs.

To illustrate the Markov analysis technique, consider a complex system that can be in only three states; functioning, degraded and failed, defined as states S1, S2, S3 respectively. Each day, the system exists in one of these three states. Table B.3 shows the probability that tomorrow, the system is in state S*i* where *i* can be 1, 2 or 3.

Table B.2 – Markov matrix

		State today		
		S1	S2	S3
State tomorrow	S1	0,95	0,3	0,2
	S2	0,04	0,65	0,6
	S3	0,01	0,05	0,2

This array of probabilities is called a Markov matrix, or transition matrix. Notice that the sum for each of the columns is 1 as they are the sum of all the possible outcomes in each case. The system, can also be represented by a Markov diagram where the circles represent the states, and the arrows represent the transition, together with the accompanying probability.

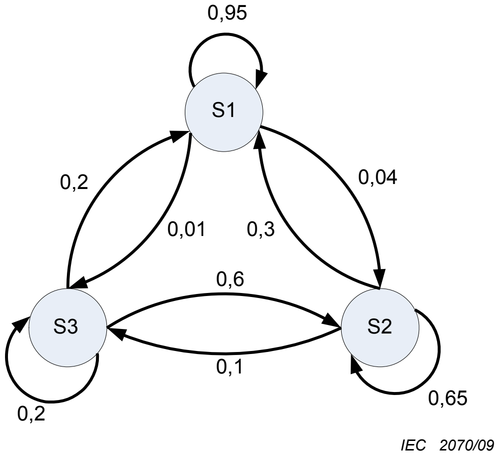


Figure B.9 – Example of system Markov diagram

The arrows from a state to itself are not usually shown, but are shown within these examples for completeness.

Let P*i* represent the probability of finding the system in state *i* for *i* = 1, 2, 3, then the simultaneous equations to be solved are:

$$P1 = 0{,}95\ P1 + 0{,}30\ P2 + 0{,}20\ P3 \qquad (B.1)$$

$$P2 = 0{,}04\ P1 + 0{,}65\ P2 + 0{,}60\ P3 \qquad (B.2)$$

$$P3 = 0{,}01\ P1 + 0{,}05\ P2 + 0{,}20\ P3 \qquad (B.3)$$

These three equations are not independent and will not solve the three unknowns. The following equation should be used and one of the above equations discarded.

$$1 = P1 + P2 + P3 \qquad (B.4)$$

The solution is 0,85, 0,13, and 0.02 for the respective states 1, 2, 3. The system is fully functioning for 85 % of the time, in the degraded state for 13 % of the time and failed for 2 % of the time.

Consider two items operating in parallel with either required to be operational for the system to function. The items can either be operational or failed and the availability of the system is dependent upon the status of the items.

The states can be considered as:

State 1 Both items are functioning correctly;

State 2 One item has failed and is undergoing repair, the other is functioning;

State 3 Both items have failed and one is undergoing repair.

If the continuous failure rate for each item is assumed to be λ and the repair rate to be μ, then the state transition diagram is:

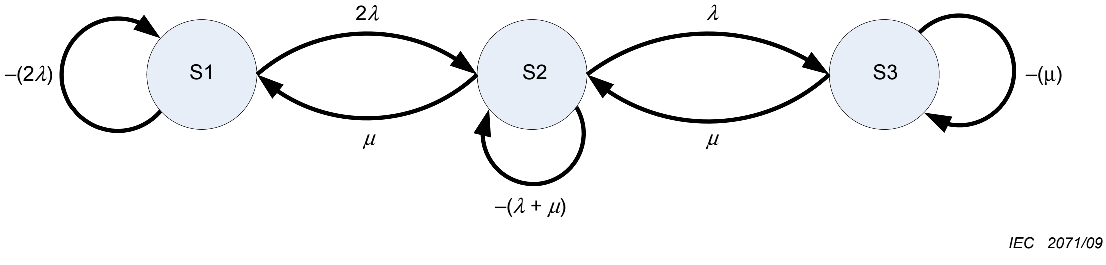


Figure B.10 – Example of state transition diagram

Note that the transition from state 1 to state 2 is 2λ as failure of either of the two items will take the system to state 2.

Let P*i*(*t*) be the probability of being in an initial state *i* at time *t*; and

Let P*i*(*t* + *δt*) be the probability of being in a final state at time *t* + *δt*

The transition probability matrix becomes:

Table B.3 – Final Markov matrix

		Initial state		
		$P1(t)$	$P2(t)$	$P3(t)$
	$P1(t + \delta t)$	-2λ	μ	0
Final state	$P2(t + \delta t)$	2λ	$-(\lambda + \mu)$	μ
	$P3(t + \delta t)$	0	λ	$-\mu$

It is worth noting that the zero values occur as it is not possible to move from state 1 to state 3 or from state 3 to state 1. Also, the columns sum to zero when specifying rates.

The simultaneous equations become:

$$dP1/dt = -2\lambda P1(t) + \mu P2(t) \qquad \text{(B.5)}$$

$$dP2/dt = 2\lambda P1(t) + -(\lambda + \mu) P2(t) + \mu P3(t) \qquad \text{(B.6)}$$

$$dP3/dt = \lambda P2(t) + -\mu P3(t) \qquad \text{(B.7)}$$

For simplicity, it will be assumed that the availability required is the steady state availability.

When δt tends to infinity, dPi/dt will tend to zero and the equations become easier to solve. The additional equation as shown in Equation (B.4) above should also be used:

Now the equation $A(t) = P1(t) + P2(t)$ can be expressed as:

$A = P1 + P2$

Hence $A = (\mu^2 + 2\lambda\mu) / (\mu^2 + 2\lambda\mu + \lambda^2)$

B.24.5 Output

The output from a Markov analysis is the various probabilities of being in the various states, and therefore an estimate of the failure probabilities and/or availability, one of the essential components of a system.

B.24.6 Strengths and limitations

Strengths of a Markov analysis include:

- ability to calculate the probabilities for systems with a repair capability and multiple degraded states.

Limitations of a Markov analysis include:

- assumption of constant probabilities of change of state; either failure or repairs;
- all events are statistically independent since future states are independent of all past states, except for the state immediately prior;
- needs knowledge of all probabilities of change of state;
- knowledge of matrix operations;
- results are hard to communicate with non-technical personnel.

B.24.7 Comparisons

Markov analysis is similar to a Petri-Net analysis by being able to monitor and observe system states, although different since Petri-Net can exist in multiple states at the same time.

B.24.8 Reference documents

IEC 61078, *Analysis techniques for dependability – Reliability block diagram and boolean methods*

IEC 61165, *Application of Markov techniques*

ISO/IEC 15909 (all parts)*, Software and systems engineering – High-level Petri nets*

B.25 Monte Carlo simulation

B.25.1 Overview

Many systems are too complex for the effects of uncertainty on them to be modelled using analytical techniques, but they can be evaluated by considering the inputs as random variables and running a number N of calculations (so-called simulations) by sampling the input in order to obtain N possible outcomes of the wanted result.

This method can address complex situations that would be very difficult to understand and solve by an analytical method. Systems can be developed using spreadsheets and other conventional tools, but more sophisticated tools are readily available to assist with more complex requirements, many of which are now relatively inexpensive. When the technique was first developed, the number of iterations required for Monte Carlo simulations made the process slow and time consuming, but advances in computers and theoretical developments, such as Latin-hypercube sampling, have made processing time almost insignificant for many applications.

B.25.2 Use

Monte Carlo simulation provides a means of evaluating the effect of uncertainty on systems in a wide range of situations. It is typically used to evaluate the range of possible outcomes and the relative frequency of values in that range for quantitative measures of a system such as cost, duration, throughput, demand and similar measures. Monte Carlo simulation may be used for two different purposes:

- uncertainty propagation on conventional analytical models;
- probabilistic calculations when analytical techniques do not work.

B.25.3 Input

The input to a Monte Carlo simulation is a good model of the system and information on the types of inputs, the sources of uncertainty that are to be represented and the required output. Input data with uncertainty is represented as random variables with distributions which are more or less spread according to the level of uncertainties. Uniform, triangular, normal and log normal distributions are often used for this purpose.

B.25.4 Process

The process is as follows:

a) A model or algorithm is defined which represents as closely as possible the behaviour of the system being studied.

b) The model is run multiple times using random numbers to produce outputs of the model (simulations of the system); Where the application is to model the effects of uncertainty the model is in the form of an equation providing the relationship between input parameters and an output. The values selected for the inputs are taken from appropriate probability distributions that represent the nature of the uncertainty in these parameters.

c) In either case a computer runs the model multiple times (often up to 10,000 times) with different inputs and produces multiple outputs. These can be processed using conventional statistics to provide information such as average values, standard deviation, confidence intervals.

An example of a simulation is given below.

Consider the case of two items operating in parallel and only one is required for the system to function. The first item has a reliability of 0,9 and the other 0,8.

It is possible to construct a spreadsheet with the following columns.

Table B.4 – Example of Monte Carlo simulation

	Item 1		**Item 2**		
Simulation number	**Random number**	**Functions?**	**Random number**	**Functions?**	**System**
1	0,577 243	YES	0,059 355	YES	1
2	0,746 909	YES	0,311 324	YES	1
3	0,541 728	YES	0,919 765	NO	1
4	0,423 274	YES	0,643 514	YES	1
5	0,917 776	NO	0,539 349	YES	1
6	0,994 043	NO	0,972 506	NO	0
7	0,082 574	YES	0,950 241	NO	1
8	0,661 418	YES	0,919 868	NO	1
9	0,213 376	YES	0,367 555	YES	1
10	0,565 657	YES	0,119 215	YES	1

The random generator creates a number between 0 and 1 which is used to compare with the probability of each item to determine if the system is operational. With just 10 runs, the result of 0,9 should not be expected to be an accurate result. The usual approach is to build in a calculator to compare the total result as the simulation progresses to achieve the level of accuracy required. In this example, a result of 0,979 9 was achieved after 20 000 iterations.

The above model can be extended in a number of ways. For example:

- by extending the model itself (such as considering the second item becoming immediately operational only when the first item fails);
- by changing the fixed probability to a variable (a good example is the triangular distribution) when the probability cannot be accurately defined;
- using failure rates combined with the randomizer to derive a time of failure (exponential, Weibull, or other suitable distribution) and building in repair times.

Applications include, amongst other things, the assessment of uncertainty in financial forecasts, investment performance, project cost and schedule forecasts, business process interruptions and staffing requirements.

Analytical techniques are not able to provide relevant results or when there is uncertainty in the input data and so in the outputs.

B.25.5 Output

The output could be a single value, as determined in the above example, it could be a result expressed as the probability or frequency distribution or it could be the identification of the main functions within the model that has the greatest impact on the output.

In general, a Monte Carlo simulation will be used to assess either the entire distribution of outcomes that could arise or key measures from a distribution such as:

- the probability of a defined outcome arising;
- the value of an outcome in which the problem owners have a certain level of confidence that it will not be exceeded or beaten, a cost that there is less than a 10 % chance of exceeding or a duration that is 80 % certain to be exceeded.

An analysis of the relationships between inputs and outputs can throw light on the relative significance of the factors at work and identify useful targets for efforts to influence the uncertainty in the outcome.

B.25.6 Strengths and limitations

Strengths of the Monte Carlo analysis include the following:

- the method can, in principle, accommodate any distribution in an input variable, including empirical distributions derived from observations of related systems;
- models are relatively simple to develop and can be extended as the need arises;
- any influences or relationships arising in reality can be represented, including subtle effects such as conditional dependencies;
- sensitivity analysis can be applied to identify strong and weak influences;
- models can be easily understood as the relationship between inputs and outputs is transparent;
- efficient behavioural models such as Petri Nets (future IEC 62551) are available which prove to be very efficient for Monte Carlo simulation purposes;
- provides a measure of the accuracy of a result;
- software is readily available and relatively inexpensive.

Limitations are as follows:

- the accuracy of the solutions depends upon the number of simulations which can be performed (this limitation is becoming less important with increased computer speeds);
- it relies on being able to represent uncertainties in parameters by a valid distribution;
- large and complex models may be challenging to the modeller and make it difficult for stakeholders to engage with the process;
- the technique may not adequately weigh high-consequence/low probability events and therefore not allow an organization's risk appetite to be reflected in the analysis.

B.25.7 Reference documents

IEC 61649, *Weibull analysis*

IEC 62551, *Analysis techniques for dependability – Petri net techniques*[1]

ISO/IEC Guide 98-3:2008, *Uncertainty measurement – Part 3: Guide to the of uncertainty in measurement (GUM:1995)*

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[1] Currently under consideration.

B.26 Bayesian statistics and Bayes Nets

B.26.1 Overview

Bayesian statistics are attributed to the Reverend Thomas Bayes. Its premise is that any already known information (the Prior) can be combined with subsequent measurement (the Posterior) to establish an overall probability. The general expression of the Bayes Theorem can be expressed as:

$$\mathrm{P}(A \mid B) = \{\mathrm{P}(A)\mathrm{P}(B \mid A)\} / \sum_i \mathrm{P}(B \mid \mathrm{E}_i)\mathrm{P}(\mathrm{E}_i)$$

where

the probability of X is denoted by P(X);

the probability of X on the condition that Y has occurred is denoted by P(X|Y); and

E_i is the ith event.

In its simplest form this reduces to $\mathrm{P}(A|B) = \{\mathrm{P}(A)\mathrm{P}(B|A)\} / \mathrm{P}(B)$.

Bayesian statistics differs from classical statistics in that is does not assume that all distribution parameters are fixed, but that parameters are random variables. A Bayesian probability can be more easily understood if it is considered as a person's degree of belief in a certain event as opposed to the classical which is based upon physical evidence. As the Bayesian approach is based upon the subjective interpretation of probability, it provides a ready basis for decision thinking and the development of Bayesian nets (or Belief Nets, belief networks or Bayesian networks).

Bayes nets use a graphical model to represent a set of variables and their probabilistic relationships. The network is comprised of nodes that represent a random variable and arrows which link a parent node to a child node, (where a parent node is a variable that directly influences another (child) variable).

B.26.2 Use

In recent years, the use of Bays' theory and Nets has become widespread partly because of their intuitive appeal and also because of the availability of software computing tools. Bayes nets have been used on a wide range of topics: medical diagnosis, image modelling, genetics, speech recognition, economics, space exploration and in the powerful web search engines used today. They can be valuable in any area where there is the requirement for finding out about unknown variables through the utilization of structural relationships and data. Bayes nets can be used to learn causal relationships to give an understanding about a problem domain and to predict the consequences of intervention.

B.26.3 Input

The inputs are similar to the inputs for a Monte Carlo model. For a Bayes net, examples of the steps to be taken include the following:

- define system variables;
- define causal links between variables;
- specify conditional and prior probabilities;
- add evidence to net;
- perform belief updating;
- extract posterior beliefs.

B.26.4 Process

Bayes theory can be applied in a wide variety of ways. This example will consider the creation of a Bayes table where a medical test is used to determine if the patient has a disease. The belief before taking the test is that 99 % of the population do not have this disease and 1 % have the disease, i.e the Prior information. The accuracy of the test has shown that if the person has the disease, the test result is positive 98 % of the time. There is also a probability that if you do not have the disease, the test result is positive 10 % of the time. The Bayes table provides the following information:

Table B.5 – Bayes' table data

	PRIOR	PROBABILITY	PRODUCT	POSTERIOR
Have disease	0,01	0,98	0,009 8	0,090 1
No disease	0,99	0,10	0,099 0	0,909 9
SUM	1		0,108 8	1

Using Bayes rule, the product is determined by combining the prior and probability. The posterior is found by dividing the product value by the product total. The output shows that a positive test result indicates that the prior has increased from 1 % to 9 % . More importantly, there is a strong chance that even with a positive test, having the disease is unlikely. Examining the equation (0,01×0,98)/((0,01×0,98)+(0,99×0,1)) shows that the 'no disease-positive result' value plays a major role in the posterior values.

Consider the following Bayes net:

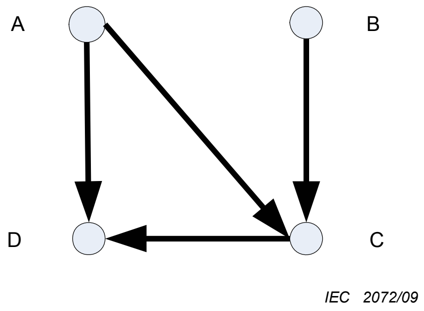


Figure B.11 – Sample Bayes' net

With the conditional prior probabilities defined within the following tables and using the notation that Y indicates positive and N indicates negative, the positive could be "have disease" as above, or could be High and N could be Low.

Table B.6 – Prior probabilities for nodes A and B

P(A = Y)	P(A = N)	P(B = Y)	P(B = N)
0,9	0,1	0,6	0,4

Table B.7 – Conditional probabilities for node C with node A and node B defined

A	B	P(C = Y)	P(C = N)
Y	Y	0,5	0,5
Y	N	0,9	0,1
N	Y	0,2	0,8

N	*N*	0,7	0,3

Table B.8 – Conditional probabilities for node D with node A and node C defined

A	*C*	$P(D = Y)$	$P(D = N)$
Y	*Y*	0,6	0,4
Y	*N*	1,0	0,0
N	*Y*	0,2	0,8
N	*N*	0,6	0,4

To determine the posterior probability of $P(A|D=N,C=Y)$, it is necessary to first calculate $P(A,B|D=N,C=Y)$.

Using Bayes' rule, the value $P(D|A,C)P(C|A,B)P(A)P(B)$ is determined as shown below and the last column shows the normalized probabilities which sum to 1 as derived in the previous example (result rounded).

Table B.9 – Posterior probability for nodes A and B with node D and node C defined

A	*B*	$P(D|A,C)P(C|A,B)P(A)P(B)$	$P(A,B|D=N,C=Y)$
Y	*Y*	0,4 × 0,5 × 0,9 × 0,6 = 0,110	0,4
Y	*N*	0,4 × 0,9 × 0,9 × 0,4 = 0,130	0,48
N	*Y*	0,8 × 0,2 × 0,1 × 0,6 = 0,010	0,04
N	*N*	0,8 × 0,7 × 0,1 × 0,4 = 0,022	0,08

To derive $P(A|D=N,C=Y)$, all values of *B* need to be summed:

Table B.10 – Posterior probability for node A with node D and node C defined

$P(A=Y|D=N,C=Y)$	$P(A=N|D=N,C=Y)$
0,88	0,12

This shows that the prior for $P(A=N)$ has increased from 0,1 to a posterior of 0,12 which is only a small change. On the other hand, $P(B=N|D=N,C=Y)$ has changed from 0,4 to 0,56 which is a more significant change.

B.26.5 Outputs

The Bayesian approach can be applied to the same extent as classical statistics with a wide range of outputs, e.g. data analysis to derive point estimators and confidence intervals. Its recent popularity is in relation to Bayes nets to derive posterior distributions. The graphical output provides an easily understood model and the data can be readily modified to consider correlations and sensitivity of parameters.

B.26.6 Strengths and limitations

Strengths:

- all that is needed is knowledge on the priors;
- inferential statements are easy to understand;
- Bayes' rule is all that is required;
- it provides a mechanism for using subjective beliefs in a problem.

Limitations:

- defining all interactions in Bayes nets for complex systems is problematic;
- Bayesian approach needs the knowledge of a multitude of conditional probabilities which are generally provided by expert judgment. Software tools can only provide answers based on these assumptions.

B.27 FN curves

B.27.1 Overview

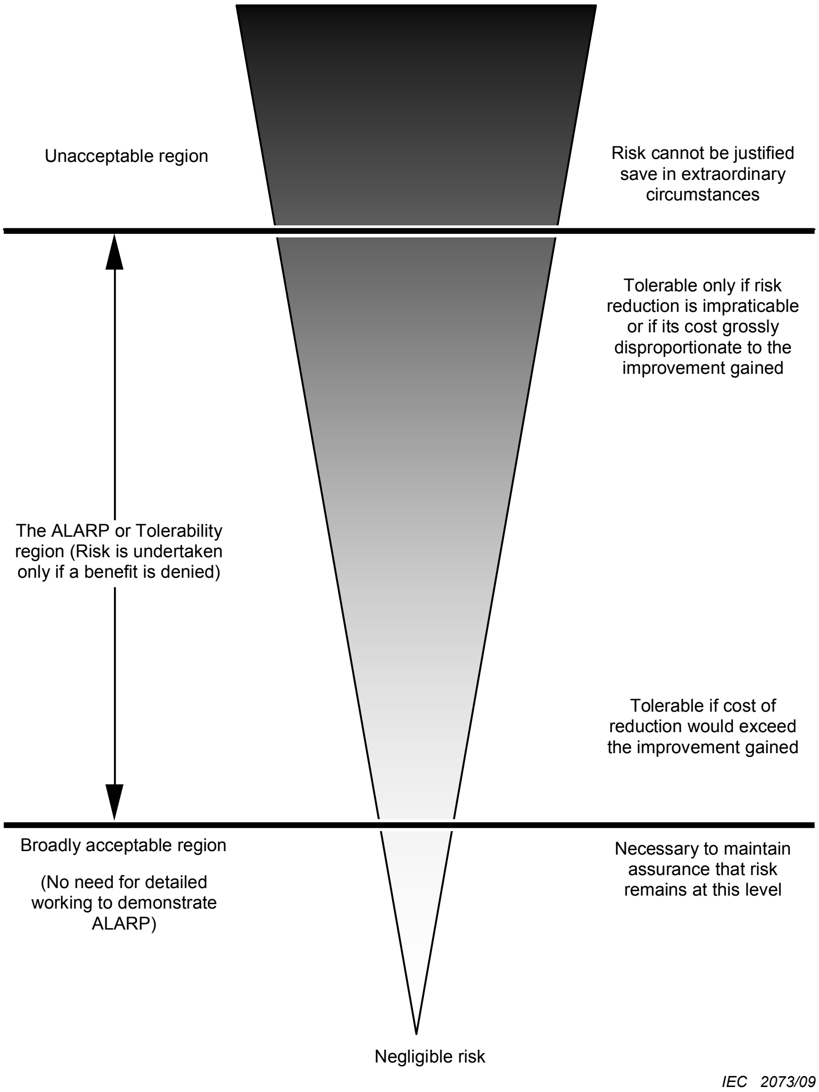


Figure B.12 – The ALARP concept

FN curves are a graphical representation of the probability of events causing a specified level of harm to a specified population. Most often they refer to the frequency of a given number of casualties occurring.

FN curves show the cumulative frequency (*F*) at which *N* or more members of the population that will be affected. High values of *N* that may occur with a high frequency *F* are of significant interest because they may be socially and politically unacceptable.

B.27.2 Use

FN curves are a way of representing the outputs of risk analysis. Many events have a high probability of a low consequence outcome and a low probability of a high consequence outcome. The FN curves provide a representation of the level of risk that is a line describing this range rather than a single point representing one consequence probability pair.

FN curves may be used to compare risks, for example to compare predicted risks against criteria defined as an FN curve, or to compare predicted risks with data from historical incidents, or with decision criteria (also expressed as an F/N curve).

FN curves can be used either for system or process design, or for management of existing systems.

B.27.3 Input

The inputs are either:

- sets of the probability consequence pairs over a given period of time;
- the output of data from a quantitative risk analysis giving estimated probabilities for specified numbers of casualties;
- data from both historical records and a quantitative risk analysis.

B.27.4 Process

The available data is plotted onto a graph with the number of casualties (to a specified level of harm, i.e. death) forming the abscissa with the probability of *N* or more casualties forming the ordinate. Because of the large range of values, both axes are normally on logarithmic scales.

FN curves may be constructed statistically using “real” numbers from past losses or they can be calculated from simulation model estimates. The data used and assumptions made may mean that these two types of FN curve give different information and should be used separately and for different purposes. In general, theoretical FN curves are most useful for system design, and statistical FN curves are most useful for management of a particular existing system.

Both derivation approaches can be very time-consuming so it is not uncommon to use a mixture of both. Empirical data will then form fixed points of precisely known casualties that occurred in known accidents/incident in a specified period of time and the quantitative risk analysis providing other points by extrapolation or interpolation.

The need to consider low-frequency, high-consequence accidents may require consideration of long periods of time to gather enough data for a proper analysis. This in turn may make the available data suspect if the initiating events happen to change over time.

B.27.5 Output

A line representing risk across a range of values of consequence that can be compared with criteria that are appropriate for the population being studied and the specified level of harm.

B.27.6 Strengths and limitations

FN curves are a useful way of presenting risk information that can be used by managers and system designers to help make decisions about risk and safety levels. They are a useful way of presenting both frequency and consequence information in an accessible format.

FN curves are appropriate for comparison of risks from similar situations where sufficient data is available. They should not be used to compare risks of different types with varying characteristics in circumstances where quantity and quality of data varies.

A limitation of FN curves is that they do not say anything about the range of effects or outcomes of incidents other than the number of people impacted, and there is no way of identifying the different ways in which the level of harm may have occurred. They map a particular consequence type, usually harm to people. FN curves are not a risk assessment method, but one way of presenting the results of risk assessment.

They are a well established method for presenting risk assessment results but require preparation by skilled analysts and are often difficult for non specialists to interpret and evaluate

B.28 Risk indices

B.28.1 Overview

A risk index is a semi-quantitative measure of risk which is an estimate derived using a scoring approach using ordinal scales. Risk indices can be used to rate a series of risks using similar criteria so that they can be compared. Scores are applied to each component of risk, for example contaminant characteristics (sources), the range of possible exposure pathways and the impact on the receptors.

Risk indices are essentially a qualitative approach to ranking and comparing risks. While numbers are used, this is simply to allow for manipulation. In many cases where the underlying model or system is not well known or not able to be represented, it is better to use a more overtly qualitative approach.

B.28.2 Use

Indices can be used for classifying different risks associated with an activity if the system is well understood. They permit the integration of a range of factors which have an impact on the level of risk into a single numerical score for level of risk

Indices are used for many different types of risk usually as a scoping device for classifying risk according to level of risk. This may be used to determine which risks need further in-depth and possibly quantitative assessment.

B.28.3 Input

The inputs are derived from analysis of the system, or a broad description of the context. This requires a good understanding of all the sources of risk, the possible pathways and what might be affected. Tools such as fault tree analysis, event tree analysis and general decision analysis can be used to support the development of risk indices.

Since the choice of ordinal scales is, to some extent, arbitrary, sufficient data is needed to validate the index.

B.28.4 Process

The first step is to understand and describe the system. Once the system has been defined, scores are developed for each component in such a way that they can be combined to provide a composite index. For example, in an environmental context, the sources, pathway and receptor(s) will be scored, noting that in some cases there may be multiple pathways and receptors for each source. The individual scores are combined according to a scheme that takes account of the physical realities of the system. It is important that the scores for each part of the system (sources, pathways and receptors) are internally consistent and maintain their correct relationships. Scores may be given for components of risk (e.g. probability, exposure, consequence) or for factors which increase risk.

Scores may be added, subtracted, multiplied and/or divided according to this high level model. Cumulative effects can be taken into account by adding scores (for example, adding scores for different pathways). It is strictly not valid to apply mathematical formulae to ordinal scales. Therefore, once the scoring system has been developed, the model should be validated by applying it to a known system. Developing an index is an iterative approach and several different systems for combining the scores may be tried before the analyst is comfortable with the validation.

Uncertainty can be addressed by sensitivity analysis and varying scores to find out which parameters are the most sensitive.

B.28.5 Output

The output is a series of numbers (composite indices) that relate to a particular source and which can be compared with indices developed for other sources within the same system or which can be modelled in the same way.

B.28.6 Strengths and limitations

Strengths:

- indices can provide a good tool for ranking different risks;
- they allow multiple factors which affect the level of risk to be incorporated into a single numerical score for the level of risk.

Limitations:

- if the process (model) and its output are not well validated, the results may be meaningless. The fact that the output is a numerical value for risk may be misinterpreted and misused, for example in subsequent cost/benefit analysis;
- in many situations where indices are used, there is no fundamental model to define whether the individual scales for risk factors are linear, logarithmic or of some other form, and no model to define how factors should be combined. In these situations, the rating is inherently unreliable and validation against real data is particularly important.

B.29 Consequence/probability matrix

B.29.1 Overview

The consequence/probability matrix is a means of combining qualitative or semi-quantitative ratings of consequence and probability to produce a level of risk or risk rating.

The format of the matrix and the definitions applied to it depend on the context in which it is used and it is important that an appropriate design is used for the circumstances.

B.29.2 Use

A consequence/probability matrix is used to rank risks, sources of risk or risk treatments on the basis of the level of risk. It is commonly used as a screening tool when many risks have been identified, for example to define which risks need further or more detailed analysis, which risks need treatment first, or which need to be referred to a higher level of management. It may also be used to select which risks need not be considered further at this time. This kind of risk matrix is also widely used to determine if a given risk is broadly acceptable, or not acceptable (see 5.4) according to the zone where it is located on the matrix.

The consequence/probability matrix may also be used to help communicate a common understanding for qualitative levels of risks across the organization. The way risk levels are set and decision rules assigned to them should be aligned with the organization's risk appetite.

A form of consequence/probability matrix is used for criticality analysis in FMECA or to set priorities following HAZOP. It may also be used in situations where there is insufficient data for detailed analysis or the situation does not warrant the time and effort for a more quantitative analysis

B.29.3 Input

Inputs to the process are customized scales for consequence and probability and a matrix which combines the two.

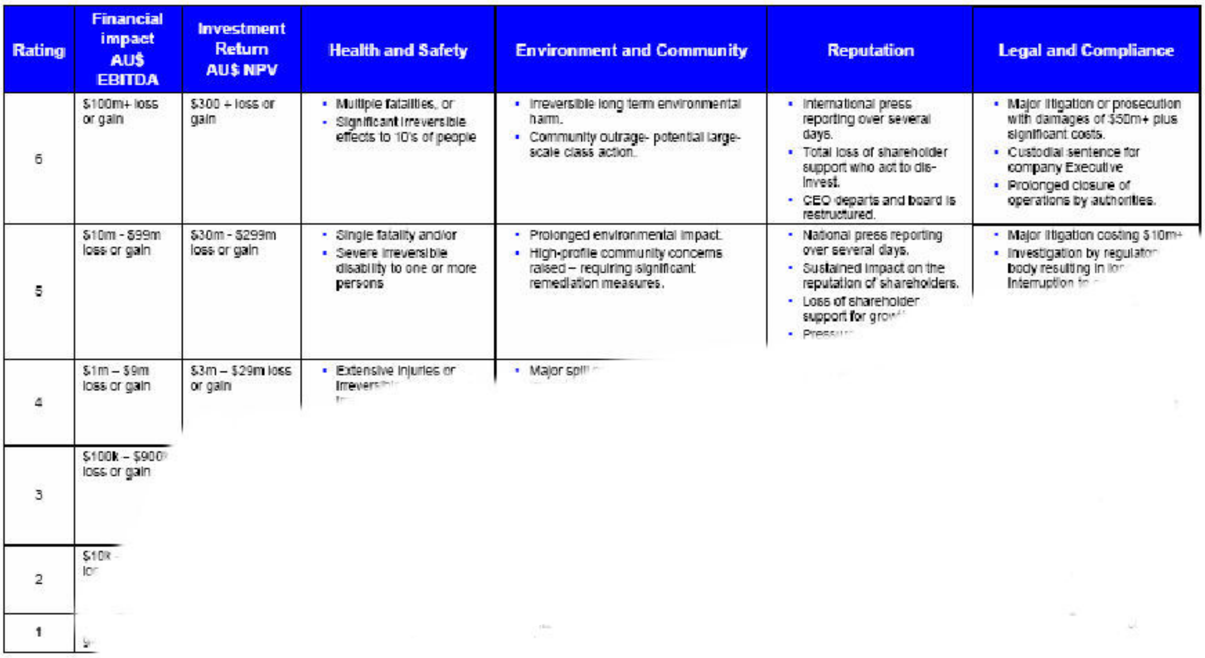
The consequence scale (or scales) should cover the range of different types of consequence to be considered (for example: financial loss; safety; environment or other parameters, depending on context) and should extend from the maximum credible consequence to the lowest consequence of concern. A part example is shown in Figure B.6.

The scale may have any number of points. 3, 4 or 5 point scales are most common.

The probability scale may also have any number of points. Definitions for probability need to be selected to be as unambiguous as possible. If numerical guides are used to define different probabilities, then units should be given. The probability scale needs to span the range relevant to the study in hand, remembering that the lowest probability must be acceptable for the highest defined consequence, otherwise all activities with the highest consequence are defined as intolerable. A part example is shown in Figure B.7.

A matrix is drawn with consequence on one axis and probability on the other. Figure B.8 shows part of an example matrix with a 6 point consequence and 5 point probability scales.

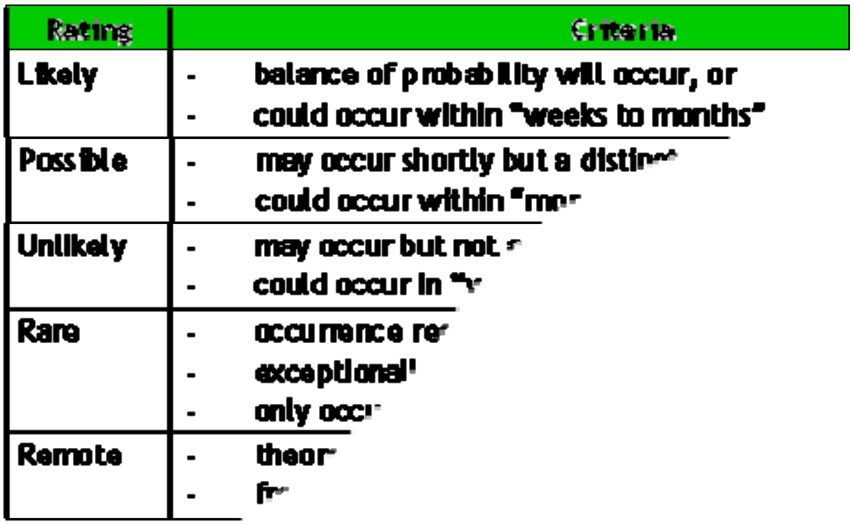
The risk levels assigned to the cells will depend on the definitions for the probability/ consequence scales. The matrix may be set up to give extra weight to consequences (as shown) or to probability, or it may be symmetrical, depending on the application. The levels of risk may be linked to decision rules such as the level of management attention or the time scale by which response is needed.



Rating	Financial impact AU$ EBITDA	Investment Return AU$ NPV	Health and Safety	Environment and Community	Reputation	Legal and Compliance
6	$100m+ loss or gain	$300 + loss or gain	- Multiple fatalities, or - Significant irreversible effects to 10's of people	- Irreversible long term environmental harm. - Community outrage- potential large-scale class action.	- International press reporting over several days. - Total loss of shareholder support who act to dis-invest. - CEO departs and board is restructured.	- Major litigation or prosecution with damages of $50m+ plus significant costs. - Custodial sentence for company Executive - Prolonged closure of operations by authorities.
5	$10m - $99m loss or gain	$30m - $299m loss or gain	- Single fatality and/or - Severe irreversible disability to one or more persons	- Prolonged environmental impact. - High-profile community concerns raised – requiring significant remediation measures.	- National press reporting over several days. - Sustained impact on the reputation of shareholders. - Loss of shareholder support for grow - Pressu	- Major litigation costing $10m+ - Investigation by regulator body resulting in lo Interruption
4	$1m – $9m loss or gain	$3m – $29m loss or gain	- Extensive injuries or irreversi	- Major spil		
3	$100k – $900 loss or gain					
2	$10k lo					
1	$					

IEC 2074/09

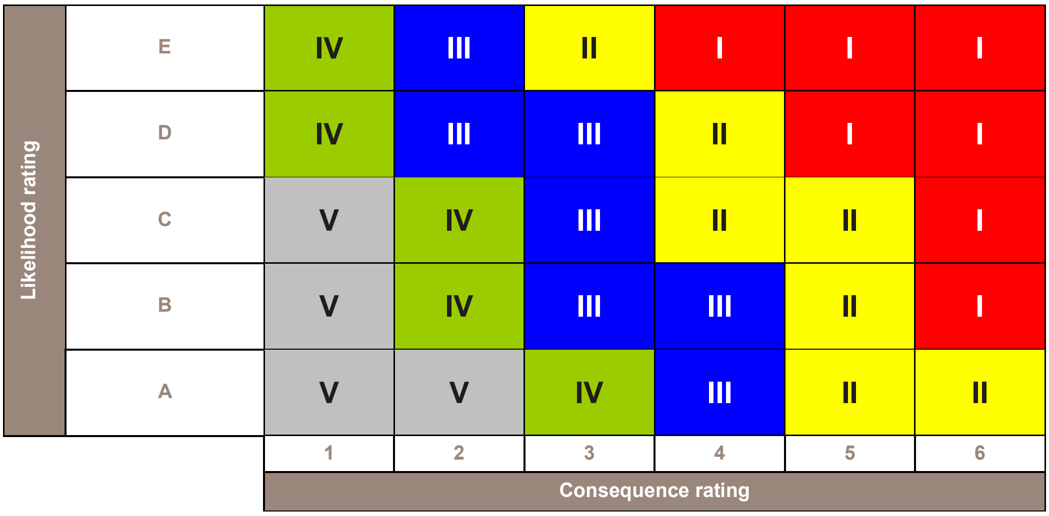
Figure B.13 – Part example of a consequence criteria table



Rating	Criteria
Likely	- balance of probability will occur, or - could occur within "weeks to months"
Possible	- may occur shortly but a distin - could occur within "mo
Unlikely	- may occur but not - could occur in "
Rare	- occurrence re - exceptional - only occ
Remote	- theor - fr

IEC 2075/09

Figure B.14 – Part example of a risk ranking matrix



Likelihood rating	1	2	3	4	5	6
E	IV	III	II	I	I	I
D	IV	III	III	II	I	I
C	V	IV	III	II	II	I
B	V	IV	III	III	II	I
A	V	V	IV	III	II	II

Consequence rating

IEC 2076/09

Figure B.15 – Part example of a probability criteria matrix

Rating scales and a matrix may be set up with quantitative scales. For example, in a reliability context the probability scale could represent indicative failure rates and the consequence scale the dollar cost of failure.

Use of the tool needs people (ideally a team) with relevant expertise and such data as is available to help in judgements of consequence and probability.

B.29.4 Process

To rank risks, the user first finds the consequence descriptor that best fits the situation then defines the probability with which those consequences will occur. The level of risk is then read off from the matrix.

Many risk events may have a range of outcomes with different associated probability. Usually, minor problems are more common than catastrophes. There is therefore a choice as to whether to rank the most common outcome or the most serious or some other combination. In many cases, it is appropriate to focus on the most serious credible outcomes as these pose the largest threat and are often of most concern. In some cases, it may be appropriate to rank both common problems and unlikely catastrophes as separate risks. It is important that the probability relevant to the selected consequence is used and not the probability of the event as a whole.

The level of risk defined by the matrix may be associated with a decision rule such as to treat or not to treat the risk.

B.29.5 Output

The output is a rating for each risk or a ranked list of risk with significance levels defined.

B.29.6 Strengths and limitations

Strengths:

- relatively easy to use;
- provides a rapid ranking of risks into different significance levels.

Limitations:

- a matrix should be designed to be appropriate for the circumstances so it may be difficult to have a common system applying across a range of circumstances relevant to an organization;
- it is difficult to define the scales unambiguously;
- use is very subjective and there tends to be significant variation between raters;
- risks cannot be aggregated (i.e. one cannot define that a particular number of low risks or a low risk identified a particular number of times is equivalent to a medium risk);
- it is difficult to combine or compare the level of risk for different categories of consequences.

Results will depend of the level of detail of the analysis, i.e. the more detailed the analysis, the higher the number of scenarios, each with a lower probability. This will underestimate the actual level of risk. The way in which scenarios are grouped together in describing risk should be consistent and defined at the start of the study.

B.30 Cost/benefit analysis (CBA)

B.30.1 Overview

Cost/benefit analysis can be used for risk evaluation where total expected costs are weighed against the total expected benefits in order to choose the best or most profitable option. It is an implicit part of many risk evaluation systems. It can be qualitative or quantitative or involve a combination of quantitative and qualitative elements. Quantitative CBA aggregates the monetary value of all costs and all benefits to all stakeholders that are included in the scope and adjusts for different time periods in which costs and benefits accrue. The net present value (NPV) which is produced becomes an input into to decisions about risk. A positive NPV associated with an action would normally mean the action should occur. However, for some negative risks, particularly those involving risks to human life or damage to the environment the ALARP principle may be applied. This divides risks into three regions: a level above which negative risks are intolerable and should not be taken except in extraordinary circumstances; a level below which risks are negligible and need only to be monitored to ensure they remain low; and a central band where risks are made as low as reasonably practicable (ALARP). Towards the lower risk end of this region, a strict cost benefit analysis may apply but where risks are close to intolerable, the expectation of the ALARP principle is that treatment will occur unless the costs of treatment are grossly disproportionate to the benefit gained.

B.30.2 Uses

Cost/benefit analysis can be used to decide between options which involve risk.

For example

- as input into a decision about whether a risk should be treated,
- to differentiate between and decide on the best form of risk treatment,
- to decide between different courses of action.

B.30.3 Inputs

Inputs include information on costs and benefits to relevant stakeholders and on uncertainties in those costs and benefits. Tangible and intangible costs and benefits should be considered. Costs include resources expended and negative outcomes, benefits include positive outcomes, negative outcomes avoided and resources saved.

B.30.4 Process

The stakeholders who may experience costs or receive benefits are identified. In a full cost benefit analysis all stakeholders are included.

The direct and indirect benefits and costs to all relevant stakeholders of the options being considered are identified. Direct benefits are those which flow directly from the action taken, while indirect or ancillary benefits are those which are coincidental but might still contribute significantly to the decision. Examples of indirect benefits include reputation improvement, staff satisfaction and “peace of mind”. (These are often weighted heavily in decision-making).

Direct costs are those that are directly associated with the action. Indirect costs are those additional, ancillary and sunk costs, such as loss of utility, distraction of management time or the diversion of capital away from other potential investments. When applying a cost benefit analysis to a decision on whether to treat a risk, costs and benefits associated with treating the risk, and with taking the risk, should be included

In quantitative cost/benefit analysis, when all tangible and intangible costs and benefits have been identified, a monetary value is assigned to all costs and benefits (including intangible costs and benefits). There are a number of standard ways of doing this including the ‘willingness to pay’ approach and using surrogates. If, as often happens, the cost is incurred over a short period of time (e.g. a year) and the benefits flow for a long period thereafter, it is normally necessary to discount the benefits to bring them into “today’s money” so that a valid comparison can be obtained. All costs and benefits are expressed as a present value. The present value of all costs and all benefits to all stakeholders can be combined to produce a net present value (NPV). A positive NPV implies that the action is beneficial. Benefit cost ratios are also used see B30.5

If there is uncertainty about the level of costs or benefits, either or both terms can be weighted according to their probabilities.

In qualitative cost benefit analysis no attempt is made to find a monetary value for intangible costs and benefits and, rather than providing a single figure summarizing the costs and benefits, relationships and trade-offs between different costs and benefits are considered qualitatively.

A related technique is a cost-effectiveness analysis. This assumes that a certain benefit or outcome is desired, and that there are several alternative ways to achieve it. The analysis looks only at costs and which is the cheapest way to achieve the benefit.

B.30.5 Output

The output of a cost/benefit analysis is information on relative costs and benefits of different options or actions. This may be expressed quantitatively as a net present value (NPV) an internal rate of return (IRR) or as the ratio of the present value of benefits to the present value of costs. Qualitatively the output is usually a table comparing costs and benefits of different types of cost and benefit, drawing attention to trade offs.

B.30.6 Strengths and limitations

Strengths of cost benefit analysis:

- it allows costs and benefits to be compared using a single metric (money);
- it provides transparency of decision making;
- it requires detailed information to be collected on all possible aspects of the decision. This can be valuable in revealing ignorance as well as communicating knowledge.

Limitations:

- quantitative CBA can yield dramatically different numbers, depending on the methods used to assign economic values to non-economic benefits;
- in some applications it is difficult to define a valid discounting rate for future costs and benefits;

- benefits which accrue to a large population are difficult to estimate, particularly those relating to public good which is not exchanged in markets;
- the practice of discounting means that benefits gained in the long term future have negligible influence on the decision depending on the discounting rate chosen. The method becomes unsuitable for consideration of risks affecting future generations unless very low or zero discount rates are set.

B.31 Multi-criteria decision analysis (MCDA)

B.31.1 Overview

The objective is to use a range of criteria to objectively and transparently assess the overall worthiness of a set of options. In general, the overall goal is to produce a preference of order between the available options. The analysis involves the development of a matrix of options and criteria which are ranked and aggregated to provide an overall score for each option.

B.31.2 Use

MCDA can be used for

- comparing multiple options for a first pass analysis to determine preferred and potential options and inappropriate option,
- comparing options where there are multiple and sometimes conflicting criteria,
- reaching a consensus on a decision where different stakeholders have conflicting objectives or values.

B.31.3 Inputs

A set of options for analysis. Criteria, based on objectives that can be used equally across all options to differentiate between them.

B.31.4 Process

In general a group of knowledgeable stakeholders undertakes the following process:

a) define the objective(s);

b) determine the attributes (criteria or performance measures) that relate to each objective;

c) structure the attributes into a hierarchy;

d) develop options to be evaluated against the criteria;

e) determine the importance of the criteria and assign corresponding weights to them;

f) evaluate the alternatives with respect to the criteria. This may be represented as a matrix of scores.

g) combine multiple single-attribute scores into a single aggregate multi attribute score;

h) evaluate the results.

There are different methods by which the weighting for each criteria can be elicited and different ways of aggregating the criteria scores for each option into a single multi-attribute score. For example, scores may be aggregated as a weighted sum or a weighted product or using the analytic hierarchy process, an elicitation technique for the weights and scores based on pairwise comparisons. All these methods assume that the preference for any one criterion does not depend on the values of the other criteria. Where this assumption is not valid, different models are used.

Since scores are subjective, sensitivity analysis is useful to examine the extent to which the weights and scores influence overall preferences between options.

B.31.5 Outputs

Rank order presentation of the options goes from best to least preferred. If the process produces a matrix where the axes of the matrix are criteria weighted and the criteria score for each option, then options that fail highly weighted criteria can also be eliminated.

B.31.6 Strengths and limitations

Strengths:

- provides a simple structure for efficient decision-making and presentation of assumptions and conclusions;
- can make complex decision problems, which are not amenable to cost/benefit analysis, more manageable;
- can help rationally consider problems where tradeoffs need to be made;
- can help achieve agreement when stakeholders have different objectives and hence criteria.

Limitations:

- can be affected by bias and poor selection of the decision criteria;
- most MCDA problems do not have a conclusive or unique solution;
- aggregation algorithms which calculate criteria weights from stated preferences or aggregate differing views can obscure the true basis of the decision.

B Risk Assessment Methods & Models in all Fields

[Marhavilas et al., 2011] has researched 6163 papers in six scientific journals from 2000-2009. From the 6163 papers 404 papers were selected which had as main the risk assessment and risk analysis techniques. It should be noted that this research has been done for all type of fields not solely for the MTS. The journals researched are:

1. **JSS**: Safety Science
2. **JLPPI**: Journal of Loss Prevention in the Process Industries
3. **JAAP**: Accident Analysis and Prevention
4. **JSR**: Journal of Safety Research
5. **IJIE**: International Journal of Industrial Ergonomics
6. **JRESS**: Reliability Engineering & System Safety

The overview of 404 papers that is created by [Marhavilas et al., 2011] discussed for each paper the name of the technique used in that paper, the method's type; so either quantitative, qualitative or a hybrid combination / semi-quantitative, the type of paper (e.g. case study, empirical data, accident data, theoretical foundations, database), the field of application and the journal that the paper is found in.

In addition to presenting the methods and models for risk assessment proposed by [Marhavilas et al., 2011]. They are divided in categories; Qualitative, Quantitative and Hybrid techniques. For each of these models the advantages, disadvantages of selecting and using them for risk assessment are discussed. In addition future improvements for each method are stated.

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Risk analysis and assessment methodologies in the work sites: On a review, classification and comparative study of the scientific literature of the period 2000–2009

P.K. Marhavilas [a,b,*], D. Koulouriotis [b], V. Gemeni [b]

[a] Lab. of Electromagnetism, Dep. of Electrical & Computer Engineering, Democritus Univ. of Thrace, Vas. Sofias 12 St., 67100 Xanthi, Greece
[b] Dep. of Production & Management Engineering, Democritus Univ. of Thrace, Vas. Sofias 12 St., 67100 Xanthi, Greece

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ABSTRACT

The objective of this work is to determine and study, analyze and elaborate, classify and categorize the main risk analysis and risk-assessment methods and techniques by reviewing the scientific literature. The paper consists of two parts: a) the investigation, presentation and elaboration of the main risk-assessment methodologies and b) the statistical analysis, classification, and comparative study of the corresponding scientific papers published by six representative scientific journals of Elsevier B.V. covering the decade 2000–2009. The scientific literature reviewing showed that the risk analysis and assessment techniques are classified into three main categories: (a) the qualitative, (b) the quantitative, and (c) the hybrid techniques (qualitative–quantitative, semi-quantitative). The qualitative techniques are based both on analytical estimation processes, and on the safety managers–engineers ability. According to quantitative techniques, the risk can be considered as a quantity, which can be estimated and expressed by a mathematical relation, under the help of real accidents' data recorded in a work site. The hybrid techniques, present a great complexity due to their ad hoc character that prevents a wide spreading. The statistical analysis shows that the quantitative methods present the highest relative frequency (65.63%) while the qualitative a lower one (27.68%). Furthermore the hybrid methods remain constantly at a very low level (6.70%) during the entire processing period.

1. Introduction

Public interest in the field of risk analysis has expanded in leaps and bounds during the last three decades, while risk analysis has emerged as an effective and comprehensive procedure that supplements and complements the overall management of almost all aspects of our life. Managers of health care, the environment, and physical infrastructure systems all incorporate risk analysis in their decision-making process. Moreover the omnipresent adaptations of risk analysis by many disciplines, along with its deployment by industry and government agencies in decision-making, have led to an unprecedented development of theory, methodology, and practical tools (Haimes, 2009).

Risk has been considered as the chance that someone or something that is valuated will be adversely affected by the hazard (Woodruff, 2005) while "hazard" is any unsafe condition or potential source of an undesirable event with potential for harm or damage (Reniers, Dullaert, Ale, & Soudan, 2005). Moreover, risk has been defined as a measure under uncertainty of the severity of a hazard (Høj & Kröger, 2002), or a measure of the probability and severity of adverse effects (Haimes, 2009). In general, "danger" should be defined as an attribute of substances or processes, which may potentially cause harm (Høj & Kröger, 2002).

A complex human–machine system is seen as being composed of humans, of machines, and of the interaction between them, which could properly be described by a system model. The role of a system model is essential in thinking about how systems can malfunction, or in other words in thinking about accidents. A fundamental distinction is whether accidents are due to specific malfunctions or "error mechanisms", or whether they are due to unfortunate coincidences. Over the years, the efforts to explain and predict accidents have involved a number of stereotypical ways of accounting for how events may take place (Hollnagel, 2004, 2006; Hollnagel, Woods, & Leveson, 2006; Qureshi, 2007).

Furthermore, risk assessment is an essential and systematic process for assessing the impact, occurrence and the consequences

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* Corresponding author. Lab. of Electromagnetism, Dep. of Electrical & Computer Engineering, Democritus Univ. of Thrace, Vas. Sofias 12 St., 67100 Xanthi, Greece. Tel.: +30 2541079973.
E-mail addresses: marhavil@ee.duth.gr (P.K. Marhavilas), jimk@pme.duth.gr (D. Koulouriotis), vickygemeni@hotmail.com (V. Gemeni).

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of human activities on systems with hazardous characteristics (van Duijne, Aken, & Schouten, 2008) and constitutes a needful tool for the safety policy of a company. The diversity in risk analysis procedures is such that there are many appropriate techniques for any circumstance and the choice has become more a matter of taste (Reniers et al., 2005; Rouvroye & van den Bliek, 2002). We can consider the risk as a quantity, which can be measured and expressed by a mathematical relation, under the help of real accidents' data (Marhavilas & Koulouriotis, 2007, 2008; Marhavilas, Koulouriotis, & Voulgaridou, 2009).

The objective of this work is to determine and study, classify and categorize, analyze and overview, the main risk analysis and assessment (RAA) methods and techniques by reviewing the scientific literature. The paper consists of two parts: a) the presentation of the main risk-assessment methodologies and b) the statistical analysis, classification, and elaboration of the corresponding scientific papers published by Elsevier B.V. covering the last decade.

2. An overview of risk analysis and assessment techniques

The procedure of reviewing the scientific literature, revealed a plethora of published technical articles on safety, and risk analysis referred to many different fields, like engineering, medicine, chemistry, biology, agronomics, etc. These articles address concepts, tools, technologies, and methodologies that have been developed and practiced in such areas as planning, design, development, system integration, prototyping, and construction of physical infrastructure; in reliability, quality control, and maintenance. Furthermore, our reviewing shows that the risk analysis and assessment (RAA) techniques are classified into three main categories: (a) the qualitative, (b) the quantitative, and (c) the hybrid techniques (qualitative–quantitative, semi-quantitative). The qualitative techniques are based both on analytical estimation processes, and on the safety managers–engineers ability. According to quantitative techniques, the risk can be considered as a quantity, which can be estimated and expressed by a mathematical relation, under the help of real accidents' data recorded in a work site. The hybrid techniques, present a great complexity due to their ad hoc character that prevents a wide spreading. Fig. 1 illustrates the classification of the main risk analysis and assessment methodologies. Below, we present an overview of them having in mind this classification.

2.1. Qualitative techniques

a) *Checklists*: Checklist analysis is a systematic evaluation against pre-established criteria in the form of one or more checklists, which are enumeration of questions about operation, organization, maintenance and other areas of installation safety concern and represent the simplest method used for hazard identification. A brief summary of its characteristics is as follows: (i) It is a systematic approach built on the historical knowledge included in checklist questions, (ii) It is applicable to any activity or system, including equipment issues and human factors issues, (iii) It is generally performed by an individual trained to understand the checklist questions, or sometimes by a small group, (iv) It is based mostly on interviews, documentation reviews, and field inspections, (v) It generates qualitative lists of conformance and non-conformance determinations with recommendations for correcting non-conformances, (vi) The quality of evaluation is determined primarily by the experience of people creating the checklists and the training of the checklist users, (vii) It is used for high-level or detailed analysis, including root cause analysis, (viii) It is used most often to guide boarding teams through inspection of critical vessel systems, (ix) It is also used as a supplement to or integral part of another method, especially what-if-analysis, to address specific requirements. Although checklist analysis is highly effective in identifying various system hazards, this technique has two key limitations: (a) The structure of checklist analysis relies exclusively on the knowledge built into the checklists to identify potential problems. If the checklist does not address a key issue, the analysis is likely to overlook potentially important weaknesses. (b) Traditionally provides only qualitative information. Most checklist reviews produce only qualitative results, with no quantitative estimates of risk-related characteristics. This simplistic approach offers great value for minimal investment, but it can answer more complicated risk-related questions only if some degree of quantification is added, possibly with a relative ranking/risk

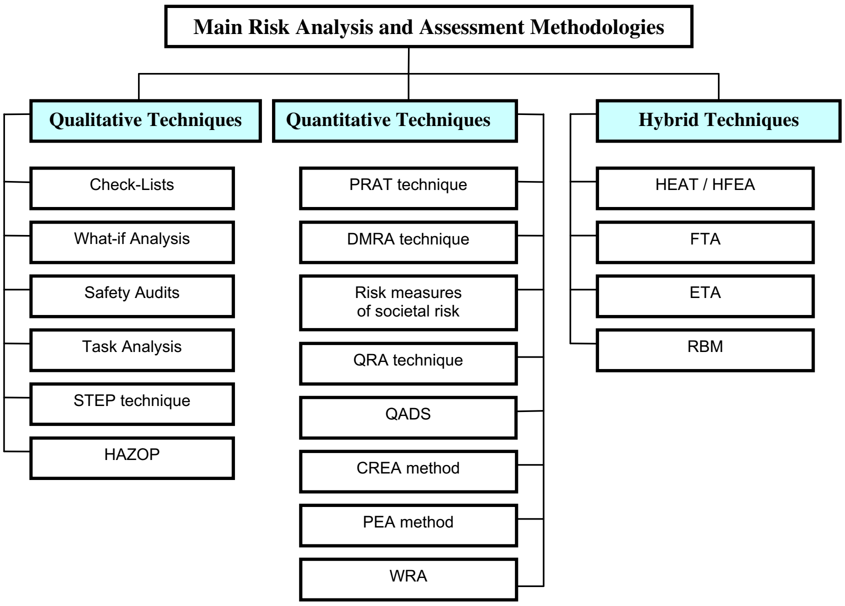

Fig. 1. It is presented the classification of the main risk analysis and assessment (RAA) methodologies.

indexing approach (Arvanitogeorgos, 1999; Ayyub, 2003; Harms-Ringdahl, 2001; Marhavilas et al., 2009; Reniers et al., 2005; http://www.oshatrain.org).

b) *What-if-analysis*: It is an approach that (1) uses broad, loosely structured questioning to postulate potential upsets that may result in accidents or system performance problems and (2) determines what things can go wrong and judges the consequences of those situations occurring (Ayyub, 2003; Doerr, 1991; Reniers et al., 2005). The main characteristics of the technique are briefly summarized as follows:
   - It is a systematic, but loosely structured, assessment, relying on a team of experts to generate a comprehensive review and to ensure that appropriate safeguards are in place.
   - Typically is performed by one or more teams with diverse backgrounds and experience that participate in group review meetings of documentation and field inspections.
   - It is applicable to any activity or system.
   - It is used as a high-level or detailed risk-assessment technique.
   - It generates qualitative descriptions of potential problems, in the form of questions and responses, as well as lists of recommendations for preventing problems.
   - The quality of the evaluation depends on the quality of the documentation, the training of the review team leader, and the experience of the review teams.
   - It is generally applicable for almost every type of risk-assessment application, especially those dominated by relatively simple failure scenarios.
   - Occasionally it is used alone, but most often is used to supplement other, more structured techniques (especially checklist analysis).

The procedure for performing a what-if-analysis consists of the following seven steps:

- We specify and clearly define the boundaries for which risk-related information is needed.
- We specify the problems of interest that the analysis will address (safety problems, environmental issues, economic impacts, etc.).
- We subdivide the subject into its major elements (e.g. locations on the waterway, tasks, or subsystems), so that the analysis will begin at this level.
- We generate “what-if” questions for each element of the activity or system.
- We respond to each of the “what-if” questions and develop recommendations for improvements wherever the risk of potential problems seems uncomfortable or unnecessary.
- We further subdivide the elements of the activity or system, if it is necessary or more detailed analysis is desired. The section of some elements into successively finer levels of resolution until further subdivision will (1) provide no more valuable information or (2) exceed the organization’s control or influence to make improvements. Generally, the goal is to minimize the level of resolution necessary for a risk assessment.
- We use the results in decision-making. So we evaluate recommendations from the analysis and implement those that will bring more benefits than they will cost in the life cycle of the activity or system.

c) *Safety audits*: They are procedures by which operational safety programs of an installation, a process or a plant are inspected. They identify equipment conditions or operating procedures that could lead to a casualty or result in property damage or environmental impacts (Ayyub, 2003). An auditor or an audit team reviews critical features to verify the implementation of appropriate design criteria, operating conditions and procedures, safety measures and related risk-management programs. The result of an audit is a report that provides corporate management with an overview of the level of performance for various safety aspects of operations. Reporting results should make reasonable recommendations and suggestions about safety procedure improvements and safety awareness of operating personnel (Harms-Ringdahl, 2001; Reniers et al., 2005).

d) *Task Analysis (TA)*: This process analyzes the way that people perform the tasks in their work environment and how these tasks are refined into subtasks and describes how the operators interact both with the system itself and with other personnel in that system. It can be used to create a detailed picture of human involvement using all the information necessary for an analysis in an adequate degree of details (Brauchler & Landau, 1998; Doytchev & Szwillus, 2008; Kirwan, 1994; Kontogiannis, 2003; Landau, Rohmert, & Brauchler, 1998). Task analysis involves the study of activities and communications undertaken by operators and their teams in order to achieve a system goal. The result of a task analysis is a Task Model. The task analysis process usually involves three phases: (i) collection of data about human interventions and system demands, (ii) representation of those data in a comprehensible format or graph, and (iii) comparison between system demands and operator capabilities. The primary objective of task analysis is to ensure compatibility between system demands and operator capabilities, and if necessary, to alter those demands so that the task is adapted to the person. A widely used form of task analysis is the hierarchical task analysis (HTA). Through its hierarchical approach it provides a well-structured overview of the work processes even in realistically sized examples. HTA is an easy to use method of gathering and organizing information about human activities and human interaction, and enables the analyst to find safety-critical tasks. It is time-consuming in case of complex tasks and requires the cooperation of experts from the application domain, knowledgeable about the task operation conditions. Other analysis techniques are the Tabular Task Analysis, Timeline Analysis, Operator Action Event Trees, the GOMS-methods (Goals, Operators, Methods, and Selection Rules), Critical Action and Decision Evaluation Technique etc (Brauchler & Landau, 1998; Landau et al., 1998).

e) *The Sequentially Timed Event Plotting (STEP) technique*: It provides a valuable overview of the timing and sequence of events/actions that contributed to the accident, or in other words, a reconstruction of the harm process by plotting the sequence of events that contributed to the accident. The main concepts in STEP are the initiation of the accident through an event or change that disrupted the technical system, the agents which intervene to control the system and the elementary “event building blocks”. The analysts construct an STEP worksheet which charts the evolution of events and system interventions (on the horizontal axis) performed by the agents (on the vertical axis). Subsequently, they identify the main events/actions that contributed to the accident and construct their “event building blocks” which contain the following information: a) the time at which the event started, b) the duration of the event, c) the agent which caused the event, d) the description of the event, and e) the name of the source which offered this information. In the second stage, the events are interconnected with arrows. All events should have incoming and outgoing arrows which show “precede” and “follow” relationships between events. Converging arrows show dependencies between events while divergent arrows show the impact on following events (Hendrick & Benner, 1987; Kontogiannis, Leopoulos, & Marmaras, 2000).

f) *The HAZOP method (Hazard and Operability study)*: It is a formalized methodology to identify and document hazards through imaginative thinking. It involves a very systematic examination of design documents that describe the installation or the facility under investigation. The study is performed by a multidisciplinary team, analytically examining design intent deviations. The HAZOP analysis technique uses a systematic process to (1) identify possible deviations from normal operations and (2) ensure that appropriate safeguards are in place to help prevent accidents. The basic principle of HAZOP study is that hazards arise in a plant due to deviations from normal behavior. In HAZOP study, process piping and instrument diagrams (PIDs) are examined systematically by a group of experts (HAZOP team), and the abnormal causes and adverse consequences for all possible deviations from normal operation that could arise are found for every section of the plant. Thus, the potential problems in the process plant are identified. The HAZOP team is a multidisciplinary team of experts who have extensive knowledge on design, operation, and maintenance of the process plants. Generally, a team of six members consisting of team leader, process engineer, operation representative, safety representative, control system engineer, and maintenance engineer is recommended for the study. The HAZOP team members try to imagine ways in which hazards and operating problems might arise in a process plant. To cover all the possible malfunctions in the plant, the HAZOP study team members use a set of 'guide words' for generating the process variable deviations to be considered in the HAZOP study. The sets of guide words that are often used are NONE, MORE OF, LESS OF, PART OF, and MORE THAN. When these guide words are applied to the process variables in each line or unit of the plant, we get the corresponding process variable deviation to be considered in the HAZOP study. A list of guide words with their meaning and the parameters where they can be applied is presented in Table 1. The guide words and process variables should be combined in such a way that they lead to meaningful process variable deviations. Hence, all guide words cannot be applied to all process variables. For example, when the process variable under consideration is temperature, only the guide words MORE OF and LESS OF lead to meaningful process variable deviations. The sequence of typical HAZOP study is shown in Fig. 2. The proper planning and management of HAZOP study is one of the crucial factors for better effectiveness and good reliability of the results. The HAZOP study can be planned and managed properly only when duration of each activity and for complete study is known (Ayyub, 2003; Baysari, McIntosh, & Wilson, 2008; Harms-Ringdahl, 2001; Hong, Lee, Shin, Nam, & Kong, 2009; Khan & Abbasi, 1997; Labovský, Švandová, Markoš, & Jelemenský, 2007; Reniers et al., 2005; Yang & Yang, 2005). The main characteristics of the technique are briefly summarized as follows:

- It is a systematic, highly structured assessment relying on HAZOP guide words to generate a comprehensive review and ensure that appropriate safeguards against accidents are in place
- It is typically performed by a multidisciplinary team
- It is applicable to any system or procedure
- It is used most as a system-level risk-assessment technique
- It generates primarily qualitative results, although some basic quantification is possible

Table 1
The list of guide words and their meaning (Khan & Abbasi, 1997).

Guide words	Meaning
No/None	Complete negation to design intention
More	Quantitative increase
Less	Quantitative decrease
Part of	Only part of intention is fulfilled
As well as	In addition to design intention, something else occurs
Reverse	Logical opposition of design intention occurs
Other than	Complete substitution

3. Quantitative techniques

g) *The proportional risk-assessment (PRAT) technique*: This technique (Ayyub, 2003; Fine & Kinney, 1971; Marhavilas & Koulouriotis, 2007, 2008) uses a proportional formula for calculating the quantified risk due to hazard. The risk is calculated considering the potential consequences of an accident, the exposure factor and the probability factor. More specifically a quantitative calculation of the risk, can be given with the following proportional relation (Marhavilas & Koulouriotis, 2008):

$$R = P{\cdot}S{\cdot}F$$

where: R: the Risk; P: the Probability Factor; S: the Severity of Harm Factor; F: the Frequency (or the Exposure) Factor.

The above relation provides a logical system for safety management to set priorities for attention to hazardous situations. The validity of these priorities or these decisions is obviously a function of the validity of the estimates of the parameters P, S and F, and these estimates, apparently very simple, require the collection of information, the visit of the workplaces and the discussion with the workers about their activities (Reniers et al., 2005). The participation of the workers is thus essential as they are the only persons to know exactly how the work is actually performed. Each factor in the previous equation, takes values in the scale of 1–10 (Marhavilas & Koulouriotis, 2008; their tables 1, 2, 3), so that the quantity R can be expressed in the scale of 1–1000. We can use Table 2 to associate the gradation of the risk value R with the urgency level of required actions.

h) *The decision matrix risk-assessment (DMRA) technique*: It is a systematic approach for estimating risks, which is consisting of measuring and categorizing risks on an informed judgment basis as to both probability and consequence and as to relative importance (Ayyub, 2003; Henselwood & Phillips, 2006; Marhavilas & Koulouriotis, 2008; Haimes, 2009; Marhavilas, Koulouriotis, & Mitrakas, submitted for publication; Reniers et al., 2005; Woodruff, 2005). The combination of a consequence/severity and likelihood range, gives us an estimate of risk (or a risk ranking). More specifically, the product of severity (S) and likelihood (P) provides a measure of risk (R) which is expressed by the relation:

$$R = S{\cdot}P$$

Once the hazards have been identified, the question of assigning *severity* and *probability* ratings must be addressed. Eventually, the technique is consummated by the construction of the risk matrix (in Table 3-a) and the decision-making table (in Table 3-b). The new developed DMRA technique has two key advantages: a) It differentiates relative risks to facilitate decision-making. b) It improves the consistency and basis of decision. Moreover, it is a quantitative (due to risk measuring) and also a graphical method which can create liability issues and help the risk managers to prioritize and manage key risks (Marhavilas & Koulouriotis, 2008).

i) *Quantitative risk measures of societal risk*: The societal risk associated with operation of given complex technical system

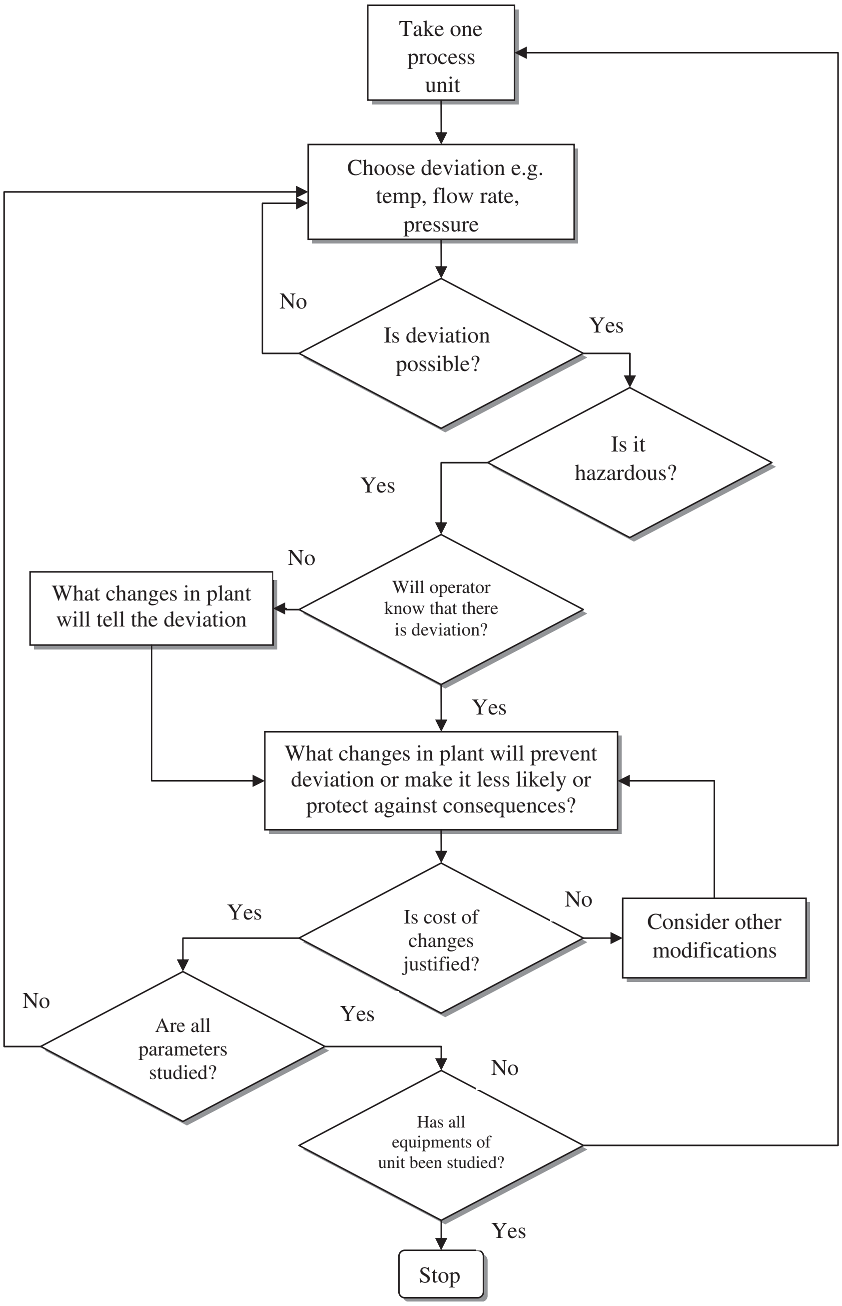

Fig. 2. Procedure of HAZOP study (Khan & Abbasi, 1997).

is evaluated (Kosmowski, 2002, 2006) on the basis of a set of the triples:

$$R = \{\langle S_k, F_k, N_k \rangle\}$$

where S_k is k-th accident scenario (usually representing an accident category) defined in the determined modeling process, F_k is the frequency of this scenario (evaluated as probability per time unit, usually one year), and N_k denotes the consequences of k-th scenario, i.e. potential losses (the number of injuries and fatalities) or financial losses. On the basis of the above relation the F–N curve (CCDF: complementary cumulative distribution function) is to be drawn. Fig. 3 illustrates an example of such curve in double logarithmic co-ordinates to be compared with criteria lines: D (lower line) and G (upper line). The social risk for a given technical system is accepted when F–N curve is below the criterion line D (a defined function with regard to societal preferences) for all N. If the F–N curve is situated between criteria lines D and G, then the ALARP (as low as reasonably practicable) principle should be applied to indicate the ways to reduce risk. If for any N the F–N curve is above

Table 2
Gradation of the risk value in association with the urgency level of required actions (Marhavilas & Koulouriotis, 2008).

Risk Value (R)	Urgency level of required actions
700–1000	Immediate action
500–700	Required Action earlier than 1 day
300–500	Required Action earlier than 1 month
200–300	Required Action earlier than 1 year
<200	Immediate action is not necessary but it is required the event surveillance

Table 3
The decision matrix risk-assessment technique: (a) The risk matrix. (b) The decision-making table (Marhavilas & Koulouriotis, 2008).

Severity of consequences ratings (S)	Hazard probability ratings (P)					
	6	5	4	3	2	1
6	36	30	24	18	12	6
5	30	25	20	15	10	5
4	24	20	16	12	8	4
3	18	15	12	9	6	3
2	12	10	8	6	4	2
1	6	5	4	3	2	1

■	*Unacceptable*	18-36
▨	*Undesirable*	10-16
░	*Acceptable with controls*	5-9
☐	*Acceptable*	1-4

the upper criteria line G, the risk is intolerable and the system must re-designed (e.g. functionally and structurally modified) to reduce risk as required. A measure of societal risk can be the average rate of death evaluated according to the formula:

$$R = \sum_k F_k N_k$$

where: F_k is the frequency of k-th accident scenario [a^{-1}]; and N_k is the number of fatalities resulting from k-th scenario.

j) *The QRA (Quantitative Risk-Assessment) tool.* The QRA tool has been developed for the external safety of industrial plants with a dust explosion hazard. This tool provides a consistent basis to analyze the individual and societal risk, it consists of a combination of sub models, and an overview is presented in Fig. 4. First the scenarios and their frequencies are defined. The individual risk is defined as the probability (frequency) of lethality for an unprotected person in the vicinity of a hazardous location. The societal risk takes the actual environment into account. For example, an industrial plant is divided into two groups of modules, defined by their size, shape, and constructional properties. Then the relevant explosion scenarios are determined, together with their frequency of occurrence. These include scenarios in which one module participates, as well as domino scenarios. The frequency is partly based on casuistry. The QRA tool offers the possibility to define four types of objects: unprotected people, cars, domestic houses and office buildings, each with their own protection level against the different explosion effects. The development of the dust explosion and the process of venting and the launch of module parts are predicted for each scenario.

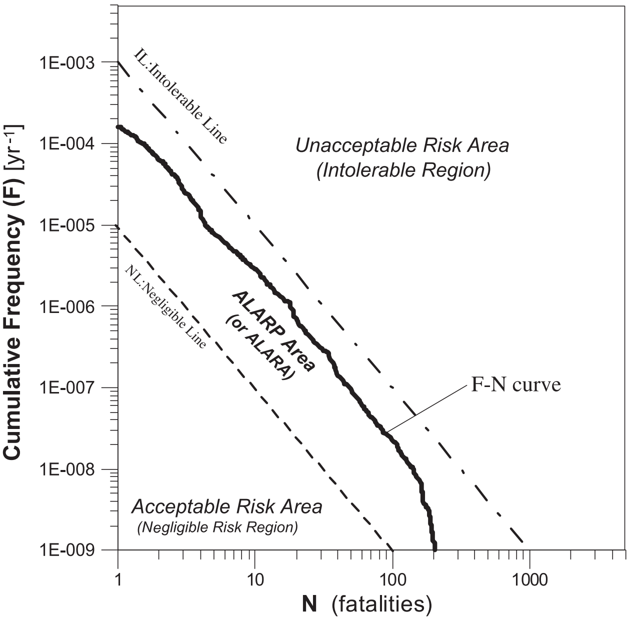

Fig. 3. Examples of the F–N curve and criteria functions for societal risk.

As a result the individual risk is independent of the contributions from window failure due to blast effects. The flame jet is only relevant if the height of its origin is situated less than 5 m above the unprotected person. Debris throwing and bulk outflow are always relevant for the individual risk. The results are input for explosion effect calculations, followed by a prediction of the consequences for people. The consequences and the scenario frequency are then combined to the individual and societal risk, which can be compared to the relevant regulations (Van der Voort et al., 2007).

k) *Quantitative assessment of domino scenarios (QADS).* The domino effect is assumed as an accident in which a primary event propagates to nearby equipment, triggering one or more secondary events resulting in overall consequences more severe than those of the primary event. Furthermore, an accident is usually considered as a “domino event” only if its overall severity is higher or at least comparable to that of the primary accidental scenario, while domino accidental scenarios result from the escalation of a primary accidental event. The escalation is usually caused by the damage of at least one equipment item, due to the physical effects of the primary event. Four elements may be considered to characterize a domino event: (i) A primary accidental scenario, which triggers the domino effect. (ii) A propagation effect following the primary event, due to the effect of escalation vectors caused by the primary event on secondary targets. (iii) One or more secondary accidental scenarios, involving the same or different plant units, causing the propagation of the primary event. (iv) An escalation of the consequences of the primary event, due to the effect of the secondary scenarios. The quantitative assessment of domino accidents requires the identification, the frequency evaluation and the consequence assessment of all the credible domino scenarios, including all the different combinations of secondary events that may be originated by each primary event. The identification of the credible domino scenarios should be based on escalation criteria addressing the possible damage of equipment due to the physical effects generated in the primary scenarios. In the approach to the frequency assessment of domino scenarios, the damage probability of

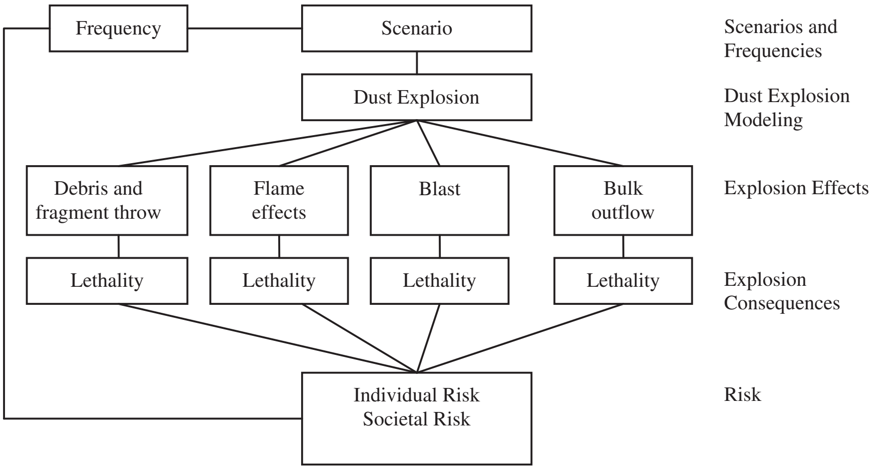

Fig. 4. An overview of the QRA tool is presented (van der Voort et al., 2007).

a unit due to a given primary event may be considered independent on the possible contemporary damage of other units. Thus, if n possible target units are present, a single primary event may cause a maximum of n different secondary events, each having an overall probability to take place equal to $P_{d,i}$. However, each secondary event may take place contemporary to other secondary events. A single domino scenario may thus be defined as an event involving the contemporary damage of k units resulting in k secondary events, with k comprised between 1 and n. If each of the n secondary units is labeled by a numerical indicator comprised between 1 and n, a domino scenario may thus be indicated as a vector $J_m^k = [\gamma_1, \ldots, \gamma_k]$ whose elements are the indexes of the secondary units involved in the event. Since $k \le n$, in general more than one domino scenario may involve k units. Therefore, the subscript m of vector J indicates that the single domino scenario is the mth combination of k secondary events. The number of domino scenarios involving k different secondary events may be calculated by the following expression:

$$s_k = \frac{n!}{(n-k)!k!}$$

The total number of different domino scenarios that may be generated by the primary event, S_d, may be calculated as follows:

$$S_d = \sum_{k=1}^{n} s_k = 2^n - 1$$

The probability of a single domino scenario involving the contemporary damage of k units resulting in k secondary events, identified by the vector J_m^k, may be evaluated as follows:

$$P_d^{(k,m)} = \prod_{i=1}^{n} \left[1 - P_{d,i} + \delta\left(i, J_m^k\right)\left(2 \cdot P_{d,i} - 1\right)\right]$$

where the function $\delta(i, J_m^k)$ equals 1 if the ith event belongs to the mth combination, 0 if not. The last equation is the algebraic expression obtained from the union of the probabilities of the k events belonging to the mth combination, calculated considering as independent the secondary events. The expected frequency of the mth domino scenario involving k contemporary events, $f_d^{(k,m)}$, may thus be calculated as

$$f_d^{(k,m)} = f_P \cdot P_d^{(k,m)}$$

where f_p is the expected frequency of the primary event that triggers the escalation (Cozzani, Antonioni, & Spadoni, 2006).

l) *The CREA (Clinical Risk and Error Analysis) method*. CREA is a methodological approach for quantitative risk analysis, consisting of five steps (see Fig. 5) according to the work of Trucco and Cavallin (2006) and based on techniques which are well-established in industry, and have been adapted for the medical domain. CREA allows the analyst to join data which have been collected through direct observation of processes or interviews to clinical operators to statistical data reported in literature. The risk assessment for CREA method is condensed to the following: For each activity k, the probability $P(\mathrm{EM}_{ik})$ of occurrence of the EM_i-th error mode (EM) and the severity index $D(\mathrm{EM}_{ik})$ of the associated harm have to be calculated on the basis of available data and the experts' judgment; their product represents the Risk Index $R(\mathrm{EM}_{ik})$ for each EM, as shown in the classical equation:

$$R(\mathrm{EM}_{ik}) = P(\mathrm{EM}_{ik}) \times D(\mathrm{EM}_{ik})$$

For each EM, only its occurrence probability related to the whole process in known, but in fact the same EM could happen in several tasks in one or more process activities. Thus, the experts estimate the likelihood to have a particular EM within the various activities of the process (y_{ik}), making it possible to calculate the probability of

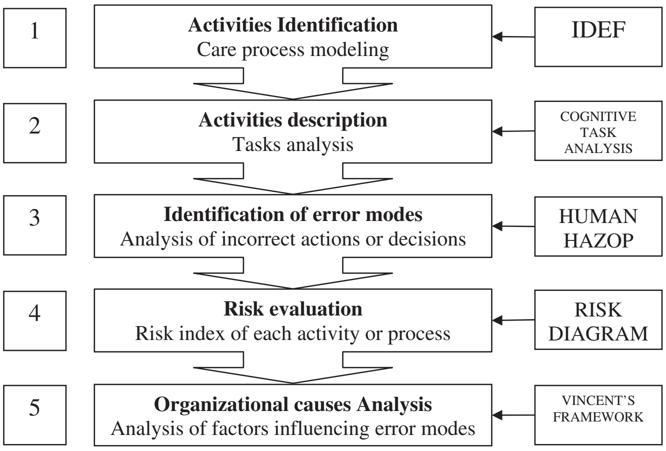

Fig. 5. Fundamental steps and tools of CREA (Trucco & Cavallin, 2006).

the error mode *i* which occurred in the activity *k* by multiplying the probability of occurrence of EM *i* for the estimated likelihood, as follows:

$$P(\mathrm{EM}_{ik}) = y_{ik} \times [P(\mathrm{EM}_i)]_{\mathrm{AVERAGE}}$$

As far as the severity index $D(\mathrm{EM}_{ik})$ is concerned, it is calculated as the linear combination of the conditional probabilities x_{ijk} of the severity class *j*, weighted with a coefficient M_j, that grows with the severity of the harm.

$$D(\mathrm{EM}_{ik}) = \sum_{j=A}^{E} \left(M_j \cdot x_{ijk}\right)$$

The values of coefficient M_j could be adjusted on the basis of the risk perception of the team which is conducting the analysis. The estimates of probabilities of occurrence of EMs, the likelihood of severity classes and the Risk Index of each activity can be presented in Tables. The Risk Index of each activity *k* (ACT_k) is given by the sum of the risk indexes of each EM detected in the same activity, as follows:

$$R(\mathrm{ACT}_k) = \sum_i R(\mathrm{EM}_{ik})$$

Each error mode of every activity is mapped in risk diagrams, in that three iso-risk curves allow four risk control areas to be identified: emergency ($R > 0.05$), urgency ($0.01 < R < 0.05$), planning ($0.0050 < R < 0.01$) and monitoring ($R < 0.005$). Risk mapping can also be done on several aggregation levels. For example, in the drug therapy management process, the error modes are presented in Table 4, while the coefficients M_j, in Table 5, according to the work of Trucco and Cavallin (2006).

m) *The PEA (Predictive, Epistemic Approach) method*. This procedure is based on the so-called predictive, epistemic approach to risk assessment. It provides formal means for combining hard data and subjective information and allows forecasting the abnormal (accidental) actions (AA) in the form of mathematical models, which quantify epistemic (state-of-knowledge) uncertainties in characteristics of the actions. The epistemic models allow a rough, knowledge-based estimation of probabilities of damage from abnormal actions. These models are considered to be the first step toward preventing (reducing) losses associated with damage from abnormal actions. The damage can be assessed by either deterministic or probabilistic structural analysis. The prevailing practice of modeling abnormal (accidental) actions is representing them by fixed values (conservative percentiles of action characteristics called the characteristic and design values) which are usually specified in structural design codes. Outside the regulatory area of the codes, attempts were undertaken to specify AAs in terms of probability distributions (p.d.'s) assigned in the framework of a classical statistical approach (CSA) which dominates the structural reliability analysis. The application of the fixed values and p.d. specified in line with CSA to a mechanical damage assessment is vulnerable to criticism. A fundamentally different approach to forecasting AAs consists in a numerical simulation of physical phenomena involving AAs. So the forecasting of abnormal actions in the framework of the predictive, epistemic approach is achieved by a stochastic simulation of accident courses (scenarios) involving AA(s) or, in short, a stochastic accident simulation (SAS). This simulation will serve as a means of propagating epistemic uncertainty. The AAs forecasting should be considered a part of a broader problem of a quantitative risk analysis (QRA) and carried out using knowledge-based methods of QRA. They allow using a wider spectrum of diverse knowledge related to AAs than the methods provided by CSA. The problem considered is how to answer the question "what is the frequency (annual probability, probability per year of operation, etc.) of exceeding a given magnitude *m* of an abnormal action" or, in brief, "what is the value of the product $Fr(\mathrm{AA}) \times P(m|\mathrm{AA})$", where $Fr(\mathrm{AA})$ is the frequency of imposition of the AA (random event AA) and $P(m|\mathrm{AA})$ is the conditional probability of exceeding *m* given AA. An answer to this question depends on an interpretation of $F(\mathrm{AA})$ and $P(m|\mathrm{AA})$. Specifying the frequency $Fr(\mathrm{AA})$ and p.d. $P(m|\mathrm{AA})$ solely on the basis of the data gained from occurrences of AAs will more often than not be impossible. Data on AAs are usually sparse or irrelevant to a particular situation of exposure of a structure to AAs (exposure situation) or, what is not uncommon, unavailable at all. This situation may be alleviated by mixing hard data (relevant experience data) with engineering judgment (subjective information expressed as expert opinions, judgments of analysts and analyst groups, etc.). A methodological framework for such a mixing is provided by a predictive, epistemic approach to QRA (PEA). This approach uses the concept of probability as the "engineer's measure of uncertainty" or "degree of belief". In view of forecasting AAs, PEA may be defined as a way of interpreting and specifying the frequency $Fr(\mathrm{AA})$ and p.d. $P(m|\mathrm{AA})$. PEA is focused on a future occurrence of observable events, like AA and "exceeding *m* given AA", and not on true, although unobservable values of $Fr(\mathrm{AA})$ and $P(m|\mathrm{AA})$. In PEA, there exists only one type of uncertainty, namely, an epistemic uncertainty in (the engineer's degree of

Table 4
Error modes in the drug therapy management process (Trucco & Cavallin, 2006).

Error mode (EM) Code	Description
EM1	Wrong patient
EM2	Inadequate monitoring after administration
EM3	Wrong dose (overdose or underdose)
EM4	Wrong dosage form
EM5	Wrong administration frequency
EM6	Wrong drug preparation
EM7	Order misunderstanding
EM8	Unauthorized drug
EM9	Different drug preparation or administration
EM10	Omitted dose
EM11	Wrong time
EM12	Extra dose
EM13	Deteriorated drug error
EM14	Drug-drug interaction or drug allergies
EM15	Wrong route
EM16	Wrong administration technique
EM17	Wrong rate

Table 5
The severity class and related weights (Trucco & Cavallin, 2006).

Class of severity	Description	Weight M_j
A-no consequences	No harm or increase of patient monitoring	$M_A = 0.1$
B-minor harm	Temporary harm to patient, whit additional therapeutic intervention or prolonged hospitalization inside one month	$M_B = 0.3$
C-medium harm	Temporary harm to patient (temporary disability) or prolonged hospitalization over one month	$M_C = 0.5$
D-serious harm	Permanently harm to patent (permanently disability), life-threatening harm or near death event	$M_D = 0.7$
E-death	Death of patient	$M_E = 0.9$

belief concerning) a future occurrence of AA and “exceeding m given AA” (Vaidogas, 2006). In line with PEA, the final result of forecasting an AA (Abnormal Action) can be expressed by an action model defined as

$$Fr(x) = Fr(\mathrm{AA})(1 - F_X(x|\pi_x))$$

where x is the vector of AA characteristics, X is the random vector with a distribution function (d.f.) $F_X(x|\pi_x)$ which models an epistemic uncertainty in x, $Fr(\mathrm{AA})$ is the frequency expressing the epistemic uncertainty related to a future occurrence of AA. The d.f. $F_X(x|\pi_x)$ expresses epistemic uncertainty in the event $X <= x$ (“is less component wise”). Thus, the value $Fr(x)$ quantifies epistemic uncertainty in the frequency of exceeding at least one component of x. $Fr(x)$ by its form is a generalization of a hazard curve. If the direct data on components of X is sparse or absent, both $Fr(\mathrm{AA})$ and $F_X(x|\pi_x)$ can in some cases be assigned indirectly by a SAS which can generate samples of AA characteristics and yield an estimate of $Fr(\mathrm{AA})$. The d.f. $F_X(x|\pi_x)$ can be fitted to the generated samples. Such a SAS can be used for a propagation of epistemic uncertainties and relate stochastic models of the physical phenomena preceding AA to epistemic uncertainties in characteristics of AA (Vaidogas, 2006).

n) *The weighted risk analysis (WRA)*: In order to balance safety measures with aspects, such as environmental, quality, and economical aspects, a weighted risk analysis methodology is used. The weighted risk analysis is a tool comparing different risks, such as investments, economical losses and the loss of human lives, in one-dimension (e.g. money), since both investments and risks could be expressed solely in money (Suddle, 2009). When a risk analysis is performed, not only technical aspects but also economical, environmental, comfort related, political, psychological and societal acceptance are aspects that play an important role. In some cases or scenarios with great consequences, weighing factors for all risk dimensions are used in order to make them comparable to each other and to relate them to the measures that must be taken for possible risk reduction. It is therefore, recommendable to compare and to integrate different decision-making elements, such as political, social, psychological, environmental, and quality risks or benefits, in a “one-dimensional” weighted risk R_w, e.g. in terms of money, as following (Suddle, 2009; Suddle & Waarts, 2003):

$$R_w = \sum_{j=1} a_j \sum_{i=1} R_{ij}$$

in which R_w is the weighted risk (cost unit per year); α_j is the (monetary) value per considered loss (cost unit). It has to be noted that the weighted risk R_w may consist of cost unities, which can be financial, but not necessarily. The weighted risk R_w can easily be extended into multiple decision-making elements, depending on the origin of the decision-maker. The previous formula can be specified into particular risk components:

$$R_w = a_1 \sum_{i=1} R_{\mathrm{human},i} + a_2 \sum_{j=1} R_{\mathrm{economic},j} + a_3 \sum_{k=1} R_{\mathrm{environment},k} + a_4 \sum_{l=1} R_{\mathrm{quality},l} + \cdots$$

in which α_1 is the (monetary) value per fatality or injury (cost unit); α_2 is the (monetary) value per environmental risk (cost unit); α_3 is the (monetary) value per economical risk (cost unit) (mostly $\alpha_3 = 1$), α_4 is the (monetary) value per quality risk (cost unit), and so on. If these non-safety-related aspects are quantified in the proposed weighted risk (analysis), and thus in one (monetary) dimension, safety measures can be balanced and optimized in respect of decision-making, shown as follows:

$$\text{Minimise}: \quad C_{\mathrm{tot}} = C_0(y) + \sum_{i=1} \frac{R_{wj}}{(1+r)^j}$$

in which C_{tot} is the total costs (money); $C_0(y)$ is the investment in a safety measure (money); y is the decision parameter; j is the number of the year and r is the real rate of interest. The above equation provides an overall mathematical-economic decision problem for balancing safety measures for all kinds of aspects by expressing both positive/negative risks and benefits of a project. The components of the weighted risk can only be computed quantitatively, if the monetary value per considered risk α_j is determined. Some of these values can be found in literature. It should be noted that these values are depending on local circumstances, which themselves depending on cultural and political aspects of the local policy.

3.1. *Hybrid techniques*

o) *Human Error Analysis Techniques (HEAT) or Human Factor Event Analysis (HFEA)*: Human errors have become widely recognized as a major contributory cause of serious accidents/incidents in a wide range of industries. The systematic consideration of human error in the design, operation, and maintenance of highly complex systems can lead to improved safety and more efficient operation (Attwood, Khan, & Veitch, 2006a,b; Baysari et al, 2008; Hollywell, 1996; Kontogiannis, 1999; Kontogiannis & Malakis, 2009). Work place design, safety culture, in addition to training, competence, task complexity, stress, etc. constitute a group of factors that influence operators’ behavior. These factors are called Performance Shaping Factors (PSF) (Kim & Jung, 2003), concern all work-related areas that exert certain influence on the operators performance, they are used in HEAT techniques (Kirwan, 1994), and “can be cause of some failures in other complex industrial systems” (Bellamy, Geyer, & Wilkinson, 2008; Cilingir & Mackhieh, 1998). Doytchev and Szwillus (2008), and Kirwan (1994) have listed different human error analysis techniques, including ATHEANA (A Technique for Human Error Analysis), CREAM (Cognitive Reliability and Error Analysis Method), HEART (Human Error Analysis and Reduction Technique), HEIST (Human Error Identification in System Tools), THERP (Technique for Human Error Rate Prediction) and others. The goal of these techniques is to determine the reasons for human error occurrence, the factors that influence human performance, and how likely the errors are to occur (Zarboutis & Marmaras, 2007). Moreover, a commonly utilized tool for investigating human contributions to accidents under a widespread evaluation scheme is the HFACS (Human Factors Analysis and Classification System) method which quantitatively characterizes the role of human errors (Celik & Cebi, 2009). Li, Shu-dong, and Xiang-rui (2003) have studied some mathematical tools for incorporating human factors (HF) in system reliability analyses. The overall method, called “HF event analysis” (HFEA) relied on two analytic methods (i) “technique for human error rate prediction” (THERP), which provided a human event tree model, and (ii) “human cognitive reliability” (HCR), which determined human errors during the diagnosis stage of an accident. Balkey and Phillips (1993) have proposed a practical approach to quantifying human error within the accident process. A mathematical relationship was proposed to model the likelihood (P) of occurrence of a human error event, as follows:

$$P(\text{human\_error}) = \left[\left(1 - \frac{1}{\#\text{options}}\right) \times \text{feedback} \times \text{adjuster} \times \text{redundancy}\right]$$

The variables in the equation are expected to affect the likelihood (P) of human error according to the following comments:

- *#Options*: as the choices faced by an individual increase, so does the opportunity for, and likelihood of, error.
- *Feedback*: visual feedback (e.g. the ability to actually see an action performed) will reduce the likelihood of human error.
- *Adjusters (external or internal)*: these cover the environment experienced by the operator – including temperature, humidity, clothing, mental and physical capabilities, and training.
- *Redundancy*: this is defined as a real-time repeat of the investigation of whether a human error is occurring.

p) *Fault-tree analysis (FTA)*: It is a deductive technique focusing on one particular accident event and providing a method for determining causes of that event. In other words FTA is an analysis technique that visually models how logical relationships between equipment failures, human errors, and external events can combine to cause specific accidents. Fault trees are constructed from events and gates. Basic events can be used to represent technical failures that lead to accidents while intermediate events can represent operator errors that may intensify technical failures. The gates of the fault trees can be used to represent several ways in which machine and human failures combine to give rise to the accident. For instance, an AND gate implies that both initial events need to occur in order to give rise to the intermediate event. Conversely, an OR gate means that either of two initial events can give rise to the intermediate event (Ayyub, 2003; Haimes, 2009; Harms-Ringdahl, 2001; Hong et al., 2009; Kontogiannis et al., 2000; Reniers et al., 2005; Vesely, Goldberg, Roberts, & Haasl, 1981; Yuhua & Datao, 2005). Below it is presented a summary of the graphics most commonly used to construct a fault tree.
   - *Top event and intermediate events:* The rectangle is used to represent the TOP event and any intermediate fault events in a fault tree. The TOP event is the accident that is being analyzed. Intermediate events are system states or occurrences that somehow contribute to the accident.
   - *Basic events:* The circle is used to represent basic events in a fault tree. It is the lowest level of resolution in the fault tree.
   - *Undeveloped events:* The diamond is used to represent human errors and events that are not further developed in the fault tree.
   - *AND gates:* The event in the rectangle is the output event of the AND gate below the rectangle. The output event associated with this gate exists only if all of the input events exist simultaneously.
   - *OR gates:* The event in the rectangle is the output event of the OR gate below the rectangle. The output event associated with this gate exists if at least one of the input events exists.
   - *Inhibit gates:* The event in the rectangle is the output event of the INHIBIT gate below the rectangle. This gate is a special case of the AND gate. The output event associated with this gate exists only if the input event exists and if the qualifying condition (the inhibiting condition shown in the oval) is satisfied.
   - *Transfer symbols:* Transfer symbols are used to indicate that the fault tree continues on a different page.

Procedure for Fault-Tree Analysis: The procedure for performing a fault-tree analysis consists of the following eight steps:

- *Define the system of interest.* Specify and clearly define the boundaries and initial conditions of the system for which failure information is needed.
- *Define the TOP event for the analysis.* Specify the problem of interest that the analysis will address. This may be a specific quality problem, shutdown, safety issue, etc.
- *Define the treetop structure.* Determine the events and conditions (i.e. intermediate events) that most directly lead to the TOP event.
- *Explore each branch in successive levels of detail.* Determine the events and conditions that most directly lead to each intermediate event. Repeat the process at each successive level of the tree until the fault-tree model is *complete*.
- *Solve the fault tree for the combinations of events contributing to the TOP event.* Examine the fault-tree model to identify all the possible combinations of events and conditions that can cause the TOP event of interest. A combination of events and conditions sufficient and necessary to cause the TOP event is called a *minimal cut set*. For example, a minimal cut set for over-pressurizing a tank might have two events: (1) pressure controller fails and (2) relief valve fails.
- *Identify important dependent failure potentials and adjust the model appropriately.* Study the fault-tree model and the list of minimal cut sets to identify potentially important dependencies among events. Dependencies are single occurrences that may cause multiple events or conditions to occur at the same time. This step is qualitative common cause failure analysis.
- *Perform quantitative analysis.* Use statistical characterizations regarding the failure and repair of specific events and conditions in the fault-tree model to predict future performance for the system.
- *Use the results in decision-making.* Use results of the analysis to identify the most significant vulnerabilities in the system and to make effective recommendations for reducing the risks associated with those vulnerabilities.

For example a vessel's hydraulic steering system (Fig. 6a) will fail if both hydraulic pumps fail to operate. The TOP event for the analysis is "both pumps transfer off", and the treetop structure is illustrated in Fig. 6b.

q) *The ETA method (Event Tree Analysis)*. Event tree analysis (ETA) is a technique that uses decision trees and logically develops visual models of the possible outcomes of an initiating event. Furthermore, it is a graphical representation of the logic model that identifies and quantifies the possible outcomes following the initiating event. The models explore how safeguards and external influences, called lines of assurance, affect the path of accident chains (Ayyub, 2003; Beim & Hobbs, 1997; Hong et al., 2009). In this method, an initiating event such as the malfunctioning of a system, process, or construction is considered as the starting point and the predictable accidental results, which are sequentially propagated from the initiating event, are presented in order graphically. ETA is a system model representing system safety based on the safeties of subevents. It is called an event tree because the graphical presentation of sequenced events grows like a tree as the number of events increase. An event tree consists of an initiating event, probable subsequent events and final results caused by the sequence of

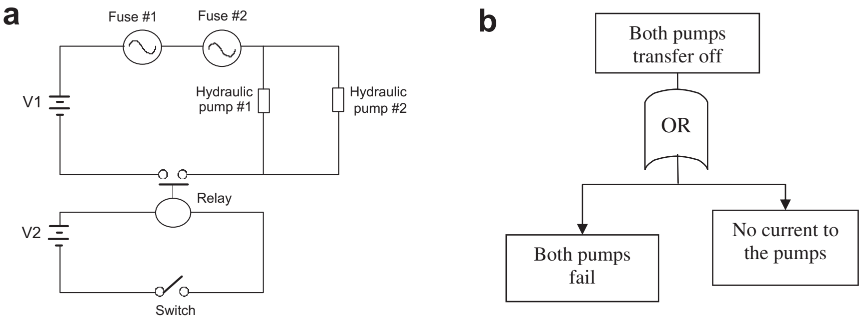

Fig. 6. (a) A drawing of a vessel's hydraulic steering system. (b) The treetop structure produced by the application of FTA.

events. Probable subsequent events are independent to each other and the specific final result depends only on the initiating event and the subsequent events following. Therefore, the occurrence probability of a specific path can be obtained by multiplying the probabilities of all subsequent events existing in a path. In an event tree, all events in a system are described graphically and it is very effective to describe the order of events with respect to time because the tree is related to the sequence of occurrences. In the design stage, ETA is used to verify the criterion for improving system performance; to obtain fundamental information of test operations and management; and to identify useful methods to protect a system from failure. The ETA technique is applicable not only to design, construction, and operation stages, but also to the change of operation and the analysis of accident causes. The main characteristics of the technique are briefly summarized as follows:

- It models the range of possible accidents resulting from an initiating event.
- It is a risk-assessment technique that effectively accounts for timing, dependence, and domino effects among various accident contributors that are cumbersome to model in fault trees
- It is an analysis technique that generates the following:
  - ○ Qualitative descriptions of potential problems as combinations of events producing various types of problems from initiating events
  - ○ Quantitative estimates of event frequencies or likelihoods and relative importance of various failure sequences and contributing events
  - ○ Lists of recommendations for reducing risks
  - ○ Quantitative evaluations of recommendation effectiveness

r) *The RBM Method (Risk-based Maintenance)*. This is a comprehensive hybrid (quantitative/qualitative) technique for risk-based maintenance and can be applied to all types of assets irrespective of their characteristics. The quantitative description of risk is affected by the quality of the consequence study and the accuracy of the estimates of the probability of failure. The methodology of RBM is broken down into three main modules: (i) risk determination, which consists of risk identification and estimation, (ii) risk evaluation, which consists of risk aversion and risk acceptance analysis, and (iii) maintenance planning considering risk factors (Khan & Haddara, 2003).

Module I: risk estimation. This module comprises four steps, which are logically linked as shown in Fig. 7.

Step I.1: Failure scenario development. A failure scenario is a description of a series of events which may lead to a system failure. It may contain a single event or a combination of sequential events. Usually a system failure occurs as a result of interacting sequence of events. The expectation of a scenario does not mean it will indeed occur, but that there is a reasonable probability that it would occur. A failure scenario is the basis of the risk study; it tells us what may happen so that we can devise ways and means of preventing or minimizing the possibility of its occurrence. Such scenarios are generated based on the operational characteristics of the system; physical conditions under which operation occur; geometry of the system, and safety arrangements, etc.

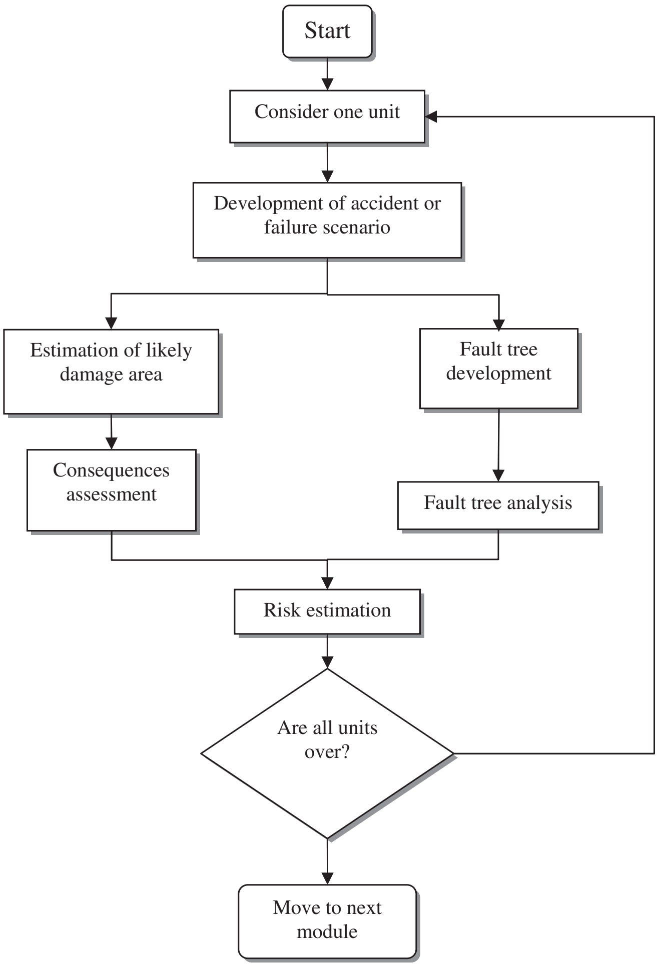

Fig. 7. Description of the risk-estimation model according to RBM technique (Khan & Haddara, 2003).

Table 6
Quantification scheme for system performance function (Khan & Haddara, 2003).

Class	Description	Function (operation)
I	Very important for system operation Failure would cause system to stop functioning	8–10
II	Important for good operation Failure would cause impaired performance and adverse consequences	6–8
III	Required for good operation Failure may affect the performance and may lead to subsequent failure of the system	4–6
IV	Optional for good performance Failure may not affect the performance immediately but prolonged failure may cause system to fail	2–4
V	Optional for operation Failure may not affect the system's performance	0–2

Step I.2: Consequence assessment. The objective here is to prioritize equipment and their components on the basis of their contribution to a system failure. Consequence analysis involves assessment of likely consequences if a failure scenario does materialize. Initially, consequences are quantified in terms of damage radii (the radius of the area in which the damage would readily occur), damage to property (shattering of window panes, caving of buildings), and toxic effects (chronic/acute toxicity, mortality). The calculated damage radii are used to assess the effect on human health, and environmental and production losses. The total consequence assessment is a combination of four major categories:

2.a) *System performance loss:* Factor *A* accounts for the system's performance loss due to component/unit failure. This is estimated semi-qualitatively based on the expert's opinion. In the work of Khan and Haddara (2003), it is suggested using the following relation for determining the value of this parameter: $A_i = function\ (performance)$, where details of the function are given in Table 6.

2.b) *Financial loss:* Factor *B* accounts for the damage to the property or assets and may be estimated for each accident scenario using the following relations:

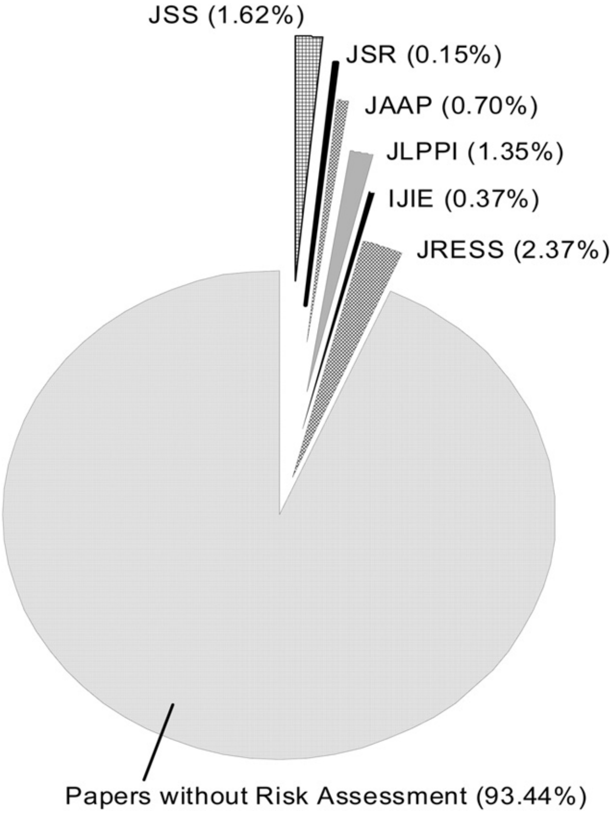

Fig. 8. It is presented the distribution of the relative occurrence-frequencies $f_i = n_i/N$, concerning papers including RAA techniques, as a result of six scientific journals reviewing, covering the period of 2000–2009.

$$B_i = (\mathrm{AR})_i \cdot (\mathrm{AD})_i / \mathrm{UFL}$$

$$B = \sum_{i=1,n} B_i$$

where *i* denotes the number of events (i.e. fire, explosion, toxic release, etc.). The UFL in the first equation signifies the level of an unacceptable loss. This value is subjective and may change from case to case as per an organization's criterion (Khan & Haddara,

Table 7
It presents for the period 2000–2009, the statistical results of six scientific journals investigation, concerning papers with as main aim the risk analysis and assessment (RAA) techniques.

Journal	Number of investigated papers (*Absolute frequency N_i*)	Relative frequency ($F_i = N_i/N$) [%]	Number of papers with risk-assessment techniques (*Absolute frequency of occurrence n_i*)	Relative frequency of occurrence ($f_i = n_i/N$) [%]	Normalized per journal frequency of occurrence ($f_i^* = n_i/N_i$) [%]
(A)	(B)	(C) = (B)/N	(D)	(E) = (D)/N	(F) = (D)/(B)
Safety science (JSS)	768	12.46	100	1.62	13.02
Journal of Safety Research (JSR)	658	10.68	9	0.15	1.37
Accident Analysis and Prevention (JAAP)	1411	22.90	43	0.70	3.05
Journal of Loss Prevention in the Process Industries (JLPPI)	892	14.47	83	1.35	9.31
International Journal of Industrial Ergonomics (IJIE)	868	14.08	23	0.37	2.65
Reliability Engineering & System Safety (JRESS)	1566	25.41	146	2.37	9.32
Total	6163	100.00	404	6.56	

Annotations: Total absolute frequency (i.e. the total number of investigated papers): $N = 6163$; Total absolute frequency of occurrence (i.e. the total number of papers with risk-assessment techniques): $n = 404$; Total relative frequency of occurrence: $f = 0.0656$ (6.56%).

2003) use for UFL the value of 1000). AR: The area under the damage radius (m^2); AD: The asset density in the vicinity of the event (up till ∼500 m radius) ($\$/m^2$).

2.c) *Human health loss*: A fatality factor is estimated for each accident scenario using the following equations:

$$\mathrm{PDI} = \mathrm{PDI}\cdot\mathrm{PDFI}$$

$$C_i = (\mathrm{AR})_i\cdot(\mathrm{PDI})_i/\mathrm{UFR}$$

$$C = \sum_{i=1,n} C_i$$

where UFR denotes an unacceptable fatality rate. The suggested value for UFR is 10^{-3} (subjective value and may change from case to case).

The PDF1 defines the population distribution factor, which reflects heterogeneity of the population distribution. If the population is uniformly distributed in the region of study (∼500 m radius), the factor is assigned a value of 1; if the population is localized and away from the point of accident the lowest value 0.2 is assigned. PDI: The population density in the vicinity of the event (up till ∼500 m radius) (persons/m^2)

2.d) *Environment and/or ecological loss:* The factor D signifies damage to the ecosystem, which can be estimated as:

$$D_i = (\mathrm{AR})_i x(\mathrm{IM})_i/\mathrm{UDA}$$

$$D = \sum_{i=1,n} D_i$$

where UDA indicates a level for the unacceptable damaging area, the suggested value for this parameter is 1000 m^2 (subjective value and may change from case to case); IM denotes importance factor. IM is unity if the damage radius is higher than the distance between an accident and the location of the ecosystem. This parameter is quantified by Khan & Haddara (2003) (see their figure 4).

Finally, the factors A, B, C and D are combined together to yield the factor Con (consequence assessment factor)

$$\mathrm{Con} = \left[0.25A^2 + 0.25B^2 + 0.25C^2 + 0.25D^2\right]^{0.5}$$

Step I.3: Probabilistic failure analysis. Probabilistic failure analysis is conducted using fault-tree analysis (FTA). The use of FTA, together with components' failure data and human reliability data, enables the determination of the frequency of occurrence of an accident.

Step I.4: Risk estimation. The results of the consequence and the probabilistic failure analyses are then used to estimate the risk that may result from the failure of each unit.

Module II: risk evaluation. The evaluation algorithm comprises two steps as detailed below:

Step II.1. Setting up the acceptance criteria. In this step, we identify the specific risk acceptance criteria to be used. Different acceptance risk criteria are available in the literature.

Step II.2. Risk comparison against acceptance criteria. In this step, we apply the acceptance criteria to the estimated risk for each unit in the system. Units whose estimated risk exceeds the acceptance criteria are identified. These are the units that should have an improved maintenance plan.

Module III: maintenance planning. Units whose level of estimated risk exceeds the acceptance criteria are studied in detail with the objective of reducing the level of risk through a better maintenance plan.

Step III.1. Estimation of optimal maintenance duration. The individual failure causes are studied to determine which one affects the probability of failure adversely. A reverse fault analysis is carried out to determine the required value of the probability of failure of the root event. A maintenance plan is then completed.

Step III.2. Re-estimation and re-evaluation of risk. The last step in this methodology aims at verifying that the maintenance plan developed produces acceptable total risk level for the system.

4. Statistical analysis and results of the scientific literature reviewing

The second objective of the work was the statistical analysis, classification, and comparative study of the scientific papers with as main aim the risk analysis and assessment (RAA) techniques. This objective was achieved by the investigation of six representative scientific journals published by Elsevier B.V. during the last decade. So, we exhaustively searched the journals (a) Safety Science (JSS), (b) Journal of Loss Prevention in the Process Industries (JLPPI), (c) Accident Analysis and Prevention (JAAP), (d) Journal of Safety Research (JSR), (e) International Journal of Industrial Ergonomics (IJIE), and (f) Reliability Engineering and System Safety (JRESS), covering the period 2000–2009.

More specifically, we studied and investigated all the published papers of the above referred journals, gathering a total number of 6163 papers. The reviewing of the scientific literature (i) revealed a plethora of 404 published technical articles including risk analysis and assessment (RAA) techniques concerning many different fields, like engineering, medicine, chemistry, biology, agronomics, etc. and (ii) showed that the risk analysis and assessment techniques are classified into three main categories the qualitative, the quantitative and the hybrid techniques (qualitative–quantitative, semi-quantitative). These articles address concepts, tools, technologies, and methodologies that have been developed and practiced in such areas as planning, design, development, system integration, prototyping, and construction of physical infrastructure; in reliability, quality control, and maintenance.

In the Appendix (Table A) we depict the above referred 404 selected papers, taking into account the basic classification of Fig. 1, and using seven columns e.g. (A) the number (or numerical code) of the paper, (B) the paper's citation information, (C) the name of the risk analysis or/and assessment technique, (D) the type of the main methodology, (E) the kind of the paper's data or material, (F) the field of application, and (G) the source (JSS, JSR, JAAP, JLPPI, IJIE, JRESS).

Table 7 illustrates the statistical results of the investigation including the following: (a) the absolute frequency N_i i.e. the number of investigated papers per journal (JSS:768, JSR:658, JAAP:1411, JLPPI:892, IJIE:868, JRESS:1566), (b) the relative frequency $F_i = N_i/N$ (JSS:12.46%, JSR:10.68%, JAAP:22.90%, JLPPI:14.47%, IJIE:14.08%, JRESS:25.41%), (c) the absolute frequency of occurrence n_i i.e. the number of papers with risk-assessment techniques (JSS:100, JSR:9, JAAP:43, JLPPI:83, IJIE:23, JRESS:146), (d) the relative frequency of occurrence $f_i = n_i/N$ (JSS:1.62%, JSR:0.15%, JAAP:0.70%, JLPPI:1.35%, IJIE:0.37%, JRESS:2.37%), and (e) the normalized (per journal) frequency of occurrence $f_i^* = n_i/N_i$ which has been used in order to weigh up the contribution of each journal (JSS:13.02%, JSR:1.37%, JAAP:3.05%, JLPPI:9.31%, IJIE:2.65%, JRESS:9.32%).

Table 8
The table (i) compares the various risk analysis and assessment methodologies focusing on the advantages (column a) and disadvantages (column b) and (ii) highlights areas of future improvements (column c).

Techniques	Advantages	Disadvantages	Future Improvements
	(a)	(b)	(c)
Qualitative Techniques			
Checklists	• It is a systematic approach built on the historical knowledge included in checklist questions • It is applicable to any activity or system, including equipment issues and human factors issues • It is generally performed by an individual trained to understand the checklist questions, or sometimes by a small group • It ensures that organizations are complying with standard practices • Easy application of the technique • It could answer more complicated risk-related questions only if some degree of quantification is added, possibly with a relative ranking/risk indexing approach	• The inability of identifying complex hazard sources • The quality of evaluation is determined primarily by the experience of people creating the checklists and the training of the checklist users • It is used as a supplement to or integral part of another method • The structure of checklist analysis relies exclusively on the knowledge built into the checklists to identify potential problems. • If the checklist does not address a key issue, the analysis is likely to overlook potentially important weaknesses • Traditionally provides only qualitative information, with no quantitative estimates of risk-related characteristics	• Some degree of quantification should be incorporated, possibly with a relative ranking/risk indexing approach • A special, graphical type of checklist could be developed for a more effective cause analysis • An integrated risk analysis scheme, which will incorporate and combine a well-considered selection of techniques (includingchecklist, what-if-analysis, safety-analysis, task analysis, STEP and HAZOP) could be developed, achieving more efficient results on the risk analysis
What-If -Analysis	• Identifies hazards, hazardous situations or specific accident events that could result in undesirable consequences • Relative easy the application of the technique • It is not very expensive • It is applicable to any activity or system. • Occasionally it is used alone, but most often is used to supplement other, more structured techniques	• It produces only qualitative results • It determines only hazard consequences • It is a loosely structured assessment • The quality of the evaluation depends on the quality of the documentation, the training of the review team leader, and the experience of the review teams	• A special, graphical type of the technique could be developed for a more effective analysis • An integrated risk analysis scheme, which will incorporate and combine a well-considered selection of techniques (including checklist, what-if -analysis, safety analysis, task analysis, STEP and HAZOP) could be developed, achieving more efficient results on the risk analysis • A combination of Hazop analysis, What-If-analysis and the Risk Matrix into one framework (Hazwim: according to Reniers et al., 2005) could be developed, constituting a meta-technical tool for optimizing the organization of discussing process hazard analysis performances by employees of neighboring companies in an industrial area • It could be incorporated in the development of an external domino accident prevention (EDAP) framework
Safety Audits	• Identifies equipment conditions or operating procedures that could lead to a casualty or result in property damage or environmental impacts • Easy application of the technique • It is cheap	• It cannot be used for identifying technical installation hazard sources • The result is only a report that provides corporate management with an overview of the level of performance for various safety aspects of operations	• A graphical type of the technique could be developed for a more effective analysis • An integrated risk analysis scheme, which will incorporate and combine a well-considered selection of techniques (including checklist, what-if -analysis, safety analysis, task analysis, STEP and HAZOP) could be developed, achieving more efficient results on the risk analysis
Task Analysis	• It can be used to create a detailed picture of human involvement using all the information necessary for an analysis in an adequate degree of details • Through its hierarchical approach it provides a well-structured overview of the work processes • In its hierarchical approach it is an easy to use method of gathering and organizing information about human activities and human interaction • In its hierarchical approach, it enables the analyst to find safety critical tasks	• It is time-consuming in case of complex tasks • It requires the cooperation of experts from the application domain, knowledgeable about the task operation conditions	• An integrated risk analysis scheme, which will incorporate and combine a well-considered selection of techniques (including checklist, what-if-analysis, safety analysis, task analysis, STEP and HAZOP) could be developed, achieving more efficient results on the risk analysis • The hierarchical approach of the technique should be expanded • The phase of data collection about human interventions and system demands should be improved • The representation of data which are collected in the frame of Task analysis should be improved in a comprehensible format or graph

STEP technique	• It provides a valuable overview of the timing and sequence of events/actions that contributed to the accident • It provides a reconstruction of the harm process by plotting the sequence of events that contributed to the accident	• It is time-consuming in case of complex sequence of events • It produces only qualitative results	• An integrated risk analysis scheme, which will incorporate and combine a well-considered selection of techniques (including checklist, what-if-analysis, safety analysis, task analysis, STEP and HAZOP) could be developed, achieving more efficient results on the risk analysis • A special, graphical type of the technique could be developed for a more effective analysis
HAZOP	• It is a formalized and systematic methodology to identify and document hazards through imaginative thinking • Identifies system deviations and their causes that can lead to undesirable consequences and determine recommended actions to reduce the frequency and/or consequences of the deviations • It determines hazard causes and hazard consequences • Very popular technical method • It is applicable to any system or procedure • It is a highly structured assessment relying on guide words to generate a comprehensive review	• It is expensive and difficult • It requires a multidisciplinary team of experts to be used • It produces only qualitative results • It is a time-consuming technique	• An integrated risk analysis scheme, which will incorporate and combine a well-considered selection of techniques (including checklist, what-if-analysis, safety analysis, task analysis, STEP and HAZOP) could be developed, achieving more efficient results on the risk analysis • A combination of Hazop analysis, What—If-analysis and the Risk Matrix into one framework (Hazwim: according to Reniers et al., 2005) could be developed, constituting a meta-technical tool for optimizing the organization of discussing process hazard analysis performances by employees of neighboring companies in an industrial area • It could be incorporated in the development of an external domino accident prevention (EDAP) framework • The technique could be extended by the development of domino effects-specific guidewords and parameters
Quantitative Techniques			
PRAT	• Easy application of the technique • It is a quantitative technique • The mathematical risk evaluation • Safe results, based on the recorded data of undesirable events or accidents • It combines risk analysis with risk evaluation • It can be incorporated in databases • It can help with their numerical results other risk-assessment techniques • It can help the safety managers/engineers to predict hazards, unsafe conditions and undesirable events/situations, and also to prevent fatal accidents. • It can be applied to any company/corporation or productive procedure	• It requires efficient safety managers to record the undesirable events • It is a time-consuming technique in order to record data of undesirable events of a company • The results depend on the opinion of expert safety managers or production engineers	• It could be incorporated in databases, where statistic information of accidents are being registered, in order to help other risk-assessment techniques • It could be incorporated in computer automated toolkits in order to identify the weak spots in an industrial area • It could be incorporated to an integrated quantitative risk analysis scheme, which will combine a well-considered selection of widespread quantitative techniques • It could be combined with stochastic (like time-series (TSP)) and quantitative risk-assessment (like PRAT, SRE) methodologies, achieving a more realistic forecasting and risk-assessment process in the worksites (see the proposed PRAT-TSP-SRE scheme of Marhavilas & Koulouriotis, submitted for publication)
DMRA	• Easy application of the technique • Safe results, based on the recorded data of undesirable events or accidents • It combines risk analysis with risk evaluation • It can help the safety managers/engineers to predict hazards, unsafe conditions and undesirable events/situations, and also to prevent fatal accidents. • It can be applied to any company/corporation or productive procedure • It is a quantitative and also a graphical method which can create liability issues and help the risk managers to prioritize and manage key risks	• The results depend on the opinion of expert safety managers or production engineers	• A combination of Hazop analysis, What—If-analysis and the Risk Matrix into one framework (Hazwim: according to Reniers et al., 2005) could be developed, constituting a meta-technical tool for optimizing the organization of discussing process hazard analysis performances by employees of neighboring companies in an industrial area • It could be incorporated in the development of an external domino accident prevention (EDAP) framework • It could be incorporated in databases, where statistic information of accidents are being registered, in order to help other risk-assessment techniques • It could be incorporated in computer automated toolkits in order to identify the weak spots in an industrial area • It could be incorporated to an integrated quantitative risk analysis scheme, which will combine a well-considered selection of widespread quantitative techniques

(*continued on next page*)

Table 8 (*continued*)

Techniques	Advantages	Disadvantages	Future Improvements
	(a)	(b)	(c)
Risk measures of societal risk (SRE)	• Easy application of the technique • It usually encompasses both public and worker risk • It depicts the historical record of incidents • It is both a quantitative and graphical technique • The information about societal risk is illustrated by simple FN-diagrams • It depicts criteria for judging the tolerability of risk • Mathematical or/and empirical risk criteria may be defined to help target risk-reduction measures, and limit the risk of major accidents • A common form of societal risk criteria is implemented easily by the drawing of specific lines on FN-plots • The system is characterized (as tolerable or intolerable) graphically and easily	• It requires efficient safety managers to record the undesirable events • It is a time-consuming technique in order to record data of undesirable events of a company	• It could be combined with stochastic (like time-series (TSP)) and quantitative risk-assessment (like PRAT, QRA) methodologies, achieving a more realistic forecasting and risk-assessment process in the worksites (see the proposed PRAT-TSP-SRE scheme of Marhavilas & Koulouriotis, submitted for publication) • Improved mathematical risk criteria should be developed • The application of empirical risk criteria should be extended • It should be clearly defined the procedure of determining empirical criteria
QRA technique	• It provides a consistent basis to analyze the individual and societal risk • It is a quantitative technique	• It is complicated because it consists of a combination of sub models • It is difficult because the scenarios and their frequencies should be defined	• It could be incorporated in databases, where statistic information of accidents are being registered, in order to help other risk-assessment techniques • It could be incorporated in computer automated toolkits in order to identify the weak spots in an industrial area • It could be incorporated to an integrated quantitative risk analysis scheme, which will combine a well-considered selection of widespread quantitative techniques • It could be combined with stochastic and quantitative risk-assessment (like PRAT, SRE) methodologies, achieving a more realistic forecasting and risk-assessment process in the worksites • It could be incorporated in the development of an external domino accident prevention (EDAP) framework
QADS	• It is a quantitative assessment of domino accidents • Escalation criteria address the possible damage of equipment due to the physical effects generated in the primary scenarios	• It is complicated • It requires a lot of time-consuming in its application • It is expensive	• It should be clearly defined the procedure of identifying credible domino scenarios • The identification of the credible domino scenarios should be based on escalation criteria • Improved escalation criteria should be developed
CREA method	• It is a quantitative method • It is based on techniques which are well-established in industry • It allows the analyst to join data which have been collected through direct observation of processes or interviews to statistical data reported in literature	• It is complicated • It requires a lot of time-consuming in its application • It requires a multidisciplinary team of experts to be used	• It should be expanded the incorporation of qualitative and/or quantitative techniques in CREA scheme
PEA method	• It is based on the so-called predictive, epistemic approach to risk assessment • It provides formal means for combining hard data and subjective information and allows forecasting the abnormal (accidental) actions in the form of mathematical models • It quantifies epistemic (state-of-knowledge) uncertainties in characteristics of the actions	• It is complicated • It requires a lot of time-consuming in its application • It requires a multidisciplinary team of experts to be used	• The epistemic models which allow a rough, knowledge-based estimation of probabilities of damage from abnormal actions, should be increased and extended • The deterministic or probabilistic structural analysis which is used in the assessment of damage could be expanded
WRA	• It is used in order to balance safety measures with aspects, such as environmental, quality, and economical aspects • It is a tool that compares different risks, such as investments, economical losses and the loss of human lives, in one-dimension	• It is very complicated and difficult • It requires a lot of time-consuming in its application • It requires a multidisciplinary team of experts to be used, because of the different risks	• Weighing factors for all risk dimensions could be extended in order to make them comparable to each other and to relate them to the measures that must be taken for possible risk reduction

Hybrid Techniques			
HEAT/HFEA	• It is a commonly utilized tool for investigating human contributions to accidents under a widespread evaluation scheme	• It is very complicated and difficult	• Sufficient mathematical tools for incorporating human factors in system reliability analyses should be developed • Practical approaches of quantifying human error within the accident process should be developed
FTA	• It identifies and models combinations of equipment failures, human errors, and external conditions that can result in an accident • It is performed primarily by an individual working with system experts through interviews and field inspections • It is a deductive modeling approach • It produces quantitative and qualitative results • It is a highly structured method • It determines accidents causes in depth • It is generally applicable for almost every type of risk-assessment application • It can be used as an effective root cause analysis tool in several applications	• It is very complicated and difficult • It requires a lot of time-consuming in its application • It is expensive • It is used most often as a system-level risk-assessment technique	• It could be combined with other accident scenario analysis techniques (ETA, Petri-Nets) in order to achieve the accident reconstruction, where the human factor is involved • It should be used to the development of accident analysis techniques which thoroughly investigates the accidents
ETA	• Identifies various sequences of events, both failures and successes that can lead to an accident • It is a graphical representation of the logic model that identifies and quantifies the possible outcomes following the initiating event • It is an inductive modeling approach • It produces quantitative and qualitative results • It is applicable not only to design, construction, and operation stages, but also to the change of operation and the analysis of accident causes	• It is very complicated and difficult • It requires a lot of time-consuming in its application • It is expensive	• It could be combined with other accident scenario analysis techniques (FTA, Petri-Nets) in order to achieve the accident reconstruction, where the human factor is involved • It should be used to the development of accident analysis techniques which thoroughly investigates the accidents
RBM	• It is a comprehensive quantitative and qualitative technique • It can be applied to all types of assets irrespective of their characteristic	• The quantitative description of risk is affected by the quality of the consequence study and the accuracy of the estimates of the probability of failure	• It could be incorporated to an integrated quantitative risk analysis scheme, which will combine a well-considered selection of widespread quantitative techniques • It could be improved a the combination scheme with other qualitative and quantitative techniques, as FTA, ETA, PRAT

Table 9
An overview illustration of the characteristics of the various risk analysis and assessment techniques, comparatively with settled evaluation criteria.

Evaluation criteria	Qualitative Techniques						Quantitative Techniques								Hybrid Techniques			
	Check -Lists	What-if -Analysis	Safety Audits	Task Analysis	STEP	HAZOP	PRAT	DMRA	Societal risk	QRA	QADS	CREA	PEA	WRA	HEAT/HFEA	FTA	ETA	RBM
Data collection	√	√	√	√			√	√	√	√		√				√	√	
Representation of the events' chain				√	√											√	√	
Identification of hazardous situations		√		√	√	√	√	√	√	√	√	√				√	√	√
Multidisciplinary experts team for the application		√		√		√					√	√	√	√				
High level of structuring				√		√	√		√	√	√	√	√	√		√	√	√
Applicable to any process or system	√	√				√	√	√	√	√			√			√	√	
Possibility of incorporation in integrated risk analysis schemes	√	√	√	√	√	√	√	√	√	√		√						
Time-consuming				√	√	√	√		√		√	√		√		√	√	
System design	√	√		√					√					√	√	√	√	√
Safety audits			√		√		√	√		√	√	√			√			√
Human orientation				√	√				√			√		√	√			√
Equipment orientation			√			√			√		√					√	√	√
Proactive use	√	√	√	√		√	√	√	√	√	√	√		√	√	√	√	
Reactive use					√		√	√	√	√			√	√		√	√	√
Mathematical background							√	√	√	√	√	√	√	√	√	√	√	√
Graphical illustration				√	√			√	√							√	√	
Possibility of incorporation in databases	√	√					√	√		√								
Possibility of incorporation in computer automated toolkits					√		√	√		√						√	√	
Prediction of potential risks					√		√	√	√	√	√	√	√	√	√	√	√	√
Individual risk orientation	√	√	√	√	√	√	√	√		√		√	√		√	√	√	√
Societal risk orientation									√	√	√			√		√	√	√

Moreover, Fig. 8 depicts the distribution of the relative occurrence-frequencies f_i. According to these illustrations, JRESS presents the highest absolute and relative frequency [$N_i = 1566$, $F_i = 25.41\%$] (Table 7/columns B, C), and the highest absolute and relative frequency of occurrence as well [$n_i = 146$, $f_i = 2.37\%$] (Table 7/col. D, E and Fig. 8), while the total frequencies are $N = 6163$, $n = 404$ and $f = 0.0656$ (or 6.56%). On the other side, JSS presents the highest normalized frequency of occurrence $f_i^* = 13.02\%$ (column F).

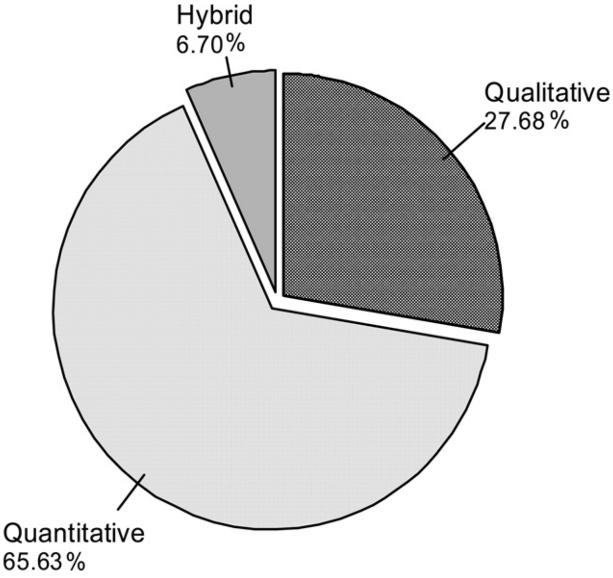

Fig. 9. It is displayed the percentage distribution of the relative frequencies of the three main RAA categories (qualitative, quantitative, hybrid) which have been determined by the journals reviewing, covering the period of 2000–2009.

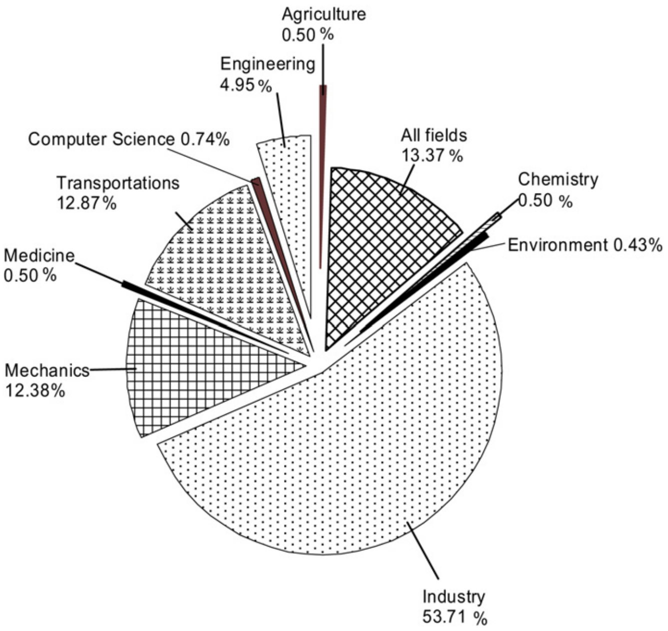

Fig. 10. It is illustrated for the reviewing period 2000–2009, the percentage distribution of papers with RAA techniques, relatively to the various fields of application.

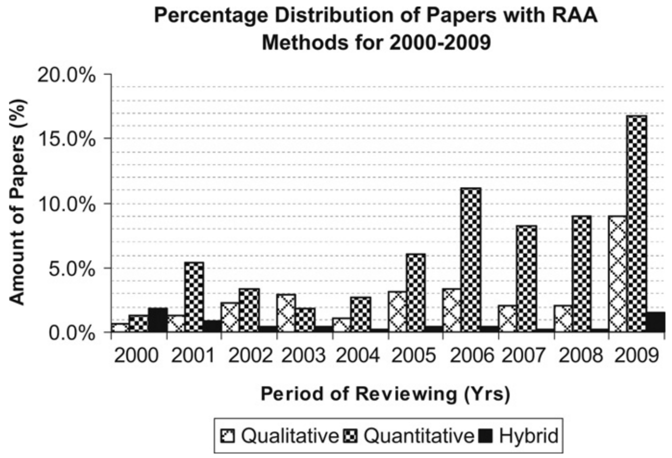

Fig. 11. It is depicted for the reviewing period of 2000–2009 the yearly percentage distribution of papers with RAA, relatively to the three main RAA classes (qualitative, quantitative, hybrid).

In Table 8 we compare the various risk analysis and assessment methodologies focusing on the advantages (column a) and disadvantages (column b) and we highlight as well, areas of future improvements (column c). To continue, in Table 9 we present an overview of the characteristics of the various risk analysis and assessment techniques, comparatively with a list of several settled evaluation criteria.

In Fig. 9 we display the percentage distribution of the relative frequencies of the three main RAA classes (qualitative, quantitative, hybrid) which have been determined by the journals reviewing, covering the period of 2000–2009. The pie-chart shows that the "quantitative" methods present the highest relative frequency (quantitative: 65.63%, qualitative: 27.68%, hybrid: 6.70%).

Furthermore, in Fig. 10 we show the percentage distribution of the papers including RAA techniques, relatively to the various fields of application (Agriculture: 0.50%, Chemistry: 0.50%, Environment: 0.50%, Industry: 53.71%, Mechanics: 12.38%, Medicine: 0.50%, Transportations: 12.87%, Computer Science: 0.74%, Engineering: 4.95%, All fields: 13.37%). The main discernible feature of this pie-chart is that the field of "Industry" concentrates the greatest number of the papers with RAA methods.

The bar-chart of Fig. 11 depicts for the period 2000–2009 the yearly percentage distribution of the papers with RAA, relatively to the three main RAA classes (qualitative, quantitative, hybrid). The graph shows that there is a gradual increasing (with intensive inclination) of papers including quantitative techniques from 2003 to 2009 with a maximum percentage amount (16.70%) in year 2009. On the other side the distribution of the papers with "hybrid" techniques remains constantly low (≤1.6%) during the entire period of reviewing (2000–2009), while the papers with "qualitative" techniques present a low level distribution (≤3.3%) during the interval 2000–2008 but an intensive increase in year 2009 (8.9%).

5. Conclusions

The objective of this work is to analyze and classify the main risk analysis and assessment (RAA) methods by reviewing the scientific literature. It consists of two parts: a) the overview of the main RAA methodologies and b) the classification and statistical analysis of the corresponding scientific papers published by six representative scientific journals of Elsevier B.V. covering the last decade (2000–2009).

The main results and conclusions of this work are summarized to the following points:

- The reviewing of the scientific literature, revealed a plethora of published technical articles on safety, and risk analysis referred to many different fields, like engineering, mechanics, industry, medicine, chemistry, biology, agronomics, etc.
- These articles address concepts, tools, technologies, and methodologies that have been developed and practiced in such areas as planning, design, development, system integration, prototyping, and construction of physical infrastructure, in reliability, quality control, and maintenance.
- The RAA techniques are classified into three main categories: (a) the qualitative, (b) the quantitative, and (c) the hybrid techniques (qualitative–quantitative, semi-quantitative).
- The papers with RAA techniques still constitute a very small part of the scientific literature i.e. taking into account the above referred investigation which covers the period 2000–2009, the total relative frequency is only 6.56%.
- The quantitative methods present the highest relative frequency (65.63%) while the qualitative a lower one (27.68%). Furthermore the hybrid methods remain constantly at a very low level (6.70%) during the entire processing period of 2000–2009.
- The qualitative techniques are based both on analytical estimation processes, and on the safety managers–engineers ability. According to quantitative techniques, the risk can be considered as a quantity, which can be estimated and expressed by a mathematical relation, under the help of real accidents' data recorded in a work site. The hybrid techniques, present a great complexity due to their ad hoc character that prevents a wide spreading.
- The field of "Industry" concentrates the greatest number of RAA methods (53.71%), while other fields with significant percentages are "Mechanics" (12.38%) and "Transportations" (12.87%).
- The yearly percentage distribution of papers with RAA shows that there is a gradual increasing (with intensive inclination) of papers including quantitative techniques from 2003 to 2009 with a maximum percentage amount (16.70%) in year 2009. The distribution of "hybrid" techniques remains constantly low (≤1.6%) during all the reviewing period (2000–2009), while the "qualitative" techniques present a low level distribution (≤3.3%) during the interval 2000–2008 but an intensive increase in year 2009 (8.9%).

A general basic ascertainment is that all of this knowledge has not been fully shared among the various scientific fields, so we think that the scientific community faces with the challenge to duplicate and transfer the commonalities from one field to another.

Acknowledgments

We acknowledge C. Mitrakas, Production & Management Engineer, for his help on the preparation of some drawings.

Appendix

The following table presents the classification results of the 404 papers with as main aim the risk analysis and assessment (RAA) techniques, which were determined by the investigation of 6163 papers of six scientific journals covering the period 2000–2009.

Table A.

Nr	Paper Citation	Technique's name	Method's type	Type of paper data or material	Field of application	Journal
(A)	(B)	(C)	(D)	(E)	(F)	(G)
1	Determination of the optimal escape routes of underground mine networks in emergency cases (Jalali & Noroozi, 2009)	Double-Sweep, Floyd Warshall and Dantzig algorithms	Quantitative	Case study	Mechanics	JSS
2	The relationship between culture and safety on offshore supply vessels (Antonsen, 2009)	Checklists/Safety Audits	Quantitative & Qualitative	Empirical data	Industry	JSS
3	Incorporating organizational factors into probabilistic risk assessment of complex socio-technical systems: Principles and theoretical foundations (Mohaghegh & Mosleh, 2009a,b)	Socio-technical risk	Quantitative	Theoretical foundations & Empirical data	Mechanics (socio-technical systems)	JSS
4	The development of a more risk-sensitive and flexible airport safety area strategy: Part I & Part II. (Wong, Pitfield, Caves, & Appleyard, 2009a,b)		Quantitative	Accidents data & aviation database	Mechanics (aviation)	JSS
5	Classification of errors contributing to rail incidents and accidents: A comparison of two human error identification techniques (Baysari, Caponecchia, McIntosh, & Wilson, 2009)	HFACS και TRACEr	Quantitative & Qualitative	Accidents data	Industry	JSS
6	Economic cost of occupational accidents: Evidence from a small island economy (Shalini, 2009)		Quantitative & Qualitative	Empirical data	Industry	JSS
7	Toward an evaluation of accident investigation methods in terms of their alignment with accident causation models (Katsakiori, Sakellaropoulos, & Manatakis, 2009)	FTA, MORT, MES, SCAT, CTM, OARU, TRIPOD, AEB, ISIM, NSB, WAIT, HSG245	Hybrid	Theoretical foundations & Empirical data	Industry	JSS
8	The implementation of a human factors engineering checklist for human–system interfaces upgrade in nuclear power plants (Jou et al., 2009)	Checklists	Quantitative & Qualitative	Empirical data (Case study)	Mechanics (nuclear power plants)	JSS
9	Severity analysis of Indian coal mine accidents – A retrospective study for 100 years (Maiti, Khanzode, & Ray, 2009)	Event evaluation algorithm (EEA)	Quantitative	Accidents data	Mechanics (coal mine)	JSS
10	Working safely with foreign contractors and personnel (Schubert & Dijkstra, 2009)		Qualitative	Empirical data	Industry	JSS
11	Designing of integrated quality and safety management system (IQSMS) for shipping operations (Celik, 2009)	IQMS	Quantitative	Theoretical foundations	Mechanics	JSS
12	Indicators to compare risk expressions, grouping, and relative ranking of risk for energy systems: Application with some accidental events from fossil fuels (Colli, Arellano, Kirchsteiger, & Ale, 2009; Colli, Serbanescu, & Ale, 2009)	Probabilistic Risk Analysis (PRA)	Quantitative	Accidents data	Mechanics	JSS
13	General assessment of the occupational accidents that occurred in Turkey between the years 2000 and 2005 (Unsar & Sut, 2009)		Quantitative	Accidents data	Mechanics	JSS
14	Portable ladder assessment tool development and validation – Quantifying best practices in the field (Dennerlein, Ronk, & Perry, 2009)	Checklists	Quantitative	Empirical data	Mechanics (Constructions)	JSS
15	The weighted risk analysis (Suddle, 2009)	WRA	Quantitative	Empirical data (Case study)	Engineering	JSS
16	A proactive approach to human error detection and identification in aviation and air traffic control (Kontogiannis & Malakis, 2009)		Qualitative	Theoretical foundations	Mechanics (aviation)	JSS
17	A fuzzy multi-attribute model for risk evaluation in workplaces (Grassi, Gamberini, Mora, & Rimini, 2009)	Fuzzy multi-attribute	Quantitative	Theoretical foundations	Industry	JSS
18	Method to assess and optimize dependability of complex macro-systems: Application to a railway signaling system (Vernez & Vuille, 2009)	Functional failure mode, effects and criticality analysis (FMECA)	Quantitative	Accidents data	Industry (railway)	JSS
19	A real-time warning model for teamwork performance and system safety in nuclear power plants (Hwang et al., 2009)	Real-time warning model (RTWM)	Quantitative	Theoretical foundations	Mechanics (nuclear power plants)	JSS

20	A simultaneous equations model of crash frequency by collision type for rural intersections (Ye, Pendyala, Washington, Konduri, & Oh, 2009)	The Negative Binomial Regression model	Quantitative	Accidents data	Industry (transportation)	JSS
21	Effectiveness of temporary traffic control measures in highway work zones (Li & Bai, 2009)	Binary logistic regression method	Quantitative	Accidents data	Industry (transportation)	JSS
22	Safety management systems: Performance differences between adopters and non-adopters (Bottani, Monica, & Vignali, 2009)	Confirmatory factor analysis (CFA)	Qualitative	Empirical data	Industry	JSS
23	Economic assessment of human errors in manufacturing environment (Liu, Hwang, & Liu, 2009; Liu, Guo, Rogers, & Mannan, 2009; Liu et al., 2009)	Cost estimation model	Quantitative	Empirical data	Industry (constructions)	JSS
24	A Bayesian network analysis of workplace accidents caused by falls from a height (Martín, Rivas, Matías, Taboada, & Argüelles, 2009)	Bayesian network analysis	Quantitative	Empirical data	Industry	JSS
25	Quantitative analysis of ATM safety issues using retrospective accident data: The dynamic risk modeling project (Leva et al., 2009)	PROCOS stochastic model	Quantitative	Accidents data/Theoretical foundations	Industry (transportation)	JSS
26	Toward system for the management of safety on board artisanal fishing vessels: Proposal for checklists and their application (Piniella & Fernández-Engo)	Checklists	Qualitative	Empirical data	Industry (navigation)	JSS
27	Injury and loss concentration by sinkings in fishing fleets (Perez-Labajos, Blanco, Azofra, Achutegui, & Eguía, 2009)		Quantitative	Empirical data (Case study)	Industry (fishing)	JSS
28	Study on the methodology for evaluating urban and regional disaster carrying capacity and its application (Chen, Tao, & Zhang, 2009)	UR-DCC evaluation model	Quantitative	Empirical data	Environment	JSS
29	A method to identify strategies for the improvement of human safety behavior by considering safety climate and personal experience (Zhou, Fang, & Wang, 2008)	Bayesian network analysis	Quantitative	Empirical data	Industry (constructions)	JSS
30	Knowledge transfer in organizational reliability analysis: From post-accident studies to normal operations studies (Etienne, 2008)		Qualitative	Empirical data	Industry	JSS
31	The impact of prevention measures and organizational factors on occupational injuries (Arocena, Núñez, & Villanueva, 2008)	Negative binomial regression	Quantitative	Empirical data	Industry	JSS
32	Analysis of trample disaster and a case study – Mihong bridge fatality in China in 2004 (Zhen, Mao, & Yuan, 2008)	Soft Systematic Methodology (SSM)	Quantitative	Accidents data	Mechanics	JSS
33	Toward risk assessment for crane activities (Aneziris, Papazoglou, Baksteen, et al., 2008; Aneziris, Papazoglou, Mud, et al., 2008)	Workgroup Occupational Risk Model (WORM)	Quantitative	Accidents data	Mechanics	JSS
34	Expert judgment study for placement ladder bowtie (Kurowicka, Cooke, Goossens, & Ale, 2008)	Bowtie diagram	Quantitative	Accidents data	Mechanics	JSS
35	The exposure–damage approach in the quantification of occupational risk in workplaces involving dangerous substances (Papadakis & Chalkidou, 2008)	COMAH	Quantitative	Accidents data (case study)	Industry	JSS
36	Suicide prevention in railway systems: Application of a barrier approach (Rådbo, Svedung, & Andersson, 2008)	FTA	Hybrid	Empirical data	Industry (railway)	JSS
37	Impact of enforcement on traffic accidents and fatalities: A multivariate multilevel analysis (Yannis, Papadimitriou, & Antoniou, 2008)	Poisson multivariate multilevel modell	Quantitative	Accidents data	Industry (transportation)	JSS
38	A fuzzy analytic network process (ANP) model to identify faulty behavior risk (FBR) in work system (Dağdeviren, Yüksel, & Kurt, 2008)	FBR, ANP	Quantitative	Fuzzy sets	Industry	JSS
39	Injuries in U.S. mining operations – A preliminary risk analysis (Komljenovic, Groves, & Kecojevic, 2008)	Holistic risk-management process	Quantitative	Accidents data	Mechanics	JSS
40	Assessment of safety management information systems for general contractors (Jung, Kang, Kim, & Park, 2008)	SMIS assessment process	Quantitative	Empirical data	Industry (constructions)	JSS

(*continued on next page*)

Table A. (*continued*)

Nr	Paper Citation	Technique's name	Method's type	Type of paper data or material	Field of application	Journal
(A)	(B)	(C)	(D)	(E)	(F)	(G)
41	Explaining safe work practices in aviation line maintenance (Pettersen & Aase, 2008)		Qualitative	Empirical data	Mechanics (aviation)	JSS
42	Quantifying occupational risk: The development of an occupational risk model (Ale et al., 2008)	Occupational Risk Model (ORM)	Quantitative	Accidents data	Engineering	JSS
43	Quantified risk assessment for fall from height (Aneziris, Papazoglou, Baksteen, et al., 2008; Aneziris, Papazoglou, Mud, et al., 2008)	Workgroup Occupational Risk Model (WORM)	Quantitative	Accidents data	Mechanics	JSS
44	Considerations in developing complete and quantified methods for risk assessment (van Duijne et al., 2008)		Quantitative	Theoretical foundations	Engineering	JSS
45	DomPrevPlanning: User-friendly software for planning domino effects prevention (Reniers & Dullaert, 2007)	DPP	Quantitative & Qualitative	Accidents data	Industry (chemical installations)	JSS
46	Driving task analysis as a tool in traffic safety research and practice (Fastenmeier & Gstalter, 2007)	TA	Qualitative	Theoretical foundations	Industry (transportation)	JLPPI
47	Assessment of hazardous material risks for rail yard safety (Glickman & Erkut, 2007)	FTA	Hybrid	Empirical data	Industry (railway)	JSS
48	A prospective hazard and improvement analytic approach to predicting the effectiveness of medication error interventions (Karnon et al., 2007)	PHIA	Quantitative	Facts	Medicine	JSS
49	Exploring the organizational preconditions for occupational accidents in food industry: A qualitative approach (Stave & Törner, 2007)	Grounded Theory Approach	Qualitative	Accidents data	Industry (food)	JSS
50	The contribution of qualitative analyses of occupational health and safety interventions: An example through a study of external advisory interventions (Baril-Gingras, Bellemare, & Brun, 2006)	Longitudinal qualitative analysis method	Qualitative	Theoretical foundations and Empirical data	Engineering	JSS
51	Perception and observation of residential safety during earthquake exposure: A case study (Akason, Olafsson, & Sigbjörnsson, 2006)		Quantitative & Qualitative	Facts	Mechanics	JSS
52	Toward a causal model for air transport safety—an ongoing research project (Ale et al., 2006)	FTA and Bayesian nets	Hybrid	Empirical data	Mechanics	JSS
53	Team crystallization (SIO_2): Dynamic model of team effectiveness evaluation under the dynamic and tactical environment at nuclear installation (Kim, Kim, & Moon, 2006)	Team crystallization dynamic mode	Quantitative	Accidents data	Mechanics	JSS
54	A quantitative approach to clinical risk assessment: The CREA method (Trucco & Cavallin, 2006)	CREA	Quantitative	Facts	Medicine	JSS
55	HEPI: A new tool for human error probability calculation for offshore operation (Khan, Amyotte, & DiMattia, 2006)	HEPI	Quantitative	Accidents data	Mechanics	JSS
56	Transferability of accident prediction models (Sawalha & Sayed, 2006)	Negative binomial regression	Quantitative	Accidents data	Industry (transportation)	JSS
57	A framework for measuring safety level for production environments (Ayomoh & Oke, 2006)	SIM, HTSD and GP	Hybrid	Facts	Mechanics	JSS
58	Understanding risks in socially vulnerable contexts: The case of waste burning in cement kilns in Brazil (de Souza Porto & de Oliveira Fernandes, 2006)	Vulnerability analysis	Qualitative	Empirical data	Industry (constructions)	JSS
59	Designing for safety in passenger ships utilizing advanced evacuation analyses—A risk-based approach (Vanem & Skjong, 2006)	What-if	Quantitative	Accidents data	Industry (navigation)	JSS
60	A new approach to quantitative assessment of reliability of passive systems (Kirchsteiger, 2005)	PSA	Quantitative	Facts	Engineering	JSS
61	Operationalizing normal accident theory for safety-related computer systems (Sammarco, 2005)	NAT	Quantitative	Facts	Engineering	JSS

62	Statistical analysis of dangerous goods accidents in Japan (Ohtani & Kobayashi, 2005)	Quantification method of the third type	Quantitative	Empirical data	Industry (transportation)	JSS
63	Effectiveness of safety belts and Hierarchical Bayesian analysis of their relative use (Abdalla, 2005)	Hierarchical Bayesian analysis	Quantitative	Empirical data	Industry (transportation)	JSS
64	A statistical model to estimate the probability of slip and fall incidents (Chang, 2004)	Probability model	Quantitative	Statistics	Mechanics	JSS
65	Qualification of Formal Safety Assessment: an exploratory study (Rosqvist & Tuominen, 2004)	Formal Safety Assessment	Qualitative	Facts	Industry (navigation)	JSS
66	A Petri Net-based approach for ergonomic task analysis and modeling with emphasis on adaptation to system changes (Kontogiannis, 2003)	Petri Net approach	Qualitative	Facts	Engineering	JSS
67	Apprenticeship in a work setting: the contribution and limits of operational resources constructed by workers (Chatigny & Montreuil, 2003)		Qualitative	Empirical data	Industry (food)	JSS
68	Assessment of programmable systems using Bayesian belief nets (Gran, 2002)	Bayesian belief nets	Quantitative	Facts	Engineering	JSS
69	Qualitative analyses of accidents and incidents to identify competencies. The electrical systems maintenance case (Vidal-Gomel & Samurçay, 2002)		Qualitative	Empirical data	Engineering	JSS
70	Use of Probabilistic Safety Assessment (PSA) for nuclear installations (Niehaus, 2002)	Probabilistic Safety Assessment	Quantitative	Facts	Mechanics	JSS
71	Probabilistic risk-assessment practices in the USA for nuclear power plants (Garrick & Christie, 2002)	PRA	Quantitative	Facts	Mechanics	JSS
72	An interactive multiobjective model for the strategic maritime transportation of petroleum products: risk analysis and routing (Iakovou, 2001)		Quantitative	Facts	Industry (transportation)	JSS
73	Engineering analysis of hazards to life safety in fires: the fire effluent toxicity component (Hartzell, 2001)		Quantitative	Empirical data	Chemistry	JSS
74	Quantification of behavior for engineering design standards and escape time calculations (Purser & Bensilum, 2001)		Quantitative	Empirical data	Engineering	JSS
75	A systemic approach to effective chemical emergency management (Kourniotis, Kiranoudis, & Markatos, 2001)	Systemic approach	Quantitative	Empirical data	Chemistry	JSS
76	An algorithm for the implementation of safety improvement programs (Cagno, Di Giulio, & Trucco, 2001)	Algorithmic approach	Quantitative	Empirical data	Industry	JSS
77	Early hazard identification of chemical plants with statechart modeling techniques (Graf & Schmidt-Traub, 2000)	HAZOP	Qualitative	Empirical data	Mechanics	JSS
78	Application of finite mixture models for vehicle crash data analysis (Park & Lord, 2009)	Negative binomial regression (Finite mixtures of Poisson)	Quantitative	Empirical data	Industry (transportation)	JAAP
79	Safety evaluation of multilane arterials in Florida (Abdel-Aty, Devarasetty, & Pande, 2009)	Bayesian method	Quantitative	Facts	Industry (transportation)	JAAP
80	Collision prediction models using multivariate Poisson-lognormal regression (El-Basyouny & Sayed, 2009)	Poisson-lognormal regression	Quantitative	Empirical data	Industry (transportation)	JAAP
81	Markov switching multinomial logit model: An application to accident-injury severities (Malyshkina & Mannering, 2009)	Markov switching	Quantitative	Empirical data	Industry (transportation)	JAAP
82	Kernel density estimation and K-means clustering to profile road accident hotspots (Anderson, 2009)	Kernel density estimation	Quantitative	Accidents data	Industry (transportation)	JAAP
83	Validation of a Full Bayes methodology for observational before–after road safety studies and application to evaluation of rural signal conversions (Lan, Persaud, Lyon, & Bhim, 2009)	Full Bayes methodology	Quantitative	Empirical data	Industry (transportation)	JAAP

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Table A. (*continued*)

Nr (A)	Paper Citation (B)	Technique's name (C)	Method's type (D)	Type of paper data or material (E)	Field of application (F)	Journal (G)
84	Markov switching negative binomial models: An application to vehicle accident frequencies (Malyshkina, Mannering, & Tarko, 2009)	Markov switching negative binomial model	Quantitative	Empirical data	Industry (transportation)	JAAP
85	The influence of heavy goods vehicle traffic on accidents on different types of Spanish interurban roads (Ramírez, Izquierdo, Fernández, & Méndez, 2009)	Poisson	Quantitative	Accidents data	Industry (transportation)	JAAP
86	Analytical HFACS for investigating human errors in shipping accidents (Celik & Cebi, 2009)	HFACS	Quantitative	Accidents data	Industry (navigation)	JAAP
87	Correcting erroneous crash locations in transportation safety analysis (Tegge & Ouyang, 2009)	Statistical regression	Quantitative	Accidents data	Industry (transportation)	JAAP
88	The predictive validity of empirical Bayes estimates of road safety (Elvik, 2008)	Empirical Bayes estimates	Quantitative	Accidents data	Industry (transportation)	JAAP
89	Development of crash-severity-index models for the measurement of work zone risk levels (Li & Bai, 2008)	Crash-severity-index models	Quantitative	Accidents data	Industry (transportation)	JAAP
90	Combining road safety information in a performance index (Hermans, Van den Bossche, & Wets, 2008)	Weighting method	Quantitative	Empirical data	Industry (transportation)	JAAP
91	Investigating the effects of the fixed and varying dispersion parameters of Poisson-gamma models on empirical Bayes estimates (Lord & Park, 2008)	Empirical Bayes estimates, Poisson	Quantitative	Empirical data	Industry (transportation)	JAAP
92	Chinese truck drivers' attitudes toward feedback by technology: A quantitative approach (Huang, Rau, Zhang, & Roetting, 2008)	Άλλες μέθοδοι	Quantitative	Empirical data	Industry (transportation)	JAAP
93	A multivariate Poisson-lognormal regression model for prediction of crash counts by severity, using Bayesian methods (Ma, Kockelman, & Damien, 2008)	Poisson-lognormal regression	Quantitative	Empirical data	Industry (transportation)	JAAP
94	The cost and risk impacts of rerouting railroad shipments of hazardous materials (Glickman, Erkut, & Zschocke, 2007)	Network model	Quantitative	Accidents data	Industry (transportation)	JAAP
95	Light truck vehicles (LTVs) contribution to rear-end collisions (Harb, Radwan, Yan, & Abdel-Aty, 2007)		Quantitative	Empirical data	Industry (transportation)	JAAP
96	A joint econometric analysis of seat belt use and crash-related injury severity (Eluru & Bhat, 2007)	Econometric analysis	Quantitative	Empirical data	Industry (transportation)	JAAP
97	Multilevel modeling for the regional effect of enforcement on road accidents (Yannis, Papadimitriou, & Antoniou, 2007)	Multilevel modeling	Quantitative	Accidents data	Industry (transportation)	JAAP
98	Sensitivity analysis of an accident prediction model by the fractional factorial method (Akgüngör & Yıldız, 2007)	Sensitivity analysis	Quantitative	Accidents data	Industry (transportation)	JAAP
99	Bayesian estimation of hourly exposure functions by crash type and time of day (Qin, Ivan, Ravishanker, Liu, & Tepas, 2006)	Bayesian estimation	Quantitative	Accidents data	Industry (transportation)	JAAP
100	Validating crash locations for quantitative spatial analysis: A GIS-based approach (Loo, 2006)	GIS-based approach	Quantitative	Accidents data	Industry (transportation)	JAAP
101	Synthesis of quantitative and qualitative evidence for accident analysis in risk-based highway planning (Lambert, Peterson, & Joshi, 2006)		Quantitative & Qualitative	Empirical data	Industry (transportation)	JAAP
102	Estimation of reduced life expectancy from serious occupational injuries in Taiwan (Ho, Hwang, & Wang, 2006)		Quantitative	Accidents data	Mechanics	JAAP
103	Association between setting quantified road safety targets and road fatality reduction (Wong et al., 2006)		Quantitative	Statistics	Industry (transportation)	JAAP
104	Analysis of traffic injury severity: An application of non-parametric classification tree techniques (Chang & Wang, 2006)	Tree technique	Qualitative	Accidents data	Industry (transportation)	JAAP

105	Estimation of incident clearance times using Bayesian Networks approach (Ozbay & Noyan, 2006)	Bayesian Networks	Quantitative & Qualitative	Facts	Industry (transportation)	JAAP
106	Bayesian methodology incorporating expert judgment for ranking countermeasure effectiveness under uncertainty: Example applied to at grade railroad crossings in Korea (Washington & Oh, 2006)	Bayesian methodology	Quantitative	Empirical data	Industry (transportation & railway)	JAAP
107	Accident prediction model for railway-highway interfaces (Oh, Washington, & Nam, 2006)	Statistical regression models	Quantitative	Empirical data	Industry (transportation & railway)	JAAP
108	Application of a human error framework to conduct train accident/incident investigations (Reinach & Viale, 2006)	HFACS, HFACS-RR	Qualitative	Empirical data	Industry	JAAP
109	Different quantitative measures of the impact of injury deaths on the community in the Guangxi Province, China (Lam, Yang, Liu, Geng, & Liu, 2005)		Quantitative	Accidents data	Mechanics	JAAP
110	Sources of error in road safety scheme evaluation: a quantified comparison of current methods (Hirst, Mountain, & Maher, 2004)		Quantitative	Empirical data	Industry (transportation)	JAAP
111	Quantifying the role of risk-taking behavior in causation of serious road crash-related injury (Turner & McClure, 2004)		Quantitative	Empirical data	Industry (transportation)	JAAP
112	A qualitative assessment methodology for road safety policy strategies (Wong, Leung, Loo, Hung, & Lo, 2004)		Qualitative	Statistics	Industry (transportation)	JAAP
113	Using logistic regression to estimate the influence of accident factors on accident severity (Al-Ghamdi, 2002)	Logistic regression	Quantitative	Accidents data	Industry (transportation)	JAAP
114	Effects of work zone presence on injury and non-injury crashes (Khattak, Khattak, & Council, 2002)	Poisson	Quantitative	Accidents data	Industry (transportation)	JAAP
115	Multiple state hazard models and workers' compensation claims: an examination of workers compensation data from Ontario (Campolieti, 2001)		Quantitative	Accidents data	Industry	JAAP
116	Diagnosis and monetary quantification of occupational injuries by indices related to human capital loss: analysis of a steel company as an illustration (Sheu, Hwang, & Wang, 2000)		Quantitative	Accidents data	Industry	JAAP
117	A comparative analysis of mathematical models for relating indoor and outdoor toxic gas concentrations in accidental releases (Montoya, Planas, & Casal, 2009)	Mathematical models	Quantitative	Facts	Industry (chemical installations)	JLPPI
118	Risk-based maintenance strategy and its applications in a petrochemical reforming reaction system (Hu, Cheng, Li, & Tang, 2009)	Risk-based maintenance	Hybrid	Facts	Industry	JLPPI
119	Performance evaluation of process safety management systems of paint manufacturing facilities (Chang & Liang, 2009)	MAVT	Quantitative	Empirical data	Industry (colour industry)	JLPPI
120	The costs of industrial accidents for the organization: Developing methods and tools for evaluation and cost—benefit analysis of investment in safety (Gavious, Mizrahi, Shani, & Minchuk, 2009)	Theory of Constraints	Quantitative	Empirical data	Industry	JLPPI
121	A mathematical model to predict the heating-up of large-scale wood piles (Ferrero, Lohrer, Schmidt, Noll, & Malow, 2009)		Quantitative	Empirical data	Industry (wood)	JLPPI
122	Inherent safety of substances: Identification of accidental scenarios due to decomposition products (Cordella, Tugnoli, Barontini, Spadoni, & Cozzani, 2009)		Quantitative	Empirical data	Industry (chemical installations)	JLPPI
123	Criticality evaluation of petrochemical equipment based on fuzzy comprehensive evaluation and a BP neural network (Guo, Gao, Yang, & Kang, 2009)	Failure mode and effects analysis (FMEA)	Quantitative	Theoretical foundations	Industry	JLPPI

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Table A. (*continued*)

Nr	Paper Citation	Technique's name	Method's type	Type of paper data or material	Field of application	Journal
(A)	(B)	(C)	(D)	(E)	(F)	(G)
124	An overview of accident forecasting methodologies (Zheng & Liu, 2009)	Scenario analysis, regression method, time-series method, Markov chain method, grey model, neural networks, Bayesian networks	Quantitative & Qualitative	Empirical data	Industry	JLPPI
125	Modeling the risk of failure in explosion protection installations (Date, Lade, Mitra, & Moore, 2009)	Residual risk model	Quantitative	Empirical data	Industry	JLPPI
126	Applications of 3D QRA technique to the fire/explosion simulation and hazard mitigation within a naphtha-cracking plant (Yet-Pole, Shu, & Chong, 2009)	3D QRA	Quantitative	Empirical data	Industry	JLPPI
127	Comprehensive risk assessment and management of petrochemical feed and product transportation pipelines (Gharabagh et al., 2009)	QRA, Pipeline comprehensive risk analysis (PCRA)	Quantitative	Empirical data	Industry	JLPPI
128	Calculations of explosion deflagrating flames using a dynamic flame surface density model (Ibrahim, Gubba, Masri, & Malalasekera, 2009)	dynamic flame surface density (DFSD)	Quantitative	Empirical data	Industry	JLPPI
129	Numerical simulation on the diffusion of hydrogen due to high-pressured storage tanks failure (Liu, Hwang, et al., 2009; Liu, Guo, et al., 2009; Liu et al., 2009)	Numerical simulation	Quantitative	Empirical data	Industry	JLPPI
130	Numerical analysis of release, dispersion and combustion of liquid hydrogen in a mock-up hydrogen refueling station (Baraldi, Venetsanos, Papanikolaou, Heitsch, & Dallas, 2009)		Quantitative	Empirical data	Industry	JLPPI
131	Application of computational fluid dynamics for LNG vapor dispersion modeling: A study of key parameters (Cormier, Qi, Yun, Zhang, & Mannan, 2009)	Parametric analysis	Quantitative	Empirical data	Industry	JLPPI
132	Fuzzy-based methodology for performance assessment of emergency planning and its application (Chen & Zhang, 2009)	Fuzzy-based methodology	Quantitative	Theoretical foundations	Industry	JLPPI
133	Risk estimation for industrial safety in raw materials manufacturing (Okabe & Ohtani, 2009)		Quantitative	Empirical data	Industry	JLPPI
134	Computational fluid dynamics analysis on the critical behavior of reactive chemicals (Liu, Hwang, et al., 2009; Liu, Guo, et al., 2009; Liu et al., 2009)		Quantitative	Facts	Industry	JLPPI
135	Process route index (PRI) to assess level of explosiveness for inherent safety quantification (Leong & Shariff, 2009)		Quantitative	Facts	Industry	JLPPI
136	A hazard and operability analysis method for the prevention of misoperations in the production of light magnesium carbonate (Wang, Gao & Guo, 2009)	HAZOP	Qualitative	Empirical data	Industry	JLPPI
137	Risk assessment of LNG importation terminals using the Bayesian–LOPA methodology (Yun, Rogers, & Mannan, 2009)	Bayesian–LOPA methodology	Quantitative	Empirical data	Industry	JLPPI
138	A risk-estimation methodological framework using quantitative assessment techniques and real accidents' data: Application in an aluminum extrusion industry (Marhavilas & Koulouriotis, 2008)	PRAT, DMRA	Quantitative	Empirical data	Industry (aluminum extrusion)	JLPPI
139	Quantification of impact of line markers on risk on transmission pipelines with natural gas (Bajcar, Širok, Cimerman, & Eberlinc, 2008)		Quantitative	Facts	Industry (natural gas)	JLPPI
140	Reliability analysis of metallic targets under metallic rods impact: Toward a simplified probabilistic approach (Mebarki, Nguyen, Mercier, Saada, & Reimeringer, 2008)	Probabilistic approach	Quantitative	Facts	Industry	JLPPI

141	Numerical simulation of hydrogen–air detonation for damage assessment in realistic accident scenarios (Bédard-Tremblay, Fang, Bauwens, Cheng, & Tchouvelev, 2008)		Quantitative	Empirical data	Industry	JLPPI
142	CFD modeling of hydrogen release, dispersion and combustion for automotive scenarios (Venetsanos, Baraldi, Adams, Heggem, & Wilkening, 2008)	CFD	Quantitative	Facts	Industry	JLPPI
143	Numerical study on the spontaneous ignition of pressurized hydrogen release through a tube into air (Xu et al., 2008)	CFD	Quantitative	Facts	Industry	JLPPI
144	A quantitative risk-assessment tool for the external safety of industrial plants with a dust explosion hazard (van der Voort et al., 2007)	QRA	Quantitative	Facts	Industry	JLPPI
145	Numerical analysis of hydrogen deflagration mitigation by venting through a duct (Makarov, Verbecke, & Molkov, 2007)	LES	Quantitative	Facts	Industry	JLPPI
146	An application of 3D gas dynamic modeling for the prediction of overpressures in vented enclosures (Karnesky, Chatterjee, Tamanini, & Dorofeev, 2007)		Quantitative	Facts	Industry	JLPPI
147	Numerical analysis of gas explosion inside two rooms connected by ducts (Hashimoto & Matsuo, 2007)	LES	Quantitative	Facts	Industry	JLPPI
148	Numerical simulation of wind-aided flame propagation over horizontal surface of liquid fuel in a model tunnel (Wang & Joulain, 2007)	LES	Quantitative	Empirical data	Industry	JLPPI
149	Model-based HAZOP study of a real MTBE plant (Labovský et al., 2007)	HAZOP	Qualitative	Empirical data	Industry	JLPPI
150	Improved qualitative fault propagation analysis (Gabbar, 2007)	POOM	Qualitative	Facts	Industry	JLPPI
151	Operational risk assessment of chemical industries by exploiting accident databases (Meel et al., 2007)	Operational risk assessment	Quantitative	Facts	Industry	JLPPI
152	A probabilistic model for the vulnerability of metal plates under the impact of cylindrical projectiles (Mebarki et al., 2007)	Probabilistic	Quantitative	Facts	Industry	JLPPI
153	*n*-Compartment mathematical model for transient evaluation of fluid curtains in mitigating chlorine releases (Palazzi, Currò, & Fabiano, 2007)		Quantitative	Facts	Industry	JLPPI
154	Prevention of thermo-hydraulic rupture of solvent transfer pipes in the pharmaceutical industry (Cronin, Byrne, & O'Leary, 2007)	Stochastic	Quantitative	Facts	Industry (pharmaceutical)	JLPPI
155	Failure of a heat exchanger generated by an excess of SO_2 and H_2S in the Sulfur Recovery Unit of a petroleum refinery (Lins & Guimarães, 2007)		Quantitative	Facts	Industry (petroleum refinery)	JLPPI
156	A posteriori hazard analysis and feedback information of an accidental event in the grains storage of an agrochemical product (Laurent, Baklouti, Corriou, & Gustin, 2006)	Posteriori hazard analysis	Quantitative	Empirical data	Industry	JLPPI
157	Computer-aided modeling of the protective effect of explosion relief vents in tunnel structures (Sklavounos & Rigas, 2006)	Geometrical model	Quantitative	Facts	Industry	JLPPI
158	Development of a database for accidents and incidents in the Greek petrochemical industry (Nivolianitou, Konstandinidou, Kiranoudis, & Markatos, 2006)		Quantitative	Facts	Industry	JLPPI
159	Integration of accident scenario generation and multiobjective optimization for safety-cost decision-making in chemical processes (Kim, Chang, & Heo, 2006)	Accident scenario generation	Quantitative	Empirical data	Industry (chemical installations)	JLPPI
160	First step toward preventing losses due to mechanical damage from abnormal actions: Knowledge-based forecasting the actions (Vaidogas, 2006)	PEA	Quantitative	Empirical data	Industry	JLPPI

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Table A. (*continued*)

Nr (A)	Paper Citation (B)	Technique's name (C)	Method's type (D)	Type of paper data or material (E)	Field of application (F)	Journal (G)
161	Offshore oil and gas occupational accidents—What is important? (Attwood et al., 2006a,b)		Quantitative	Empirical data	Industry (petroleum industry)	JLPPI
162	Aspects of risk analysis associated with major failures of fuel pipelines (Dziubiński, Frątczak, & Markowski, 2006)		Quantitative & Qualitative	Facts	Industry	JLPPI
163	A matrix-based risk-assessment approach for addressing linear hazards such as pipelines (Henselwood & Phillips, 2006)	DMRA	Quantitative	Empirical data	Industry	JLPPI
164	Quantitative assessment of domino scenarios by a GIS-based software tool (Cozzani et al., 2006)	QADS	Quantitative	Empirical data	Industry	JLPPI
165	A fuzzy set analysis to estimate loss intensity following blast wave interaction with process equipment (Salzano & Cozzani, 2006)	Fuzzy set analysis	Quantitative	Fuzzy sets	Industry	JLPPI
166	A simple model for calculating chlorine concentrations behind a water spray in case of small releases (Dandrieux-Bony, Dimbour, & Dusserre, 2005)	RED	Quantitative	Facts	Industry	JLPPI
167	Dangerous good transportation by road: from risk analysis to emergency planning (Fabiano, Currò, Reverberi, & Pastorino, 2005)		Quantitative	Empirical data	Industry (transportation)	JLPPI
168	A study on the influence of liquid water and water vapor on the self-ignition of lignite coal-experiments and numerical simulations (Lohrer, Schmidt, & Krause, 2005)	Arithmetic	Quantitative & Qualitative	Empirical data	Industry	JLPPI
169	Development of a risk-based maintenance (RBM) strategy for a power-generating plant (Krishnasamy, Khan, & Haddara, 2005)	Risk-based maintenance (RBM)	Hybrid	Facts	Industry (electric power production)	JLPPI
170	Estimation of failure probability of oil and gas transmission pipelines by fuzzy fault-tree analysis (Yuhua & Datao, 2005)	Fuzzy fault-tree analysis	Quantitative	Fuzzy sets	Industry	JLPPI
171	GAP—a fault-tree-based methodology for analyzing occupational hazards (Hauptmanns, Marx, & Knetsch, 2005)	GAP, FTA	Quantitative	Facts	Industry	JLPPI
172	Calculating overpressure from BLEVE explosions (Planas-Cuchi, Salla, & Casal, 2004)		Quantitative	Facts	Industry	JLPPI
173	Comparison of techniques for accident scenario analysis in hazardous systems (Nivolianitou, Leopoulos, & Konstantinidou, 2004)	ETA, FTA, Petri-Nets	Quantitative	Facts	Industry	JLPPI
174	Semi-quantitative fault-tree analysis for process plant safety using frequency and probability ranges (Hauptmanns, 2004)	FTA	Hybrid	Empirical data	Industry	JLPPI
175	Loss prevention in heavy industry: risk assessment of large gasholders (Bernatik & Libisova, 2004)	QRA	Quantitative	Facts	Industry	JLPPI
176	Risk analysis as a basis for safety management system (Demichela, Piccinini, & Romano, 2004)	SMS	Quantitative	Facts	Industry	JLPPI
177	A predictive risk index for safety performance in process industries (Chen & Yang, 2004)	PRI	Quantitative	Facts	Industry	JLPPI
178	Risk-based maintenance (RBM): a quantitative approach for maintenance/inspection scheduling and planning (Khan & Haddara, 2003)	RBM	Hybrid	Facts	Industry	JLPPI
179	Algorithmic fault-tree synthesis for control loops (Wang, Rogers, West, & Mannan, 2003)	FTA	Hybrid	Facts	Industry	JLPPI
180	Dynamic management of human error to reduce total risk (Jo & Park, 2003)		Quantitative	Facts	Industry	JLPPI
181	Safety analysis and risk assessment in a new pesticide production line (Rigas, Konstandinidou, Centola, & Reggio, 2003)		Quantitative & Qualitative	Empirical data	Industry	JLPPI

182	Quantification of inherent safety aspects of the Dow indices (Etowa, Amyotte, Pegg, & Khan, 2002)		Quantitative	Facts	Industry	JLPPI
183	Technical modeling in integrated risk assessment of chemical installations (Papazoglou, Aneziris, Post, & Ale, 2002)		Quantitative	Facts	Industry (chemical installation)	JLPPI
184	A new algorithm for computer-aided fault-tree synthesis (Wang, Teague, West, & Mannan, 2002; Wang, Wu, & Chang, 2002)	FTA	Hybrid	Empirical data	Industry	JLPPI
185	Analysis of hazard areas associated with high-pressure natural-gas pipelines (Jo & Ahn, 2002)		Quantitative	Facts	Industry	JLPPI
186	An integrated framework to the predictive error analysis in emergency situation (Kim & Jung, 2002)	Task Analysis	Qualitative	Facts	Industry	JLPPI
187	A methodology for assessing risk from released hydrocarbon in an enclosed area (Lee, 2002)	The Probit Approach	Quantitative	Facts	Industry	JLPPI
188	Numerical study of dust lifting in a channel with vertical obstacles (Klemens et al., 2001)		Quantitative	Facts	Industry	JLPPI
189	Evaluation of limits for effective flame acceleration in hydrogen mixtures (Dorofeev, Kuznetsov, Alekseev, Efimenko, & Breitung, 2001)		Quantitative	Facts	Industry	JLPPI
190	Use of computational modeling to identify the cause of vapor cloud explosion incidents (Clutter & Whitney, 2001)		Quantitative	Facts	Industry	JLPPI
191	A procedure for analyzing the flight of missiles from explosions of cylindrical vessels (Hauptmanns, 2001)	Monte Carlo evaluation	Quantitative	Facts	Industry	JLPPI
192	Analytical expressions for the calculation of damage percentage using the probit methodology (Vílchez, Montiel, Casal, & Arnaldos, 2001)	The Probit Approach	Quantitative	Facts	Industry	JLPPI
193	Risk analysis of a typical chemical industry using ORA procedure (Khan & Abbasi, 2001)	ORA	Quantitative & Qualitative	Facts	Industry (chemical installation)	JLPPI
194	A mathematical model for predicting thermal hazard data (Liaw, Yur, & Lin, 2000)		Quantitative	Facts	Industry	JLPPI
195	Risk analysis of LPG transport by road and rail (Bubbico, Ferrari, & Mazzarotta, 2000)		Quantitative	Facts	Industry (transportation)	JLPPI
196	A systematic Hazop procedure for batch processes, and its application to pipeless plants (Mushtaq & Chung, 2000)	HAZOP	Qualitative	Empirical data	Industry	JLPPI
197	Data mining of tree-based models to analyze freeway accident frequency (Chang & Chen, 2005)	ETA	Quantitative	Empirical data	Engineering	JSR
198	Net-cost model for workplace interventions (Lahiri, Gold, & Levenstein, 2005)	Net-Cost model	Quantitative	Facts	Mechanics	JSR
199	A comprehensive framework for assessing and selecting appropriate scaffolding based on analytic hierarchy process (Fang, Shen, Wu, & Liu, 2003)	Analytic hierarchy process	Quantitative & Qualitative	Facts	Mechanics	JSR
200	Consequences and likelihood in risk estimation: A matter of balance in UK health and safety risk-assessment practice (Woodruff, 2005)		Hybrid	Facts	Industry	JSS
201	Combining task analysis and fault-tree analysis for accident and incident analysis: A case study from Bulgaria (Doytchev & Szwillus, 2009)	FTA, TA, HEIST	Hybrid	Facts	Industry (energy production)	JAAP
202	Safety in construction – a comprehensive description of the characteristics of high safety standards in construction work, from the combined perspective of supervisors and experienced workers (Törner & Pousette, 2009)	Checklists, Safety audits	Qualitative	Empirical data	Industry (constructions)	JSR
203	A note on the effectiveness of the house-arrest alternative for motivating DWI offenders to install ignition interlocks (Roth, Marques, & Voas, 2009)	DWI	Quantitative	Facts	Transportation	JSR

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Table A. (*continued*)

Nr (A)	Paper Citation (B)	Technique's name (C)	Method's type (D)	Type of paper data or material (E)	Field of application (F)	Journal (G)
204	A framework for understanding the development of organizational safety culture (Parker, Lawrie, & Hudson, 2006)	Checklists, Safety audits	Qualitative	Empirical data	Engineering	JSS
205	Observational learning and workplace safety: The effects of viewing the collective behavior of multiple social models on the use of personal protective equipment (Olson, Grosshuesch, Schmidt, Gray, & Wipfli, 2009)		Qualitative	Experimental data	Industry	JSR
206	Work environment risk factors for injuries in wood processing (Holcroft & Punnett, 2009)		Qualitative	Facts	Industry (wood)	JSR
207	The role of production and teamwork practices in construction safety: A cognitive model and an empirical case study (Mitropoulos & Cupido, 2009)	HRC	Qualitative	Empirical data	Industry (constructions)	JSR
208	Global trend according to estimated number of occupational accidents and fatal work-related diseases at region and country level (Hämäläinen, Saarela, & Takala, 2009)		Qualitative	Accidents data	All fields	JSR
209	What is most important for safety climate: The company belonging or the local working environment? — A study from the Norwegian offshore industry (Høivik, Tharaldsen, Baste, & Moen, 2009)	ANOVA	Hybrid	Facts	Industry (petroleum)	JSS
210	Risk-assessment tools incorporating human error probabilities in the Japanese small-sized establishment (Moriyama & Ohtani, 2009)	HEP/HEA	Hybrid	Theoretical foundations & Empirical data	Industry	JSS
211	Measurement techniques for organizational safety causal models: Characterization and suggestions for enhancements (Mohaghegh & Mosleh, 2009a,b)	Probabilistic Risk Assessment (PRA)	Quantitative	Theoretical foundations & Empirical data	All	JSS
212	Age and lost working days as a result of an occupational accident: A study in a shiftwork rotation system (Blanch, Torrelles, Aluja, & Salinas, 2009)	LWDI	Quantitative	Facts	Industry	JSS
213	Deterioration of the useful visual field with aging during simulated driving in traffic and its possible consequences for road safety (Rogé & Pebaylé, 2009)		Quantitative	Facts	Transportations	JSS
214	A method for assessing health and safety management systems from the resilience engineering perspective (Costella, Saurin, & de Macedo Guimarães, 2009)	MAHS	Hybrid	Experimental data	Industry (car)	JSS
215	Development of a relative risk model for roof and side fall fatal accidents in underground coal mines in India (Maiti & Khanzode, 2009)	SME	Quantitative	Facts	Industry	JSS
216	Relation between occupational safety management and firm performance (Fernández-Muñiz, Montes-Peón, & Vázquez-Ordás, 2009)		Qualitative	Theoretical foundations	All	JSS
217	Safety is the antonym of risk for some perspectives of risk (Aven, 2009)		Qualitative	Theoretical foundations	All	JSS
218	From hanger-on to trendsetter: Decision-making on a major safety initiative in a steel company maintenance department (van Ginneken & Hale, 2009)		Qualitative	Statistics	Industry	JSS
219	Globalization and workplace hazards in developing nations (Baram, 2009)		Qualitative	Theoretical foundations	All	JSS
220	Role of beliefs in accident and risk analysis and prevention (Kouabenan, 2009)		Qualitative	Theoretical foundations	All	JSS
221	Complaints regarding occupational health and safety in the area of Thessaloniki (Greece) (Mekos, 2009)		Quantitative	Statistics	All	JSS

222	Designing continuous safety improvement within chemical industrial areas (Reniers, Ale, Dullaert, & Soudan, 2009)		Qualitative	Theoretical foundations	All	JSS
223	Effectiveness of road safety workshop for young adults (Rosenbloom, Levi, Peleg, & Nemrodov, 2009)		Qualitative	Statistics	All	JSS
224	Safety climate factors and its relationship with accidents and personal attributes in the chemical industry (Vinodkumar & Bhasi, 2009)		Quantitative	Facts	Industry	JSS
225	Workplace and organizational factors in accident analysis within the Food Industry (Jacinto, Canoa, & Soares, 2009)		Qualitative	Facts	Industry	JSS
226	Deriving the factor structure of safety climate scales (Shannon & Norman, 2009)		Qualitative	Experimental data	Agricultural	JSS
227	Agricultural accidents in north eastern region of India (Kumar & Dewangan, 2009)		Qualitative	Facts	Agricultural industry	JSS
228	Pilot study on the influence of stress caused by the need to combine work and family on occupational accidents in working women (Martín-Fernández, de los Ríos, Cazorla, & Martínez-Falero, 2009)		Qualitative	Facts	All fields	JSS
229	Risk characterization indicators for risk comparison in the energy sector (Colli, Arellano, et al., 2009; Colli, Serbanescu, et al., 2009)	Risk Characterization Indicators (RCIs)	Qualitative	Theoretical foundations	Industry (energy production)	JSS
230	Stochastic modeling of accident risks associated with an underground coal mine in Turkey (Sari, Selcuk, Karpuz, & Duzgun, 2009)	Stochastic Risk Modeling	Quantitative	Statistics	All	JSS
231	Factors correlated with traffic accidents as a basis for evaluating Advanced Driver Assistance Systems (Staubach, 2009)	Advanced Driver Assistance Systems (ADAS)	Qualitative	Facts	Transportations	JAAP
232	Occupational safety: The role of workplace sleepiness (DeArmond & Chen, 2009)		Qualitative	Facts	All	JAAP
233	A new method for assessing the risk of accident associated with darkness (Johansson, Wanvik, & Elvik, 2009)		Quantitative	Statistics	All	JAAP
234	Fuzzy Application Procedure (FAP) for the risk assessment of occupational accidents (Murè & Demichela, 2009)	FAP	Qualitative	Theoretical foundations	All	JLPPI
235	An optimizing hazard/risk analysis review planning (HARP) framework for complex chemical plants (Reniers, 2009)	HARP	Qualitative	Theoretical foundations	Industry (Chemical plants)	JLPPI
236	Force measurement in field ergonomics research and application (Bao, Spielholz, Howard, & Silverstein, 2009)	TLV	Quantitative	Empirical data	Industry	IJIE
237	Effects of ergonomics-based wafer-handling training on reduction in musculoskeletal disorders among wafer handlers (Wu, Chen, & Chen, 2009)	Checklists	Qualitative	Empirical data	Industry	IJIE
238	An occupational safety risk analysis method at construction sites using fuzzy sets (Gürcanli & Müngen, 2009)	Fuzzy event tree analysis (FETA) technique	Hybrid	Fuzzy sets	Industry (constructions)	IJIE
239	Development of a Structural Equation Model for ride comfort of the Korean-speed railway (Lee, Jin, & Ji, 2009)	The Structural Equation Model (SEM) technique	Quantitative	Empirical data	Industry	IJIE
240	Coordination indices between lifting kinematics and kinetics (Xu, Hsiang, & Mirka, 2008)	The phase angle technique & The moving correlation technique	Quantitative	Empirical data	Industry	IJIE
241	Simultaneous field measuring method of vibration and body posture for assessment of seated occupational driving tasks (Hermanns, Raffler, Ellegast, Fisher, & Göres, 2008)	OWAS & RULA techniques	Quantitative	Empirical data	Industry	IJIE
242	Optimal balancing of multiple affective satisfaction dimensions: A case study on mobile phones (Hong, Han, & Kim, 2008)	Multiple Response Surfaces (MRS) Methodology	Quantitative	Case study	Industry	IJIE

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Table A. (*continued*)

Nr	Paper Citation	Technique's name	Method's type	Type of paper data or material	Field of application	Journal
(A)	(B)	(C)	(D)	(E)	(F)	(G)
243	Discriminating relative workload level by data envelopment analysis (Chang & Chen, 2006)	Data Envelopment Analysis (DEA) Methodology	Quantitative	Case study	Industry	IJIE
244	Usability in a medical technology context assessment of methods for usability evaluation of medical equipment (Liljegren, 2006)	Usability Evaluation Methods: HTA (Hierarchical Task Analysis, CW (Cognitive Walkthroughs),HE (Heuristic Evaluation), UT (Usability Test)	Qualitative	Empirical data	Industry	IJIE
245	Semantic Differential applied to the evaluation of machine tool design (Mondragón, Company, Vergara, 2005)	User-Centered Design (UCD) Techniques, Semantic Differential approach	Quantitative & Qualitative	Empirical data	Industry	IJIE
246	An anthropometric measurement for developing an electric scooter (Chou & Hsiao, 2005)	Anthropometric data collection approach	Quantitative	Empirical data	Industry	IJIE
247	Contextual assessment of working practices in changing work (Nuutinen, 2005)	Contextual Assessment of Working Practices (CAWP) method & The core task modeling (CTM) technique	Qualitative	Case study	Industry	IJIE
248	Nuclear power plant shift supervisor's decision-making during microincidents (Carvalho, dos Santos, & Vidal, 2005)	Cognitive Task Analysis (CTA): Ergonomic Work Analysis (EWA)	Qualitative	Empirical data	Industry	IJIE
249	Prevalence of upper extremity musculoskeletal symptoms and ergonomic risk factors at a Hi-Tech company in Israel (Shuval & Donchin, 2005)	RULA technique	Qualitative	Empirical data	Industry	IJIE
250	Measurement of trust in complex and dynamic systems using a quantitative approach (Uggirala, Gramopadhye, Melloy, & Toler, 2004)	Uncertainty models	Qualitative & Quantitative	Fuzzy sets, & Empirical data	Industry	IJIE
251	A fuzzy rule-based approach to modeling affective user satisfaction toward office chair design (Park & Han, 2004)	Fuzzy rule-based model	Qualitative & Quantitative	Fuzzy sets	Industry	IJIE
252	Quality, productivity, occupational health and safety and cost effectiveness of ergonomic improvements in the test workstations of an electronic factory (Yeow & Sen, 2003)	ICET (In-Circuit Electrical Test), FCT (Functional Electrical Tests) processes, SA (Subjective Assessment)	Qualitative	Empirical data	Industry (Electronics)	IJIE
253	Identifying and analyzing hazards in manufacturing industry—a review of selected methods and development of a framework for method applicability (Willquist & Törner, 2003)	HAZOP, OSHA, checklists, HRA, THERP SLIM, HEART, Justification of Human Error Data Information (JHEDI)	Qualitative	Empirical data	Industry (manufacturing)	IJIE
254	A new approach to estimate anthropometric measurements by adaptive neuro-fuzzy inference system (Kaya, Hasiloglu, Bayramoglu, Yesilyurt, & Ozok, 2003)	Adaptive Neuro-Fuzzy Inference System (ANFIS) method	Qualitative & Quantitative	Fuzzy sets	Industry	IJIE
255	Empirical evaluation of training and a work analysis tool for participatory ergonomics (Saleem, Kleiner, & Nussbaum, 2003)	Participatory ergonomics (PE)	Qualitative & Quantitative	Empirical data	Industry	IJIE
256	Factors associated with self-reported musculoskeletal discomfort in video display terminal (VDT) users (Fogleman & Lewis, 2002)	Exploratory factor analysis, Logistic regression	Qualitative	Empirical data	Industry	IJIE
257	Ergonomic interventions for the furniture manufacturing industry. Part I—lift assist devices (Mirka, Smith, Shivers, Taylor, 2002a,b)	OSHA	Qualitative	Empirical data	Industry (furniture manufacturing)	IJIE
258	Ergonomic interventions for the furniture manufacturing industry. Part II—Handtools (Mirka et al., 2002a,b)	OSHA	Qualitative	Empirical data	Industry (furniture manufacturing)	IJIE
259	Accident sequence analysis of human—computer interface design (Fan & Chen, 2000)	FTA, ETA	Hybrid	Theoretical foundations	Computer Science	JRESS

260	Safety of long railway tunnels (Diamantidis, Zuccarelli, & Westhäuser, 2000)	ETA	Hybrid	Theoretical foundations & Empirical data	Mechanics (railway tunnels)	JRESS
261	Proving properties of accidents (Johnson, 2000)	HFEA, Conclusion-Analysis-Evidence (CAE)	Hybrid	Theoretical foundations	All	JRESS
262	An approach for assessing human decision reliability (Pyy, 2000)	Human reliability analysis (HRA)	Hybrid	Theoretical foundations	Industry (nuclear power plants)	JRESS
263	Prioritizing and quantifying the risk of outstanding corrective actions (Burns & Turcotte, 2000)	Probabilistic Risk Analysis (PRA)	Quantitative	Theoretical foundations	All	JRESS
264	Dynamic reliability: toward an integrated platform for probabilistic risk assessment (Labeau, Smidts, & Swaminathan, 2000)	Probabilistic Risk Analysis (PRA)	Quantitative	Theoretical foundations	All	JRESS
265	Safety analysis of autonomous excavator functionality (Seward, Pace, Morrey, & Sommerville, 2000)	FTA	Hybrid	Case study	Mechanics (mobile machinery)	JRESS
266	Qualitative models of equipment units and their use in automatic HAZOP analysis (Bartolozzi, Castiglione, Picciotto, & Galluzzo, 2000)	HAZOP	Qualitative	Theoretical foundations	All	JRESS
267	A simple component-connection method for building binary decision diagrams encoding a fault tree (Way & Hsia, 2000)	FTA	Hybrid	Theoretical foundations	All	JRESS
268	Quantifying human and organizational factors in accident management using decision trees: the HORAAM method (Baumont, Ménage, Schneiter, Spurgin, & Vogel, 2000)	Human and Organizational Reliability Analysis in Accident Management (HORAAM)	Hybrid	Theoretical foundations	All	JRESS
269	Risk assessment of regional systems (Gheorghe, Mock, & Kröger, 2000)	Regional risk assessment	Quantitative	Theoretical foundations	Industry	JRESS
270	Sampling of uncertain probabilities at event tree nodes with multiple branches (Philipson & Wilde, 2000)	Event Tree Analysis (ETA)	Hybrid	Theoretical foundations	All	JRESS
271	A non-probabilistic prospective and retrospective human reliability analysis method — application to railway system (Vanderhaegen, 2001)	Analysis of Consequences of Human Unreliability (ACIH)	Hybrid	Theoretical foundations	Transportations	JRESS
272	Structured information analysis for human reliability analysis of emergency tasks in nuclear power plants (Jung, Yoon, & Kim, 2001)	Human Reliability Analysis (HRA)	Hybrid	Theoretical foundations	Industry	JRESS
273	Modeling and quantification of dependent repeatable human errors in system analysis and risk assessment (Vaurio, 2001)	Human Reliability Analysis (HRA)	Hybrid	Theoretical foundations	All	JRESS
274	On the ALARP approach to risk management (Melchers, 2001)	ALARP approach	Qualitative	Theoretical foundations	All	JRESS
275	Analysis and synthesis of the behavior of complex programmable electronic systems in conditions of failure (Papadopoulos, McDermid, Sasse, & Heiner, 2001)	Hierarchically Performed Hazard Origin and Propagation Studies (HiP-HOPS)	Hybrid	Theoretical foundations	Computer Science	JRESS
276	Improving the analysis of dependable systems by mapping fault trees into Bayesian networks (Bobbio, Portinale, Minichino, & Ciancamerla, 2001)	Bayesian Networks	Quantitative	Theoretical foundations	All	JRESS
277	A case study in the integration of accident reports and constructivedesign documents (Johnson, 2001)	Accident reports	Qualitative	Theoretical foundations	All	JRESS
278	The human error rate assessment and optimizing system HEROS — a new procedure for evaluating and optimizing the man—machine interface in PSA (Richei, Hauptmanns, & Unger, 2001)	Human Error Rate Assessment and Optimizing System (HEROS)	Quantitative	Theoretical foundations	All	JRESS
279	A new importance measure for risk-informed decision-making (Borgonovo & Apostolakis, 2001)	Differential importance measure (DIM)	Quantitative	Theoretical foundations	All	JRESS
280	Efficient algorithms to assess component and gate importance in fault-tree analysis (Dutuit & Rauzy, 2001)	Binary decision diagrams (BDD)	Quantitative	Theoretical foundations	All	JRESS
281	An overview of PSA importance measures (van der Borst & Schoonakker, 2001)	Probabilistic safety assessment (PSA), Risk importance measures	Quantitative	Theoretical foundations	All	JRESS

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Table A. (*continued*)

Nr	Paper Citation	Technique's name	Method's type	Type of paper data or material	Field of application	Journal
(A)	(B)	(C)	(D)	(E)	(F)	(G)
282	Identification, ranking, and management of risks in a major system acquisition (Lambert, Haimes, Li, Schooff, & Tulsiani, 2001)	Hierarchical holographic modeling (HHM)	Qualitative	Theoretical foundations	All	JRESS
283	A fuzzy-logic-based approach to qualitative safety modeling for marine systems (Sii, Ruxton, & Wang, 2001)	Fuzzy-logic-based approach	Qualitative	Fuzzy sets	All	JRESS
284	CDF sensitivity analysis technique for ranking influential parameters in the performance assessment of the proposed high-level waste repository at Yucca Mountain, Nevada, USA (Mohanty & Wu, 2001)	CDF sensitivity analysis technique	Quantitative	Theoretical foundations	Environment	JRESS
285	Quantitative analysis methodology in safety-critical microprocessor applications (Camargo, Canzian, Almeida, Paz, & Basseto, 2001)	Quantitative analysis in safety-critical microprocessors	Quantitative	Theoretical foundations & Case study	Computer Science	JRESS
286	Integration of interlock system analysis with automated HAZOP analysis (Cocchiara, Bartolozzi, Picciotto, & Galluzzo, 2001)	HAZOP	Qualitative	Theoretical foundations	Engineering	JRESS
287	Risk indicators as a tool for risk control (Øien, 2001a,b)	Risk influencing factors	Quantitative	Theoretical foundations	Industry (petroleum)	JRESS
288	A framework for the establishment of organizational risk indicators (Øien, 2001a,b)	Organizational risk indicators	Quantitative	Theoretical foundations	Industry (petroleum)	JRESS
289	Use of risk assessment in the nuclear industry with specific reference to the Australian situation (Cameron & Willers, 2001)	HIFAR PSA (Probabilistic safety assessment),	Quantitative	Theoretical foundations	Industry (nuclear)	JRESS
290	Risk assessment of LPG automotive refueling facilities (Melchers & Feutrill, 2001)	Quantified risk analysis (QRA)	Quantitative	Theoretical foundations & Empirical data	Transportations	JRESS
291	Risk assessment in maritime transportation (Guedes Soares & Teixeira, 2001)	Quantified risk assessment	Quantitative	Theoretical foundations	Transportations (maritime)	JRESS
292	A dynamic fault tree (Cepin & Mavko, 2002)	FTA	Hybrid	Theoretical foundations	All	JRESS
293	Quantifying uncertainty under a predictive, epistemic approach to risk analysis (Apeland, Aven, & Nilsen, 2002)	Quantified risk analysis (QRA)	Quantitative	Theoretical foundations & Empirical data	All	JRESS
294	Comparing safety analysis techniques (Rouvroye & van den Bliek, 2002)	Enhanced Markov Analysis	Quantitative	Theoretical foundations	All	JRESS
295	Automated multiple failure FMEA (Price & Taylor, 2002)	Failure mode and effects analysis (FMEA)	Qualitative	Theoretical foundations	Engineering (electrical)	JRESS
296	Automatic hazard analysis of batch operations with Petri-Nets (Wang, Teague, et al., 2002; Wang, Wu, et al., 2002)	Petri Net-based model	Quantitative	Theoretical foundations & Case study	Engineering	JRESS
297	A tool based approach to checking logical consistency in accident reports (Krishnan, 2002)	Accident reports	Qualitative	Theoretical foundations	Engineering	JRESS
298	Optimization of safety equipment outages improves safety (Cepin, 2002)	Probabilistic safety assessment	Quantitative	Theoretical foundations	Engineering	JRESS
299	Risk analysis in plant commissioning: the Multilevel Hazop (Cagno, Caron, & Mancini, 2002)	Multilevel HAZOP	Qualitative	Theoretical foundations & Case study	Engineering	JRESS
300	Mode automata and their compilation into fault trees (Rauzy, 2002)	Mode automata	Qualitative	Theoretical foundations	Engineering	JRESS
301	Social and economic criteria of acceptable risk (Lind, 2002)	Cost-utility analysis	Quantitative	Theoretical foundations	All	JRESS
302	Component choice for managing risk in engineered systems with generalized risk/cost functions (Guikema & Paté-Cornell, 2002)	Risk–cost functions	Quantitative	Theoretical foundations	Engineering	JRESS
303	An analysis of safety-critical digital systems for risk-informed design (Kang & Sung, 2002)	Probabilistic safety assessment (PSA)	Qualitative	Theoretical foundations & Case study	Industry (nuclear)	JRESS
304	Modified failure mode and effects analysis using approximate reasoning (Pillay & Wang, 2003)	FMEA	Quantitative	Fuzzy sets	Industry (Marine)	JRESS

305	Development of a safety-critical software requirements verification method with combined CPN and PVS: a nuclear power plant protection system application (Son & Seong, 2003)	Colored Petri Net (CPN) & Prototype Verification System (PVS)	Qualitative & Quantitative	Empirical data	Industry (nuclear power plants)	JRESS
306	A quantification algorithm for a repairable system in the GO methodology (Zupei, Yao, & Xiangrui, 2003)	The GO methodology	Quantitative	Epmpirical data	Mechanics (engineering)	JRESS
307	Fault-tree structures of override control systems (Ju, Chen, & Chang, 2003)	Fault-Tree Analysis (FTA)	Qualitative	Theoretical foundations	Industry (chemical plants)	JRESS
308	Safety analysis of the height control system for the Elbtunnel (Ortmeier et al., 2003)	Fault-Tree Analysis (FTA)	Qualitative	Empirical data	Mechanics (tunneling)	JRESS
309	Sequential application of heterogeneous models for the safety analysis of a control system: a case study (Bobbio et al., 2003)	FTA, Bayesian Network & Stochastic Petri Net (SPN)	Qualitative	Empirical data	Industry (power generation systems)	JRESS
310	A rule induction approach to improve Monte Carlo system reliability assessment (Rocco, 2003)	Decision Tree Approach	Qualitative	Dataset	All	JRESS
311	Posbist fault-tree analysis of coherent systems (Huang, Tong, & Zuo, 2004)	Posbist Fault-Tree Analysis	Qualitative & Quantitative	Statistical data & Fuzzy sets	Mechanics (coherent systems)	JRESS
312	Monte Carlo estimation of the differential importance measure: application to the protection system of a nuclear reactor (Marseguerra & Zio, 2004)	Monte Carlo simulation	Quantitative	Empirical data	Industry (nuclear power plants)	JRESS
313	Dynamic reliability and risk assessment of the accident localization system of the Ignalina NPP RBMK-1500 reactor (Kopustinskas, Augutis, & Rimkevičius, 2005)	Accident Localization System, FTA & ALS dynamic model	Qualitative & Quantitative	Theoretical foundations	Mechanics	JRESS
314	Fault-tree construction of hybrid system requirements using qualitative formal method (Lee & Cha, 2005)	FTA & Causal Requirements Safety Analysis (CRSA)	Qualitative	Empirical data	Mechanics	JRESS
315	Approximate estimation of system reliability via fault trees (Dutuit & Rauzy, 2005)	FTA & Binary Decision Diagrams (BDD)	Qualitative & Quantitative	Empirical data	Industry	JRESS
316	Risk-informed design of IRIS using a level-1 probabilistic risk assessment from its conceptual design phase (Mizuno, Ninokata, & Finnicum, 2005)	PRA	Qualitative & Quantitative	Database	Industry (nuclear power plants)	JRESS
317	A quantitative assessment of LCOs for operations using system dynamics (Kang & Jae, 2005)	PRA & System dynamics method	Quantitative	Empirical data	Industry (nuclear power plants)	JRESS
318	A Monte Carlo simulation approach for approximating multi-state two-terminal reliability (Ramirez-Marquez & Coit, 2005)	Monte Carlo simulation	Quantitative	Empirical data	All	JRESS
319	A discrete-time Bayesian network reliability modeling and analysis framework (Boudali & Dugan, 2005)	PRA: Fault-Tree Analysis & Bayesian Networks	Qualitative & Quantitative	Empirical data	Industry	JRESS
320	Biased Monte Carlo optimization: the basic approach (Campioni, Scardovelli, & Vestrucci, 2005)	Monte Carlo method (MC) & Importance Sampling (IS) technique	Quantitative	Empirical data	All	JRESS
321	Analysis of truncation limit in probabilistic safety assessment (Čepin, 2005)	Probabilistic Safety Assessment	Quantitative	Theoretical foundations & Case study	All	JRESS
322	Software safety analysis of function block diagrams using fault trees (Oh, Yoo, Cha, & Son, 2005)	FTA	Qualitative	Empirical data	Industry (nuclear power plants)	JRESS
323	Monte Carlo-based assessment of system availability. A case study for cogeneration plants (Marquez, Heguedas, & Iung, 2005)	Monte Carlo method (MC)	Quantitative	Empirical data	Industry (Electrical power generation systems)	JRESS
324	Enhancing software safety by fault trees: experiences from an application to flight critical software (Weber, Tondok, & Bachmayer, 2005)	FTA	Qualitative	Empirical data	Mechanics (aviation)	JRESS
325	A historical overview of probabilistic risk-assessment development and its use in the nuclear power industry: a tribute to the late Professor Norman Carl Rasmussen (Keller & Modarres, 2005)	PSA	Quantitative	Theoretical foundations & Case study	Industry (nuclear power plants)	JRESS
326	First-order differential sensitivity analysis of a nuclear safety system by Monte Carlo simulation (Marseguerra, Zio, & Podofillini, 2005)	Monte Carlo method (MC)	Quantitative	Empirical data	Industry (nuclear power plants)	JRESS
327	Optimal maintenance decisions under imperfect inspection (Kallen & van Noortwijk, 2005)	Risk-Based Inspection (RBI) techniques	Quantitative	Empirical data	Industry	JRESS

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Table A. (*continued*)

Nr	Paper Citation	Technique's name	Method's type	Type of paper data or material	Field of application	Journal
(A)	(B)	(C)	(D)	(E)	(F)	(G)
328	A support tool for identifying evaluation issues of road safety measures (Jagtman, Hale, & Heijer, 2005)	HAZOP	Qualitative	Empirical data	Industry	JRESS
329	Evaluation of tunnel safety: toward an economic safety optimum (Arends, Jonkman, Vrijling, & van Gelder, 2005)	PSA	Quantitative	Empirical data	Industry (tunnels)	JRESS
330	Identification of reference accident scenarios in SEVESO establishments (Delvosalle et al., 2005)	FTA, ETA & Identification of Major Accident Hazards (MIMAH) methodology	Qualitative	Accident data & Empirical data	Industry	JRESS
331	A synergetic approach for assessing and improving equipment performance in offshore industry based on dependability (Ebrahimipour & Suzuki, 2006)	Principle Component Analysis, Importance Analysis & Data Envelopment Analysis	Quantitative	Fuzzy sets	Industry	JRESS
332	Evaluation and comparison of estimation methods for failure rates and probabilities (Vaurio & Jänkälä, 2006)	Parametric Robust Empirical Bayes (PREB) estimation methodology	Quantitative	Empirical data	Industry	JRESS
333	An analytic model for situation assessment of nuclear power plant operators based on Bayesian inference (Kim & Seong, 2006)	Human Reliability Analysis (HRA) methods	Quantitative	Empirical data	Industry (nuclear power plants)	JRESS
334	The 'PROCESO' index: a new methodology for the evaluation of operational safety in the chemical industry (Maroño, Peña, & Santamaria, 2006)	Operational Safety Index: the 'Proceso' Index (PROCedure for the Evaluation of Operational Safety)	Quantitative	Dataset	Industry (chemical process plants)	JRESS
335	Cause–consequence analysis of non-repairable phased missions (Vyzaite, Dunnett, & Andrews, 2006)	The Cause–consequence diagram methods	Qualitative & Quantitative	Accident data	Industry (non-repairable phased missions)	JRESS
336	Reliability evaluation of the power supply of an electrical power net for safety-relevant applications (Dominguez-Garcia, Kassakian, & Schindall, 2006)	FMEA & Markov model	Qualitative & Quantitative	Empirical data	Mechanics	JRESS
337	Application of Bayesian network to the probabilistic risk assessment of nuclear waste disposal (Lee & Lee, 2006)	Bayesian network	Quantitative	Empirical data	Industry (nuclear waste disposal)	JRESS
338	Process monitoring based on classification tree and discriminant analysis (Zhou, Hahn, & Mannan, 2006)	Classification tree & Fisher Discriminant Analysis (FDA)	Quantitative	Case study	Industry (process monitoring)	JRESS
339	Bayesian framework for managing preferences in decision-making (Maes & Faber, 2006)	Bayesian approach	Quantitative	Empirical data	Industry	JRESS
340	Gradient and parameter sensitivity estimation for systems evaluated using Monte Carlo analysis (Ahammed & Melchers, 2006)	Monte Carlo analysis	Quantitative	Theoretical foundations	All	JRESS
341	Application of condition-based HRA method for a manual actuation of the safety features in a nuclear power Plant (Kang & Jang, 2006)	condition-based HRA method (CBHRA)	Quantitative	Empirical data	Industry (nuclear power plants)	JRESS
342	Reliability-based failure cause assessment of collapsed bridge during construction (Choi, Lee, Choi, Cho, & Mahadevan, 2006)	ETA & Bayesian approach	Qualitative & Quantitative	Empirical data	Mechanics (construction)	JRESS
343	A fuzzy modeling application of CREAM methodology for human reliability analysis (Konstandinidou, Nivolianitou, Kiranoudis, & Markatos, 2006)	CREAM methodology	Quantitative	Fuzzy sets	Industry	JRESS
344	Reliability analysis of reinforced concrete grids with nonlinear material behavior (Neves, Chateauneuf, Venturini, & Lemaire, 2006)	Reliability analysis	Quantitative	Empirical data	Mechanics (construction)	JRESS
345	Bayesian analysis of repairable systems showing a bounded failure intensity (Guida & Pulcini, 2006)	The Bayesian procedure	Quantitative	Dataset	Mechanics	JRESS
346	A combined goal programming—AHP approach to maintenance selection problem (Bertolini & Bevilacqua, 2006)	The Analytic Hierarchy Process (AHP) technique	Quantitative	Empirical data	Industry (oil refinery plants)	JRESS

347	Designing a Bayesian network for preventive maintenance from expert opinions in a rapid and reliable way (Celeux, Corset, Lannoy, & Ricard, 2006)	Bayesian Network	Quantitative	Empirical data	Industry (nuclear power plants)	JRESS
348	Reprioritization of failures in a system failure mode and effects analysis by decision-making trial and evaluation laboratory technique (Seyed-Hosseini, Safaei, & Asgharpour, 2006)	FMEA & Decision-Making Trial and Evaluation Laboratory technique (DEMATEL)	Quantitative	Empirical data	All	JRESS
349	A supplemental algorithm for the repairable system in the GO methodology (Shen, Dai, & Huang, 2006)	The GO methodology	Quantitative	Theoretical foundations	All	JRESS
350	An evaluation system of the setting up of predictive maintenance programmes (Carnero, 2006)	The Analytic Hierarchy Process (AHP) technique	Qualitative & Quantitative	Theoretical foundations	Mechanics	JRESS
351	Cause and effect analysis by fuzzy relational equations and a genetic algorithm (Rotshtein, Posner, & Rakytyanska, 2006)	Cause and effect analysis	Quantitative	Fuzzy sets	Industry (expert systems of diagnosis and quality control)	JRESS
352	The use of global uncertainty methods for the evaluation of combustion mechanisms (Tomlin, 2006)	Monte Carlo & Morris Method	Quantitative	Empirical data	Iindustry (Chemical)	JRESS
353	Local and global uncertainty analysis of complex chemical kinetic systems (Zádor, Zsély, & Turányi, 2006)	Monte Carlo & Morris Method	Quantitative	Empirical data	Iindustry (Chemical)	JRESS
354	Sensitivity estimations for Bayesian inference models solved by MCMC methods (Pérez, Martín, & Rufo, 2006)	Markov Chain Monte Carlo (MCMC) methods	Quantitative	Empirical data	Industry (nuclear power plants)	JRESS
355	Multidisciplinary perspective on accident investigation (Basnyat, Chozos, & Palanque, 2006)	Human Error Analysis (HEA) & Barrier analysis	Qualitative	Accidents data	Industry (mining)	JRESS
356	Bayesian networks in reliability (Langseth & Portinale, 2006)	Bayesian Networks	Quantitative	Empirical data	Mechanics	JRESS
357	Deterministic and stochastic approach for safety and reliability optimization of captive power plant maintenance scheduling using GA/SA-based hybrid techniques: A comparison of results (Mohanta, Sadhu, & Chakrabarti, 2007)	Levelized reserve method & Levelized risk method	Quantitative	Empirical data	Industry (aluminium)	JRESS
358	The simulator experimental study on the operator reliability of Qinshan nuclear power plant (Zhang, He, Dai, & Huang, 2007)	Human Reliability Analysis (HRA)	Quantitative	Theoretical foundations & Case study	Industry (nuclear power plants)	JRESS
359	Formal safety assessment based on relative risks model in ship navigation (Hu, Fang, Xia, & Xi, 2007)	Formal Safety Assessment (FSA)	Quantitative	Fuzzy sets	Industry (ship navigation)	JRESS
360	Practical extensions to NHPP application in repairable system reliability analysis (Krivtsov, 2007)	Non-homogeneous Poisson Process (NHPP)	Quantitative	Facts	Industry	JRESS
361	A support vector machine integrated system for the classification of operation anomalies in nuclear components and systems (Rocco & Zio, 2007)	Support Vector Machine (SVM) approach	Quantitative	Facts	Industry (nuclear power plants)	JRESS
362	Bayesian risk-based decision method for model validation under uncertainty (Jiang & Mahadevan, 2007)	Bayesian Risk-Based Decision method	Quantitative	Experimental data	All	JRESS
363	Proposal for a sustainable framework process for the generation, validation, and application of human reliability assessment within the engineering design lifecycle (Kennedy, Siemieniuch, Sinclair, Kirwan, & Gibson, 2007)	Human Reliability Assessment (HRA) techniques	Qualitative & Quantitative	Facts	Mechanics	JRESS
364	An analytic solution for a fault tree with circular logics in which the systems are linearly interrelated (Lim & Jang, 2007)	FTA	Quantitative	Theoretical foundations	All	JRESS
365	A Monte Carlo simulation approach to the availability assessment of multi-state systems with operational dependencies (Zio, Marella, & Podofillini, 2007a,b)	Monte Carlo simulation approach	Quantitative	Theoretical foundations & Case study	All	JRESS
366	Seismic PSA method for multiple nuclear power plants in a site (Hakata, 2007)	PSA	Quantitative	Facts	Industry (nuclear power plants)	JRESS

(*continued on next page*)

Table A. (*continued*)

Nr	Paper Citation	Technique's name	Method's type	Type of paper data or material	Field of application	Journal
(A)	(B)	(C)	(D)	(E)	(F)	(G)
367	Test interval optimization of safety systems of nuclear power plant using fuzzy-genetic approach (Rao, Gopika, Kushwaha, Verma, & Srividya, 2007; Rao, Kushwaha, Verma, & Srividya, 2007)	PSA	Quantitative	Fuzzy sets	Industry (nuclear power plants)	JRESS
368	Quantification of epistemic and aleatory uncertainties in level-1 probabilistic safety assessment studies (Rao, Kushwaha, Verma, & Srividya, 2007)	PSA	Quantitative	Facts	Industry (nuclear power plants)	JRESS
369	A practical method for accurate quantification of large fault trees (Choi & Cho, 2007)	The (Minimal Cut Set) MCS-based fault-tree method	Quantitative	Theoretical foundations	All	JRESS
370	Incorporating organizational factors into probabilistic safety assessment of nuclear power plants through canonical probabilistic models (Galán, Mosleh, & Izquierdo, 2007)	PSA & Bayesian Networks	Quantitative	Dataset	Industry (nuclear power plants)	JRESS
371	EUROCONTROL—Systemic Occurrence Analysis Methodology (SOAM)—A "Reason"-based organizational methodology for analyzing incidents and accidents (Licu, Cioran, Hayward, & Lowe, 2007)	The Safety Occurrence Analysis Methodology (SOAM)	Qualitative	Facts	Industry	JRESS
372	Condition-based fault-tree analysis (CBFTA): A new method for improved fault-tree analysis (FTA), reliability and safety calculations (Shalev & Tiran, 2007)	Condition-Based FTA (CBFTA)	Quantitative	Statistical data	Mechanics	JRESS
373	Thermal–hydraulic passive system reliability-based design approach (Burgazzi, 2007)	Limit State Function (LSF)-based approach	Quantitative	Empirical data	Mechanics	JRESS
374	Importance measures-based prioritization for improving the performance of multi-state systems: application to the railway industry (Zio, Marella, & Podofillini, 2007)	The Monte Carlo (MC) method	Quantitative	Empirical data	Industry (railway)	JRESS
375	An improved decomposition scheme for assessing the reliability of embedded systems by using dynamic fault trees (Huang & Chang, 2007)	Dynamic Fault-Trees Analysis (DyFA)	Quantitative	Theoretical foundations	All	JRESS
376	Bayesian networks for multilevel system reliability (Wilson & Huzurbazar, 2007)	Bayesian Networks (BNs)	Quantitative	Theoretical foundations	All	JRESS
377	Addressing dependability by applying an approach for model-based risk assessment (Gran, Fredriksen, & Thunem, 2007)	Model-Based Risk-Assessment (MBRA) approach	Qualitative	Theoretical foundations	All	JRESS
378	Using fuzzy self-organizing maps for safety-critical systems (Kurd & Kelly, 2007)	FMEA	Qualitative & Quantitative	Fuzzy sets	Mechanics	JRESS
379	Analysis of surveillance test interval by Markov process for SDS1 in CANDU nuclear power plants (Cho & Jiang, 2008)	Markov process	Quantitative	Empirical data	Industry (nuclear power plants)	JRESS
380	A simplified CREAM prospective quantification process and its application (He, Wang, Shen, & Huang, 2008)	CREAM	Quantitative	Empirical data	Industry (nuclear power plants)	JRESS
381	The MDTA-based method for assessing diagnosis failures and their risk impacts in nuclear power plants (Kim, Jung, & Son, 2008)	The MDTA-based method	Qualitative & Quantitative	Empirical data	Industry (nuclear power plants)	JRESS
382	An analytical approach to quantitative effect estimation of operation advisory system based on human cognitive process using the Bayesian belief network (Lee, Kim, & Seong, 2008)	The Bayesian Belief Network model	Qualitative & Quantitative	Theoretical foundations	Industry (nuclear power plants)	JRESS
383	A new method for estimating human error probabilities: AHP–SLIM (Park & Lee, 2008)	AHP–SLIM method (Analytic Hierarchy Process – Success Likelihood Index Method)	Qualitative & Quantitative	Empirical data	All	JRESS

384	Security risks and probabilistic risk assessment of glazing subject to explosive blast loading (Stewart & Netherton, 2008)	PRA	Quantitative	Facts	Mechanics (buildings)	JRESS
385	Evaluation of the reliability of transport networks based on the stochastic flow of moving objects (Wu, Ning, & Ning, 2008)	The Stochastic Moving Network (SMN) model	Quantitative	Theoretical foundations	Mechanics (communications)	JRESS
386	A Bayesian Belief Network modeling of organizational factors in risk analysis: A case study in maritime transportation (Trucco, Cagno, Ruggeri, & Grande, 2008)	Bayesian Belief Networks	Qualitative & Quantitative	Empirical data	Industry (Maritime)	JRESS
387	Modeling the reliability of search and rescue operations with Bayesian Belief Networks (Norrington, Quigley, Russell, & der Meer, 2008)	Bayesian Belief Networks	Qualitative & Quantitative	Accidents data	Industry (Maritime)	JRESS
388	Development and application of a Risk-Assessment Tool (Majdara & Nematollahi, 2008)	Risk-Assessment Tool (RAT)	Qualitative & Quantitative	Facts	Industry (nuclear power plants)	JRESS
389	Reliability evaluation of deregulated electric power systems for planning applications (Ehsani, Ranjbar, Jafari, & Fotuhi-Firuzabad, 2008)		Quantitative	Empirical data	Industry	JRESS
390	Matrix-based system reliability method and applications to bridge networks (Kang, Song, & Gardoni, 2008)	The Matrix-based System Reliability (MSR) method	Qualitative & Quantitative	Empirical data	Mechanics (transportations)	JRESS
391	A neuro-fuzzy technique for fault diagnosis and its application to rotating machinery (Zio & Gola, 2009)	The Neuro-Fuzzy (NF) modeling approach	Quantitative	Fuzzy sets	Industry	JRESS
392	Probabilistic design of aluminum sheet drawing for reduced risk of wrinkling and fracture (Zhang & Shivpuri, 2009)	The Response Surface Method (RSM) based model	Quantitative	Empirical data	Industry	JRESS
393	Mathematical formulation and numerical treatment based on transition frequency densities and quadrature methods for non-homogeneous semi-Markov processes (Moura & Droguett, 2009)	Non-Homogeneous Semi-Markov Processes (NHSMP)	Quantitative	Empirical data	All	JRESS
394	On the use of the hybrid causal logic method in offshore risk analysis (Røed, Mosleh, Vinnem, & Aven, 2009)	Bayesian Belief Networks	Qualitative & Quantitative	Empirical data	Industry	JRESS
395	A generic method for estimating system reliability using Bayesian networks (Doguc & Ramirez-Marquez, 2009)	Bayesian Networks	Quantitative	Empirical data	All	JRESS
396	Bayesian approaches for detecting significant deterioration (Røed & Aven, 2009)	Bayesian analysis	Quantitative	Empirical data	Industry	JRESS
397	Model-based Monte Carlo state estimation for condition-based component replacement (Cadini, Zio, & Avram, 2009)	Model-based Monte Carlo method	Quantitative	Empirical data	Industry	JRESS
398	An integrated structural framework to cost-based FMECA: The priority-cost FMECA (Carmignani, 2009)	The priority-cost FMEA and Criticality Analysis (PC-FMECA) methodology	Qualitative & Quantitative	Empirical data	Industry	JRESS
399	Dynamic fault-tree analysis using Monte Carlo simulation in probabilistic safety assessment (Rao et al., 2009)	Dynamic Fault-Tree Analysis (DFTA)	Qualitative & Quantitative	Empirical data	Industry (nuclear power plants)	JRESS
400	Reliability assessment of passive isolation condenser system of AHWR using APSRA methodology (Nayak et al., 2009)	APSRA (Assessment of Passive System ReliAbility) methodology	Qualitative	Empirical data	Industry	JRESS
401	An automated system for batch hazard and operability studies (Palmer & Chung, 2009)	Batch HAZOP	Qualitative	Empirical data	Industry	JRESS
402	Application of the fault-tree analysis for assessment of power system reliability (Volkanovski, Čepin, & Mavko, 2009)	FTA	Qualitative & Quantitative	Empirical data	Industry (nuclear power plants)	JRESS
403	Sensitivity analysis for decision-making using the MORE method—A Pareto approach (Ravalico, Maier, & Dandy, 2009)	The Management Option Rank Equivalence (MORE) method	Qualitative & Quantitative	Empirical data	Industry	JRESS
404	Development of a new quantification method for a fire PSA (Jung, Lee, & Yang, 2009)	The Jung's Single Top And Run (JSTAR) method	Qualitative & Quantitative	Empirical data	Industry (nuclear power plants)	JRESS

Annotations: JSS: Safety Science; JLPPI: Journal of Loss Prevention in the Process Industries; JAAP: Accident Analysis and Prevention; JSR: Journal of Safety Research; IJIE: International Journal of Industrial Ergonomics; JRESS: Reliability Engineering & System Safety.

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C Risk Assessment Methods and Models for Maritime Industry

[Goerlandt and Montewka, 2015b] has analyzed 58 risk assessment and risk analysis methods applied to the MTS from 1974-2014 and compared them based on risk definition, risk perspective, approach to risk analysis science, data, model, judgment, non-epistemic values, contextual attributes etc. [Goerlandt and Montewka, 2015b] compared the various risk assessment and risk analysis methods and divided them in eight categories; strong realist, moderate realist, moderate realist with uncertainty quantification, scientific proceduralist, precautionary constructivist, moderate constructivist with uncertainty evaluation, moderate constructivist, strong constructivist.

1. Strong realist
2. Moderate realist
3. Moderate realist with uncertainty quantification
4. Scientific proceduralist
5. Precautionary constructivist
6. Moderate constructivist with uncertainty evaluation
7. Moderate constructivist
8. Strong constructivist

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Maritime transportation risk analysis: Review and analysis in light of some foundational issues

Floris Goerlandt*, Jakub Montewka

Aalto University, School of Engineering, Department of Applied Mechanics, Marine Technology, Research Group on Maritime Risk and Safety, PO Box 15300, AALTO, FI-00076, Finland

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ABSTRACT

Many methods and applications for maritime transportation risk analysis have been presented in the literature. In parallel, there is a recent focus on foundational issues in risk analysis, with calls for intensified research on fundamental concepts and principles underlying the scientific field. This paper presents a review and analysis of risk definitions, perspectives and scientific approaches to risk analysis found in the maritime transportation application area, focusing on applications addressing accidental risk of shipping in a sea area. For this purpose, a classification of risk definitions, an overview of elements in risk perspectives and a classification of approaches to risk analysis science are applied. Results reveal that in the application area, risk is strongly tied to probability, both in definitions and perspectives, while alternative views exist. A diffuse situation is also found concerning the scientific approach to risk analysis, with realist, proceduralist and constructivist foundations co-existing. Realist approaches dominate the application area. Very few applications systematically account for uncertainty, neither concerning the evidence base nor in relation to the limitations of the risk model in relation to the space of possible outcomes. Some suggestions are made to improve the current situation, aiming to strengthen the scientific basis for risk analysis.

1. Introduction

Risk analysis methods for maritime transportation have received a growing interest in recent years, even to the extent that international organizations have provided recommendations on the use of specific risk analysis and management tools [1–3]. In parallel, there is a recent focus on foundational issues in scientific environments concerned with risk analysis, with calls for intensifying research on issues such as applied terminology, principles and perspectives for analyzing and managing risk [4–6].

Answering these calls, this paper provides a review and analysis of risk analysis applications addressing the accidental risk of maritime transportation in a sea area, in light of some foundational issues as intended in [5]. A distinction is made between the science of risk analysis (concerning concepts, principles, methods and models for analyzing risk) and the practice of risk analysis (concerning specific applications) [6].

In particular, the applied risk definitions, the perspectives for describing risk, and the scientific approach to risk analysis as a tool for supporting decision-making are in focus. This distinguishes the current work from recent review papers [7–9] as only minimal attention is given to the structure and content of the methods. Rather, the methods and applications are reviewed on a high level, focusing on some risk-theoretic foundations. The research focuses on providing insight into which risk-theoretical foundations the maritime transportation area has adopted, aiming to facilitate further reflections and discussions within the maritime research community. Thus, the paper aims to support the call by Aven and Zio [5], specifically in the maritime transportation application area.

A systematic method is taken to review and analyze risk applications, considering three issues. In Section 2, a brief review of definitions for risk is provided, focusing on the question how the risk concept is defined in particular applications. In Section 3, a brief summary is given of elements of risk perspectives, focusing on which tools are applied to measure/describe risk and on the scope of the analysis (events or events and consequences). In Section 4, a classification of scientific approaches to risk analysis is presented, utilizing the framework of the realist-constructivist continuum. This concerns the underlying ontological, epistemological and normative commitments to risk analysis as a scientific activity, which amongst other have implications for the evidence types considered in the analysis, the extent of uncertainty treatment and the role of the risk analysis in decision making.

Following the methodological basis, Section 5 presents an overview of maritime transportation risk analysis applications in light of the three above aspects. In Section 6, a further analysis is performed, providing insight in historical developments and cross-dependencies

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* Corresponding author. Tel.: +358 9 470 23476; fax: +358 9 470 23493.
E-mail address: floris.goerlandt@aalto.fi (F. Goerlandt).

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between definitions, perspectives and approaches. A discussion is made in Section 7 and a conclusion in Section 8.

2. A classification of risk definitions

In Table 1, a brief overview of some categories for definitions of risk is given, based on a historic analysis of the risk concept by Aven [10]. These conceptual classes are here used as a basis to obtain insight in how risk is defined in the application area. Definitions and discussions in [10,11] are used to briefly summarize the nine categories.

Category D1 defines risk as the expected value of the probability of an event occurrence and the utility of the consequences. In D2, risk is defined risk as the probability of an undesirable event, or the chance of a loss. In D3, risk is defined as objective uncertainty, i.e. a probability distribution over an outcome range (known through calculations or from statistical data analysis). Category D4 represents definitions where risk is equal to uncertainty, understood as a statistical variation compared with an average value. In category D5, risk is defined as the possibility of an unfortunate occurrence. D6 defines risk as the combination of the probability of occurrence of an event and consequences, without combining these in one unit as in D1. D7 understands risk as objective states of the world, which are considered existing independent of an assessor. D8 defines risk as the combination of events, consequences and the uncertainties of these, where uncertainty is understood as an assessor's uncertainty about the occurrence of the events/consequences. D9 defines risk as an effect on stated objectives (i.e. a consequence), due to the presence of uncertainty.

3. Elements of risk perspectives

In this section, a brief overview is given of some commonly found elements of risk perspectives. A risk perspective is here understood as a way to describe risk, a systematic manner to analyse and make statements about risk, as in [12]. Three aspects are considered: the measurement tools (probabilities, indicators, fuzzy numbers,…), the scope of the analysis (events or events and consequences), and the tools applied to convey information regarding the confidence in the analysis (uncertainty and bias measures). One element of risk measurement tools concerns their interpretability as it has been argued that this is an important aspect of practical decision making [13,14].

Table 2 lists the risk perspective elements applicable to the current research. Each element is outlined by an abbreviation, a definition, a short description of its underlying rationale, and a selection of references where the element is more elaborately discussed.

4. A classification of approaches to the science of risk analysis

In a risk analysis, risk is measured/described with the purpose of informing a decision, but views differ about how to do this [38]. Several researchers have argued that much of the controversy about risk analysis as a tool for informing decisions is rooted in fundamentally opposing views on the foundations of risk analysis as a scientific activity and opposing views regarding the nature of the risk concept [39–42].

Table 1
A classification of risk definitions [10].

	Risk definition classes	Abbreviation
D1	Risk = Expected value	R = EV
D2	Risk = Probability of an (undesirable) event	R = P
D3	Risk = Objective uncertainty	R = OU
D4	Risk = Uncertainty	R = U
D5	Risk = Potential/possibility of a loss	R = PO
D6	Risk = Probability and scenarios/(severity of) consequences	R = P&C
D7	Risk = Event or consequence	R = C
D8	Risk = Consequences/damage/severity + uncertainty	R = C&U
D9	Risk = Effect of uncertainty on objectives	R = ISO

As the rationale behind these opposing views appears to be less known outside the more theoretically oriented risk research community, and no references have been made to it in the maritime application area, it is considered important to outline some key features. First, a general introduction to the approaches to risk analysis science is given, focusing on the earlier proposed realist-constructivist continuum. Subsequently, a classification of the scientific risk approaches is proposed, which is applied in the subsequent analysis.

4.1. Realist, constructivist and proceduralist approaches to risk analysis science

Three broadly differing views on risk analysis can be distinguished: realist, constructivist and proceduralist approaches [39–42]. The outlines given below are intended as a basis for making distinctions, acknowledging that various variations of each approach exist, e.g. related to the types of evidence considered, and the extent of uncertainty treatment.

Risk realists typically consider risk as a physically given attribute of a technology or system, which can be characterized by objective facts. Risk can thus be explained, predicted and controlled by science [40]. Under such approaches, risk is essentially characterized by quantitative (often probabilistic) information regarding events or consequences. Other dimensions sometimes attributed to risk, such as controllability, the voluntariness of exposure and fear, are seen as accidental dimensions and not part of the risk concept per se [39,42,43]. Risk realists work under the presumption that technical analyses are a representation or approximation of an absolute truth, and typically aim at accurate risk measurement. One implication of this reification of risk is the attempt to make a clear distinction between facts and non-epistemic values[1] [39,40]. Another is the strong link between the calculated risk numbers, established risk decision criteria and subsequent decision making, i.e. a risk-based decision making strategy [38,45]. Risk management decisions are seen as rational to the extent they are based on the realist, non-personal factors of technical analysis.

Risk constructivists typically hold that risk is a social construct, attributed to (rather than part of) a technology or system [40]. The risk analysis is presented as a reflection of a mind construct of a (group of) expert(s) and/or lay people. In strong constructivist approaches, risk can be characterized by quantitative (probabilistic) information regarding events or consequences, but these risk dimensions are at par with controllability, fear, the voluntariness of exposure and other psychometric factors. Neither of these are essential parts of the risk concept, and it is a contextual decision which are considered relevant [42,46]. Risk constructivists focus on the cognitive and social dimensions of knowledge claims regarding risk, place more stress on the importance of uncertainty and some argue against a strict separation between facts and values [39]. There often is a strong link to decision making, but risk analyses are used to inform a decision, requiring a managerial decision making where other factors are considered as well [38,45].

An additional distinction can be made related to the role of stakeholders in the risk analysis process. In the realist and

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[1] Non-epistemic values are of a moral, political or aesthetic nature, i.e. values which have no relevance to determining whether a claim is true but stem from a reflective consideration of what is good in a given context [44].

Table 2
Outline of the elements of risk perspectives applied in maritime transportation risk analysis.

	Definition *Rationale of the measurement tool*	**Ref.**
$\boldsymbol{P_f}$	Frequentist probability *Fraction of time a specified outcome occurs in an in principle infinite number of repeated tests* *A distinction is made between P_f as a concept and its measurement P_f^*, which is derived from empirical data, a thought-constructed "repeated experiment" or a repeated evaluation of an engineering or statistical model*	[13,15–17]
$\boldsymbol{P_s}$	Subjective probability *Degree of belief of an assessor based on evidence available to him/her,* i.e. *a measure of outcome uncertainty*	[13,15–17]
$\boldsymbol{P_x}$	Modelled probability *Calculated probability measure based on a data- or judgment-based model, mapping non-probabilistic predictor variables to a probability (or probability-like) scale*	[18–20]
$\boldsymbol{I_{QU}}$	Quantitative indicator *A ratio- or interval scale measure of a characteristic of the system, used as a proxy of the occurrence of events and/or consequences. The quantitative measure is derived from data, or by applying a model in data*	[21–23]
$\boldsymbol{I_{QL}}$	Qualitative indicator *A categorical or ordinal measure of a characteristic of the system, used as a proxy of the occurrence of events and/or consequences. The qualitative measure is based on a judgement by an assessor, obtained either through direct judgment or derived from a mathematical model*	[21–23]
F	Fuzzy number *A measure derived from the degree to which a specific instance belongs to a certain category,* i.e. *the degree of similarity between the instance and the category*	[24–26]
A	Event *A specific (defined) state of the world and how that specified state changes or develops over a time interval*	[27]
C	Consequence *A specific type of event, connected to another event through a causal relation,* i.e. *under conditions of constant conjunction, temporal succession and spatial propinquity*	[27]
$\boldsymbol{U_{QL}}$	Qualitative measure of evidential uncertainty or qualitative measure of the strength of knowledge *A linguistic or numerical measure on an ordinal or categorical scale indicating the lack of knowledge (or conversely, the strength of knowledge) for making a measurement or statement*	[28–30]
$\boldsymbol{U_{QU}}$	Quantitative measure of evidential uncertainty *A numerical measure on an interval or ratio scale, quantifying the epistemic uncertainty related to parameters of a model, e.g. applying imprecise (interval) probability, probability bound analysis, evidence theory or possibility theory*	[14,31,32]
$\boldsymbol{U_{AH}}$	Alternative hypothesis-based epistemic uncertainty *An expression of epistemic uncertainty, in particular related to model structure, by weighing multiple plausible hypotheses related to a given phenomenon*	[33,34]
B	Bias *A categorical or ordinal measure indicating the direction of deviation from what is believed to be an accurate reflection of the phenomenon, in relation to the applied representation of the phenomenon accepted in a given context*	[35–37]

constructivist approaches, risk analysis applications are mainly seen as a process of knowledge transfer from analysts and experts to decision makers. In the proceduralist approach, different stakeholders such as scientists, experts, risk-affected lay persons and policy makers, take part in a process in which risk is characterized through a shared understanding, balancing facts and values [39]. Hence, risk analysis and related decision making is understood through an analytic-deliberative process [47].

4.2. Applied classification of approaches to risk analysis science

The general approaches to risk analysis as a scientific discipline as outlined in Section 4.1 are further distinguished by considering a number of criteria used to classify the risk analysis applications in Section 5. The presented classification distinguishes eight classes, see Table 3 and Fig. 1. Following criteria are considered for classifying risk analysis applications to these classes: (i) focus on an underlying true risk, (ii) reliance on data and models from natural or engineering sciences, (iii) reliance on expert judgment, (iv) reliance on non-epistemic values, (v) reliance on lay people's judgment, (vi) extent of uncertainty assessment, (vii) stakeholder involvement, (viii) consideration of contextual attributes (fear, voluntariness, etc.), and (ix) relation between the risk analysis and decision-making.

The characteristics of the classes are summarized in Table 3, where some references are given to work where (some aspects of) the approaches are more elaborately described. A visual representation of the classification is given in Fig. 1, clearly showing the multi-faceted diversity in approaches to risk analysis.

5. Risk analysis applications for maritime transportation

In this section, a concise overview is given of the maritime transportation risk analysis applications, i.e. applications analyzing the accidental risk of maritime transportation in a given waterway or sea area. The review covers the period from 1970 to 2014, using a total of 58 applications. For each analysis, following characteristics are determined in Tables 4–7:

(i) the analysis aims and scope;
(ii) the applied definition of risk, see Table 1;
(iii) the applied tools to measure risk, see Table 2;
(iv) whether events (A), or events and consequences (A, C) are accounted for;
(v) the tools applied to convey information regarding the confidence in the analysis, see Table 2;
(vi) the applied types of evidence (data, models, expert judgments, layperson judgments, non-epistemic values);
(vii) the consideration of contextual attributes (fear, voluntary exposure, equity, etc.);
(viii) the adopted approach to risk analysis science, according to the classification of Table 3.

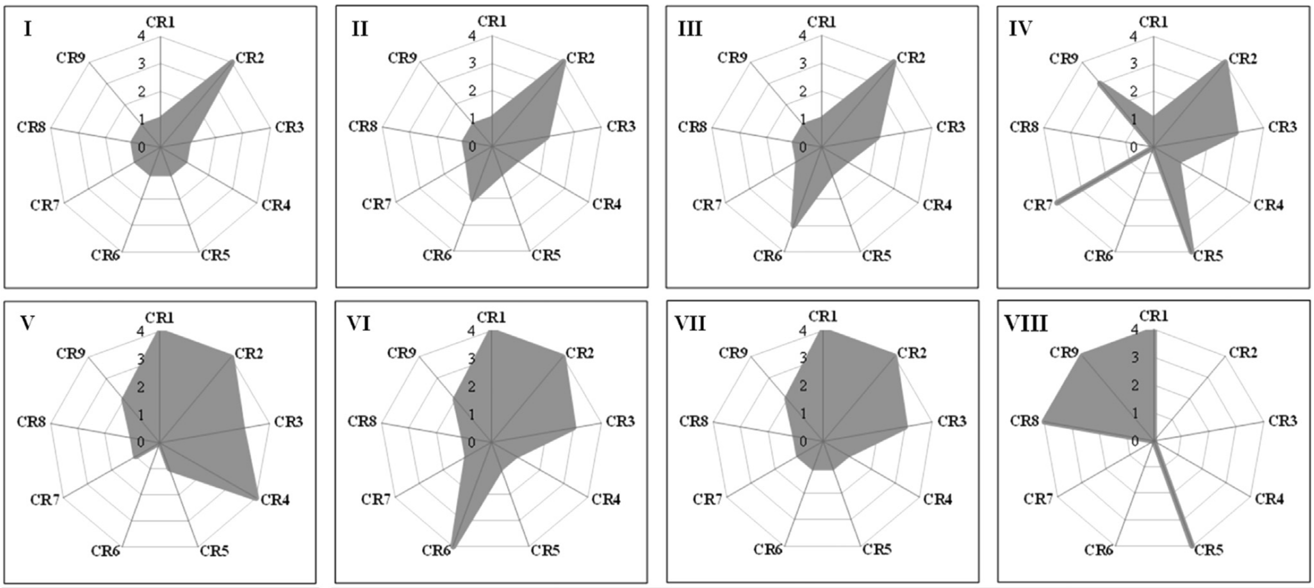
The risk perspectives are denoted as $R \sim (x_1,\ldots,x_n, y_1, y_2 | z_1,\ldots z_m)$ or $R \sim (x_1,\ldots x_n \rightarrow y_1, y_2 | z_1,\ldots z_m)$, where "∼" signifies "is described by", "→" means "refers to" and "|" represents "conditional to". For analyses where the actual occurrence of events and/or consequences is measured, the elements are simply listed. For analyses where the occurrence of events and/or consequences is not measured per se, but rather inferred from other measures, the symbol "→" is used. The

Table 3
Applied classification of approaches to risk analysis science.

RA	Approach	Characteristics	Ref.
I	**Strong realist**	• Risk is considered to exist objectively as a physical attribute of a system, and the analysis is presented as an estimate of this underlying true risk • Exclusively relies on data collected from the system or on engineering / natural science models • Expert judgment is not considered a source of evidence • Evidence uncertainty is not considered • Stakeholders are not involved in analysis process • Strict separation between facts and non-epistemic values • Contextual risk attributes are not considered • Strong relation to established risk decision criteria; risk-based decision making	[39,43]
II	**Moderate realist**	• Similar as the strong realist approach • Heavily relies on data collected from the system or on engineering / natural science models • Expert judgment considered a source of evidence, but knowledge generated by experts is seen as a last resort and/or is seen as truth approaching • Evidence uncertainty is not considered, or only sporadically mentioned	[48]
III	**Moderate realist with uncertainty quantification**	• Similar as moderate realist approach • Evidence uncertainty is considered through quantification of uncertainty about parameters of a model	[35,49,50]
IV	**Scientific proceduralist**	• Relies on data collected from the system, engineering/natural science models, as well as expert and layperson's judgment • Evidence uncertainty may or may not be considered in the analysis • Broad stakeholders process set up to perform risk analysis and decision making • Facts and non-epistemic values are considered relevant in characterizing risk • Contextual risk attributes may or may not be considered	[39,47]
V	**Precautionary constructivist**	• Similar as moderate constructivist • Evidence uncertainty may or may not be considered in the analysis • Facts and non-epistemic values are considered relevant in characterizing risk	[35,36]
VI	**Moderate constructivist with uncertainty evaluation**	• Similar as moderate constructivist • Risk exists objectively in the sense of broad-intersubjectivity • Risk is understood as an assessor's uncertainty about events/consequences • Model-based risk analysis accompanied by broad qualitative uncertainty assessment, possibly including quantitative evaluation of alternative hypotheses • Non-epistemic values are excluded from the risk characterization	[29,51–53]
VII	**Moderate constructivist**	• The analysis is presented as a reflection of an assessor's mental construct • Relies on data collected from the system, engineering / natural science models, as well as expert judgment • Evidence uncertainty is not considered • Stakeholders are not involved in analysis process • Non-epistemic values are excluded from the risk characterization • Contextual risk attributes are not considered • Clear link to decision making, in terms of a managerial review, where other decision criteria are considered along with the risk analysis	[15,54]
VIII	**Strong constructivist**	• Risk is a social construct, involving factual and psycho-perceptual attributes • Primarily lay person's judgment, which may be informed by expert judgment, data collected from the system and engineering / natural science models • Evidence uncertainty and non-epistemic values may or may not be considered • Contextual risk attributes are considered; and their importance may exceed that of data, models and expert judgment if the analysis is part of a decision process • Risk information is not necessarily part of a decision process	[39,46,55]

parameters x_i $(i=1,\ldots,n)$ are the measurement tools of Table 2, i.e. P_f^*, P_s, P_x, I_{QU}, I_{QL} or F. The parameters y_j $(j=1,2)$ are related to the scope of the analysis, i.e. events A or consequences C. In applications where consequences are not assessed, but it is stated that for performing a full risk analysis, consequences need to be considered, the symbol C^* is used. The parameters z_k $(k=1,\ldots,m)$ are the tools for conveying information regarding the confidence in the analysis, i.e. U_{QL}, U_{QU}, U_{AH} and B, see Table 2. Where the parameter z_k is placed between brackets [ ], this signifies that the application mentions the need for considering uncertainty, but that it is not systematically assessed.

A note is in place concerning the deduction of the characteristics of the risk analysis applications. Some characteristics are quite straightforward to assess. For instance, the definitions (when given), are collected directly from the text. Likewise, it is quite straightforward to determine what kind of evidence is considered relevant in the analysis, if uncertainty is assessed and if contextual attributes are considered in the analysis. However, the adopted approach to risk analysis is based on an interpretation. In most cases, it is very difficult to assess what exactly the theoretical basis of the risk assessment is as this is typically not elaborated upon. The characteristics of Table 3 are taken as a guide to make this assessment, but it is acknowledged that some classifications can be subject to discussion. In this context, it is reminded that the analysis is not aimed at a precise delineation of each method. Rather, a broad



I	Strong realist
II	Moderate realist
III	Moderate realist with uncertainty quantification
IV	Scientific proceduralist
V	Precautionary constructivist
VI	Moderate constructivist with uncertainty evaluation
VII	Moderate constructivist
VIII	Strong constructivist

Note:
0 indicates that different alternatives exist within the scientific approach

CR1	**Focus on underlying true risk**	1	Yes
		4	No
CR2	**Data and engineering / scientific models**	1	Not used
		4	Used
CR3	**Expert judgment**	1	Not used
		2	Used, but minimally
		3	Used
CR4	**Non-epistemic values**	1	Not included
		4	Included
CR5	**Lay person's judgment**	1	Not used
		4	Used
CR6	**Uncertainty assessment**	1	Not assessed
		2	Sporadically mentioned
		3	Quantitative, model-based
		4	Qualitative, beyond model
CR7	**Stakeholder involvement**	1	Not involved
		4	Involved
CR8	**Contextual attributes**	1	Not considered
		4	Considered
CR9	**Link to decision making**	1	Decision criteria, risk-based
		2	Managerial review and judgment
		3	Stakeholder process
		4	No direct link

Fig. 1. Conceptual outline of the applied classification of scientific approaches to risk analysis.

Table 4
Summary of risk analysis applications for maritime transportation, period 1970s–2000.

ID Ref Year	Analysis aim and scope Risk definition RD	RP	RA	D	M	J	NEV	CA
M1	Study effect of visibility on the number of collisions and groundings in a waterway							
[56]	Not defined							
1974	N/A	$R\sim(P_f^*, A)$	I	Y	Y	N	N	N
M2	Determine the expected number of collisions in a sea area							
[57]	Not defined							
1974	N/A	$R\sim(P_f^*, A)$	I	Y	Y	N	N	N
M3	Evaluate collision risk in a waterway environment							
[58]	Not defined							
1995	N/A	$R\sim(I_{QL}, A)$	II	Y	Y	Y	N	N
M4	Determine the frequency and consequences of collision and grounding in a waterway							
[59]	Not defined							
1995	N/A	$R\sim(P_f^*, A, C)$	I	Y	Y	N	N	N
M5	Determine the risk of collision in a waterway							
[60]	Not defined							
1995	N/A	$R\sim(P_x, A, C^*)$	I	Y	N	N	N	N
M6	Quantify effect of risk reduction measures on oil spills due to ship accidents							
[61]	Risk is the product of the probability of occurrence and the consequences (p. 236)							
1998	D1	$R\sim(P_f^*, P_x, A, C^* \mid [U_{QL}])$	IV	Y	Y	Y	N	N
M7	Determine occurrence frequency and consequences of various accident types in a sea area							
[62]	Not defined							
2000	N/A	$R\sim(P_f^*, P_s, A, C \mid [U_{QL}])$	II	Y	Y	Y	N	N
M8	Quantify effect of risk management interventions on risk of oil spills due to ship accidents							
[63]	Not defined							
2000	N/A	$R\sim(P_f^*, P_x, A, C)$	IV	Y	Y	Y	N	N

Note: ID=identification number, RD=risk definition (abbreviations as in Table 1), RP=risk perspective (abbreviations as in Table 2), RA=approach to risk analysis science (classification as in Table 3), D=data, M=model, J=judgment, NEV=non-epistemic values, CA=contextual attributes, Y=included in analysis, N=not included in analysis.

Table 5
Summary of risk analysis applications for maritime transportation, period 2001–2005.

ID	Analysis aim and scope							
Ref	Risk definition							
Year	RD	RP	RA	D	M	J	NEV	CA
M9	Quantify effect of risk reducing measures on transportation risk in a waterway area							
[64]	Risk is defined by combining likelihood of undesirable event and relevant consequences. (p. 128)							
2001	D6	$R\sim(P_f^*, P_x, A, C)$	IV	Y	Y	Y	N	N
M10	Determine frequency, damage and costs of collision and grounding accidents							
[65]	Not defined							
2002	N/A	$R\sim(P_f^*, P_s, A, C)$	II	Y	Y	Y	N	N
M11	Propose a model for collision probability in a waterway area							
[66]	Risk is defined as a product of the occurrence frequencies (or probabilities) and consequences. (p. 1)							
2002	D1	$R\sim(P_f^*, A, C)$	I	Y	Y	N	N	N
M12	Quantify effect of risk reduction measures on oil spills due to ship accidents							
[67]	Risk is a measure of the probability and severity of undesirable events. (p. 27)							
2002	D6	$R\sim(P_f^*, P_x, A, C)$	IV	Y	Y	Y	N	N
M13	Quantify the effect of implementing a Vessel Traffic Monitoring System on accident risk in sea area							
[68]	Not defined							
2002	N/A	$R\sim(P_f^*, P_x, A, C \mid B)$	V	Y	Y	Y	Y	N
M14	Determine the expected number of accidents and their consequences in a waterway area							
[69]	Risk is a parameter used to evaluate (or judge) the significance of hazards in relation to safety, […] hazards are the possible events and conditions that may result in severity. (p. 208)							
2005	D5	$R\sim(P_f^*, P_x, A, C)$	I	Y	Y	N	N	N
M15	Identify hazards, assess the risks and evaluate potential mitigation measures in a waterway							
[70]	Risk is the product of the probability of a casualty and its consequences. (p. 1–3)							
2005	D1	$R\sim(I_{QL}\rightarrow A, C)$	IV	N	N	Y	N	N

Note: ID=identification number, RD=risk definition (abbreviations as in Table 1), RP=risk perspective (abbreviations as in Table 2), RA=approach to risk analysis science (classification as in Table 3), D=data, M=model, J=judgment, NEV=non-epistemic values, CA=contextual attributes, Y=included in analysis, N=not included in analysis.

insight into the various applied risk definitions, perspectives and approaches to risk analysis is provided for facilitating further reflections and discussions.

The overview in Tables 4–7 clearly shows that risk analysis in maritime transportation has attracted increasing attention especially over the last decade. It is infeasible to discuss the classifications of risk definition, perspective and approach to risk analysis for all methods. In Appendix A, some methods are discussed in more detail to exemplify the differences.

6. Analysis of risk definitions, perspectives and approaches to risk analysis science

In this section, the risk definitions, perspectives and approaches to risk analysis as a science are analyzed, based on the overview presented in Section 5. First, a historic overview is given of the risk definitions and approaches to risk analysis. Then, the relationship between risk definitions and approaches to risk analysis science is analyzed. Finally, the perspectives in risk analysis applications are inspected, grouped by the applied risk definitions and the adopted approaches to risk analysis science.

6.1. Historic overview of risk definition and approach to risk analysis

In Fig. 2, a historic overview of the applied risk definitions is given. A wide variety of definitions is found, but in about half of the applications, no explicit definition is provided. Of the nine categories in Section 2, definitions are clustered in the categories D1 (R=EV) and D6 (R=P&C), with a few cases found in categories D5 (R=PO), D2 (R=P), D7 (R=C) and D8 (R=C&U). Thus, in the maritime transportation application area, risk has been strongly tied to probabilities. Only weak historic trends can be identified: from 2010 onwards, more applications stipulate a definition, with a continued predominance of categories D1 (R=EV) and D6 (R=P&C). Definitions D5 (R=PO) are found since 2005, D2 (R=P) and D8 (R=C&U) only recently. This diversity confirms findings in [5] that the scientific risk discipline faces terminological challenges.

The findings furthermore reflect the analysis by Aven [10] that traditional engineering definitions (D1 and D6) and definitions of decision analysts (D1) represent the predominant views on risk in technical application areas. Aven ([10], p. 40) claims that definitions D8 (R=C&U), considering uncertainty rather than probability a fundamental component of risk, have recently replaced probability-based definitions in engineering fields. From our analysis, it is seen that this is only very minimally the case for the maritime transportation application area. In fact, only one such definition is found.

A more policy-oriented issue is that many applications do not follow the suggested definitions by relevant authorities or standardization organizations. In the guidelines for Formal Safety Assessment (FSA), which is commonly seen as the premier scientific method for maritime risk analysis and for formulating maritime regulatory policy [114], risk is defined as “the combination of the frequency and the severity of the consequence” [115], i.e. a categorization in line with class C6. While definitions based on expected values (D1) are close to this view as it consists of the same elements, definitions in line with D5 and D8 represent significantly different risk classes. The ISO-definition, seeing risk as “the effect of uncertainty on objectives” [116], is not found in the application area.

In Fig. 3, a historic overview of the approach to risk analysis science is shown. It is seen that strong realist views (I) on risk analysis are found from the early work in the application area to the present day. Similarly, there has been much work in line with a moderate realist approach (II) to risk analysis over the same time span. Moderate constructivist approaches (VII) are found since about 2007. Scientific proceduralist approaches (IV) were the predominant view around the year 2000, but are overall less prominently found. Few applications are found using approaches where uncertainty is quantified (III), and also precautionary approaches (V) and constructivist approaches with a broad uncertainty evaluation (VI) are exceptions.

The historic overview clearly shows that a wide range of approaches co-exist in the application area, confirming findings in [5,39,40] that there are different paradigms to risk analysis as a scientific activity.

Table 6
Summary of risk analysis applications for maritime transportation, period 2006–2010.

ID	**Analysis aim and scope**							
Ref	**Risk definition**							
Year	**RD**	**RP**	**RA**	**D**	**M**	**J**	**NEV**	**CA**
M16	Quantify uncertainty in a maritime transportation risk assessment							
[71]	Not defined							
2006	N/A	$R\sim(P_f^*, P_x, A, C^* \mid U_{QU})$	III	Y	Y	Y	N	N
M17	Determine the relative risk of various navigation areas in a coastal waterway area							
[72]	Risk is […] the possibility of the occurrence of hazardous accidents or abnormal incidents. (p. 370) Risk is […] a consequence involved in the damages resulting from a hazardous accident. (p. 370) Risk possesses diplex-characteristics [*sic*] of possibility (F) and severity (N) […] frequency (F) can be viewed as the ratio of number of accidents against the number of ship's activities per unit time (p.370)							
2007	D5/D7	$R\sim(F, A, C)$	VII	N	N	Y	N	N
M18	Investigate the effect on collision and grounding risk of introducing a TSS in a sea area							
[73]	Risk is the product of the probability and the consequences of an unwanted event (p. 8)							
2008	D1	$R\sim(P_f^*, A, C)$	I	Y	Y	N	N	N
M19	Determine the accident probability and consequences in a sea area							
[74]	Not defined							
2008	N/A	$R\sim(A, P_f^*, C)$	I	Y	Y	N	N	N
M20	Determine the collision risk in a part waterway through a vessel-conflict technique							
[75]	Not defined							
2009	N/A	$R\sim(P_x, A)$	VII	Y	N	Y	N	N
M21	Propose a meta-model for integrated environmental oil spill risk from ship accidents							
[76]	Not defined							
2009	N/A	$R\sim(P_f^*, P_s, A, C)$	VII	Y	Y	Y	N	N
M22	Quantify effect of risk reduction measures on accident risk in a waterway area							
[77]	Not defined							
2009	N/A	$R\sim(P_f^*, P_x, A, C)$	VII	Y	Y	Y	N	N
M23	Determine the collision risk in a part waterway through a vessel-conflict technique							
[78]	Not defined							
2010	N/A	$R\sim(P_x, A)$	VII	Y	N	Y	N	N
M24	Determine the grounding frequency in a waterway							
[79]	Not defined							
2010	N/A	$R\sim(P_f^*, A, C^*)$	I	Y	Y	N	N	N
M25	Determine expected economic loss due to environmental pollution from oil tankers, for various sea areas							
[80]	Risk is the value of loss under uncertainty, i.e. it is a sum of products of probabilities of occurrence of certain damages. (p. 61)							
2010	C1	$R\sim(A, P_f^*, P_s, C)$	II	Y	Y	Y	N	N
M26	Propose a meta-model for minimizing ecological risks of maritime transportation in a sea area							
[81]	The concept of risk contains both the probability of a certain event and the magnitude of the harm caused if it becomes true							
2010	C6	$R\sim(P_f^*, P_s, A, C)$	VII	Y	Y	Y	N	N
M27	Determine the frequency and consequences of collision in a waterway							
[82]	Not defined							
2010	N/A	$R\sim(P_x, A, C)$	I	Y	Y	N	N	N
M28	Determine the ship collision probability in a sea area							
[83]	Risk is defined as the product of probability of occurrence of an undesired event and the expected consequences. (p. 573)							
2010	C1	$R\sim(P_f^*, P_x, A, C^*)$	I	Y	Y	N	N	N
M29	Calculate maritime accident frequencies in a sea area							
[84]	Risk is the product of the probability/frequency of the unwanted event and its consequences. (p. 10)							
2010	C1	$R\sim(P_f^*, A, C^*)$	I	Y	Y	N	N	N

Note: ID=identification number, RD=risk definition (abbreviations as in Table 1), RP=risk perspective (abbreviations as in Table 2), RA=approach to risk analysis science (classification as in Table 3), D=data, M=model, J=judgment, NEV=non-epistemic values, CA=contextual attributes, Y=included in analysis, N=not included in analysis.

Most of the work is rooted in the idea that a true, mind-independent risk exists in line with realist approaches as outlined in Table 3. Using different modeling approaches, many methods aim to accurately estimate this true risk. While the use of expert judgment has gained steady support, many applications rely heavily on accident and traffic data. Even when judgment is applied, it is often used as if it (should) uncover(s) an underlying true risk. Constructivist views exist, but broad assessments of uncertainty and/or bias, used to convey information regarding the confidence in the analysis, are very rare.

6.2. Relation between risk definition and approach to risk analysis science

In Fig. 4, the applied risk definitions are grouped per approach to risk analysis science. It is observed that risk definitions D1 (R=EV) are more strongly tied to realist approaches, whereas definitions in line with D6 (R=P&C) are found across the spectrum of approaches to risk science. Applications where risk is not defined also range across the different scientific approaches to risk analysis. The other applied definitions are less frequently found, precluding insight in the relation to the scientific approaches.

This result implies that the adopted definition does not necessarily provide much information regarding the adopted scientific approach. For example, defining risk through probabilities of events and consequences (D6) can lead to strong realist approaches to risk analysis if the risk concept is literally understood as such. However, the same definition can be used to subsequently introduce a risk measure in an analytic-deliberative decision process. Similar considerations can be made for the other definitions.

From this, it is clear that while providing clarity about definitions and terminology is important in applications, this does not suffice to settle deeper disputes about the feasibility of rationalist, constructivist or proceduralist approaches to risk analysis.

6.3. Risk perspectives in relation to risk definitions

In Table 8, an overview is shown of the applied risk perspectives in the applications of Section 5, grouped by risk definition.

Table 7
Summary of risk analysis applications for maritime transportation, period 2011–2014.

ID	**Analysis aim and scope**							
Ref	**Risk definition**							
Year	**RD**	**RP**	**RA**	**D**	**M**	**J**	**NEV**	**CA**
M30	Determine the ship collision probability in a sea area							
[85]	Risk is defined as the product of the probability of occurrence of an undesired event and the expected consequences. (p. 91)							
2011	D1	$R\sim(P_f^*, A, C^*)$	I	Y	Y	N	N	N
M31	Determine expected oil spill costs due to maritime accidents in a sea area							
[86]	Risk is defined as the product of the probability of occurrence of an undesirable event and the expected consequences (p. 91)							
2011	D1	$R\sim(P_f^*, P_x, A, C)$	I	Y	Y	N	N	N
M32	Quantify effect of risk reduction measures on oil spills due to ship accidents							
[87]	Risk is the complete set of triplets $\{(s_i, l_i, c_i)\}_c$ where s_i describes the context of the accident scenario, l_i the likelihood of an accident occurring in that scenario and c_i a description of the consequences. (p. 251)							
2011	D6	$R\sim(P_f^*, P_x, A, C)$	VII	Y	Y	Y	N	N
M33	Determine the sea areas where collisions are more likely and evaluate effect of speed limits							
[88]	Not defined							
2011	N/A	$R\sim(I_{QU}\rightarrow A)$	II	Y	Y	Y	N	N
M34	Determine effect of a new traffic scheme on the oil spill probability and consequences in a sea area							
[89]	Risk is the frequency of a hazard multiplied by its consequence. The term is, however, often used as a mere probability of an accident/incident with adverse consequences (p. 246)							
2012	D1/D2	$R\sim(P_f^*, A, C)$	I	Y	Y	N	N	N
M35	Quantify effect of risk reduction measures on accident risk in a waterway area							
[90]	Risk is the combination of situations, likelihoods and consequences. (p. 72)							
2012	D6	$R\sim(P_f^*, P_x, A, C)$	VII	Y	Y	Y	N	N
M36	Propose a simulation environment for evaluating the risk in a sea area							
[91]	Risk is the possibility of an adverse event. (p. 58)							
2012	D5	$R\sim(I_{QL}, A)$	II	N	Y	Y	N	N
M37	Determine the risk of oil spill and hazardous substances in a sea area							
[92]	A measure of both the likelihood and consequence, if a hazard manifests itself (p. RMN-14)							
2012	D6	$R\sim(P_f^*, P_s, A, C)$	II	Y	Y	Y	N	N
M38	Determine probability of tanker collisions and probability of an oil spill in a sea area							
[93]	Risk is a set of triplets $\{(s_i, l_i, c_i)\}$, $i=1, 2, 3\ldots$ with s_i the context of the accident scenario, l_i the likelihood of the accident occurring in that scenario and c_i the evaluation of the consequence in the scenario. (p. 381)							
2012	D6	$R\sim(P_f^*, P_s, A, C)$	II	Y	Y	Y	N	N
M39	Investigate the sensitivity and discuss uncertainty about the impact scenarios in tanker collisions							
[94]	Risk is the complete set of triplets $\{(s_i, l_i, x_i)\}_c$ where s_i defines the description of the ith risk scenario path, l_i the likelihood of the path occurrence and x_i represents the consequences of the path. (p. 75)							
2012	D6	$R\sim(P_f^*, P_s, A, C \mid [U_{QL}])$	II	Y	Y	Y	N	N
M40	Determine the collision risk in a waterway							
[95]	Not defined							
2012	N/A	$R\sim(P_x, A)$	II	Y	N	Y	N	N
M41	Determine the probability and consequences of collision between LNG vessel and harbor tug							
[96]	Risk is the product of the probability of a scenario and the consequences of a scenario. (p. 7)							
2012	D1	$R\sim(P_f^*, P_s, A, C)$	II	Y	Y	Y	N	N
M42	Calculate the collision frequency in a waterway							
[97]	Not defined							
2012	N/A	$R\sim(P_f^*, P_s, A, C^*)$	II	Y	Y	Y	N	N
M43	Determine the relative risk of coastal areas, and determine through statistical analysis if risk level is acceptable							
[98]	Risk is the possibility of a harmful event. (p.33) Risk is the consequences of the normal level of event leading to injury. (p.33) Risk is of double characteristics with frequency and consequences degree (p.33)							
2012	D5/D7/D6	$R\sim(P_f^*, I_{QL}, A, C)$	VII	Y	N	Y	N	N
M44	Determine the accidental risk of chemical tanker spills in a given sea area							
[99]	Risk is the probability of something adverse happening multiplied by the consequences. (p. 10)							
2012	D1	$R\sim(P_f^*, P_x, A, C \mid [U_{QL}])$	II	Y	Y	N	N	N
M45	Determine the areas of a waterway where collisions are more likely							
[100]	Not defined							
2012	N/A	$R\sim(P_x, I_{QU}\rightarrow A)$	II	Y	N	Y	N	N
M46	Calculate the collision frequency in a waterway							
[101]	Not defined							
2012	N/A	$R\sim(P_f^*, A, C^*)$	I	Y	Y	N	N	N
M47	Calculate collision frequency with vessels laying at an anchorage							
[102]	Risk is the combination of number of occurrences per time unit and the severity of their consequences (p. 287) Risk is the probability of an event multiplied by its expected damage. (p. 287)							
2013	D6/D1	$R\sim(P_f^*, A, C^*)$	I	Y	Y	N	N	N
M48	Determine the collision risk of maritime traffic in a sea area							
[103]	Risk can be defined as the probability of occurrence of an unwanted event multiplied by the consequences of that same event. (p. 888)							
2013	D1	$R\sim(P_f^*, A, C^*)$	I	Y	Y	N	N	N
M49	Examine the feasibility of data-based generalized linear modeling technique to risk analysis of navigation							
[104]	Not defined							
2013	N/A	$R\sim(P_x, A)$	I	Y	N	N	N	N
M50	Propose a method to quantify uncertainty related to traffic data in maritime risk assessment							
[105]	Not defined							
2013	N/A	$R\sim(P_f^*, A, C^* \mid U_{QU})$	III	Y	Y	N	N	N
M51	Determine the accident risk of maritime transportation in an inland waterway							
[106]	A risk is composed of two elements: an event or accident occurrence probability and its impact, also known as the consequence severity. (p. 96) Risk is often defined as the combination [product] of its probability and consequences (p. 100)							

Table 7 (*continued*)

ID	Analysis aim and scope							
Ref	Risk definition							
Year	RD	RP	RA	D	M	J	NEV	CA
2013	D6/D1	$R\sim(P_f^*, P_s, I_{QU}, I_{QL}, A, C)$	VII	Y	Y	Y	N	N
M52	Propose tools to assess uncertainty and bias in a maritime transportation risk model through a case study							
[107]	Risk is defined through scenarios, probabilities and consequences. (p. 2296)							
2014	D6	$R\sim(P_f^*, P_s, P_x, A, C \mid U_{QL}, B)$	V	Y	Y	Y	Y	N
M53	Determine the effect of implementing a navigation service of collision and grounding risk in a sea area							
[108]	Not defined							
2014	N/A	$R\sim(P_s, A, C^*)$	VII	N	N	Y	N	N
M54	Propose a framework for analyzing risk in a sea area through a case study of RoPax vessels							
[109]	Risk is […] a condition under which it is possible both to define a comprehensive set of all possible outcomes and to resolve a discrete set of probabilities across this array of outcomes. (p. 143)							
2014	D2	$R\sim(P_f^*, P_s, P_x, A, C \mid U_{QU})$	III	Y	Y	Y	N	N
M55	Calculate the frequency of ship sinking due to collision in a waterway							
[110]	Not defined							
2014	N/A	$R\sim(P_f^*, A, C^*)$	I	Y	Y	N	N	N
M56	Apply a method for analyzing evidence uncertainty through a case study of risk of chemical tanker collisions							
[111]	Risk could be defined and foremost taken as the uncertainty regarding (negative) outcomes. (p. 26)							
2014	D8	$R\sim(P_f^*, P_s, P_x, A, C \mid U_{QL})$	VI	Y	Y	Y	N	N
M57	Determine the risk of shipping routes in a sea area							
[112]	Not defined							
2014	N/A	$R\sim(I_{QL}, F\rightarrow A)$	VII	Y	N	Y	N	N
M58	Apply a failure mode and effects analysis (FMEA) method to ship collision risk in a sea area							
[113]	Not defined							
2014	N/A	$R\sim(F, A, C)$	VII	Y	N	Y	N	N

Note: ID=identification number, RD=risk definition (abbreviations as in Table 1), RP=risk perspective (abbreviations as in Table 2), RA=approach to risk analysis science (classification as in Table 3), D=data, M=model, J=judgment, NEV=non-epistemic values, CA=contextual attributes, Y=included in analysis, N=not included in analysis

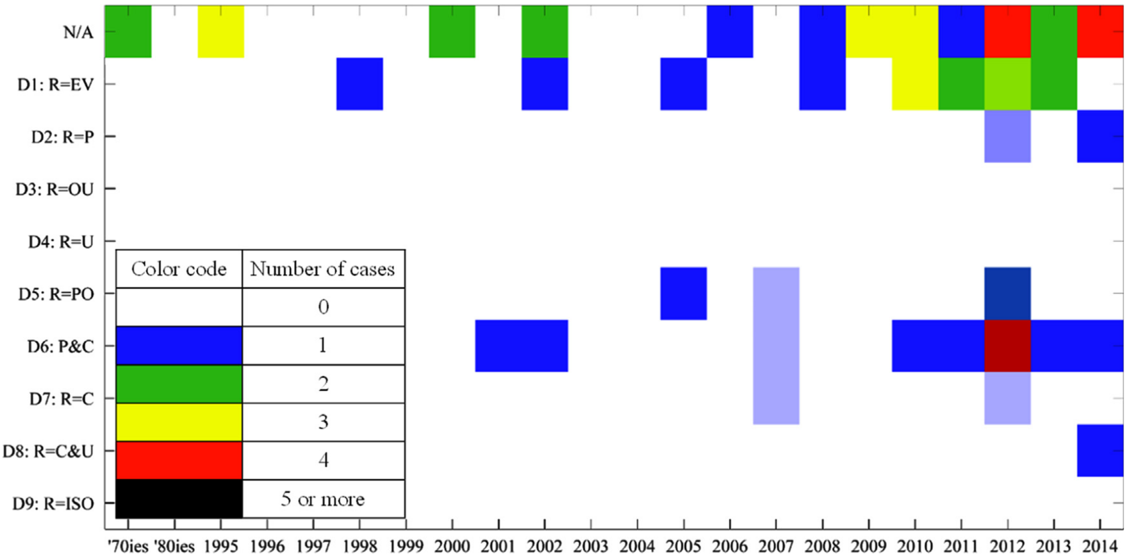


Fig. 2. Historic overview of the applied risk definitions in applications of maritime transportation risk analysis, classification as in Table 1, cases from Tables 4–7.

Only cases where an explicit definition is provided, are retained. The reader is reminded that a risk perspective is here understood as a way to describe risk, a systematic manner to analyse and make statements about risk, see Section 3. Risk descriptions contain measurement tools (P_f^*, P_s, P_x, I_{QU}, I_{QL} and F, see Table 2), which address an event (A) or events and consequences (A and C), and may be supplemented by measures regarding the confidence in the analysis (U_{QU}, U_{QL}, U_{AH} and B, see Table 2).

It is seen that the elements of the risk perspectives are usually well in line with the adopted definition. For example, applications using the definition D1 (R=EV) focus on events and consequences as implied in the definition, and use probabilities to describe risk. A similar conclusion can be drawn from perspectives in applications where definition D6 (R=P&C) is applied.

However, aberrations occur, for example regarding the scope of the analysis. In definition classes D2 (R=P) and D7 (R=C), the applications analyze events as well as consequences, whereas the definition only focuses on an event, without reference to consequences. Likewise, in definition classes D1 (R=EV) and D6 (R=P&C), there are instances where risk is not measured using probabilities (as implied in the definitions), but using indicators (e.g. M15, M43 and M51) or fuzzy numbers (M17).

It is also noteworthy that in applications where definitions D5 (R=PO) or D7 (R=C) are used, i.e. definitions where no reference

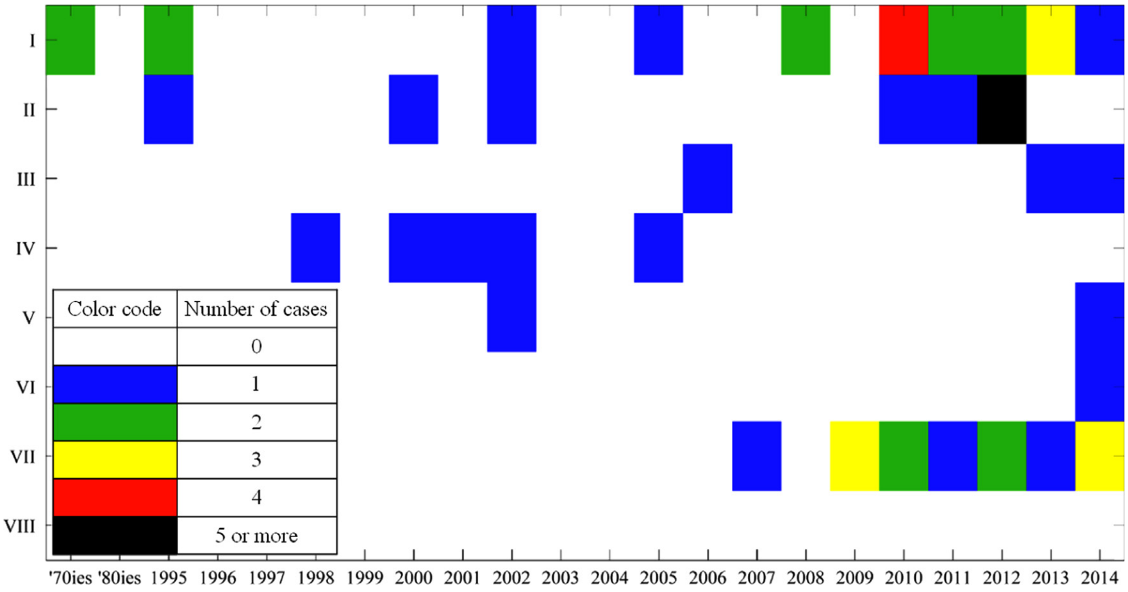


Fig. 3. Historic overview of the adopted scientific approaches to risk analysis in applications of maritime transportation risk analysis, classification as in Table 3, cases from Tables 4–7.

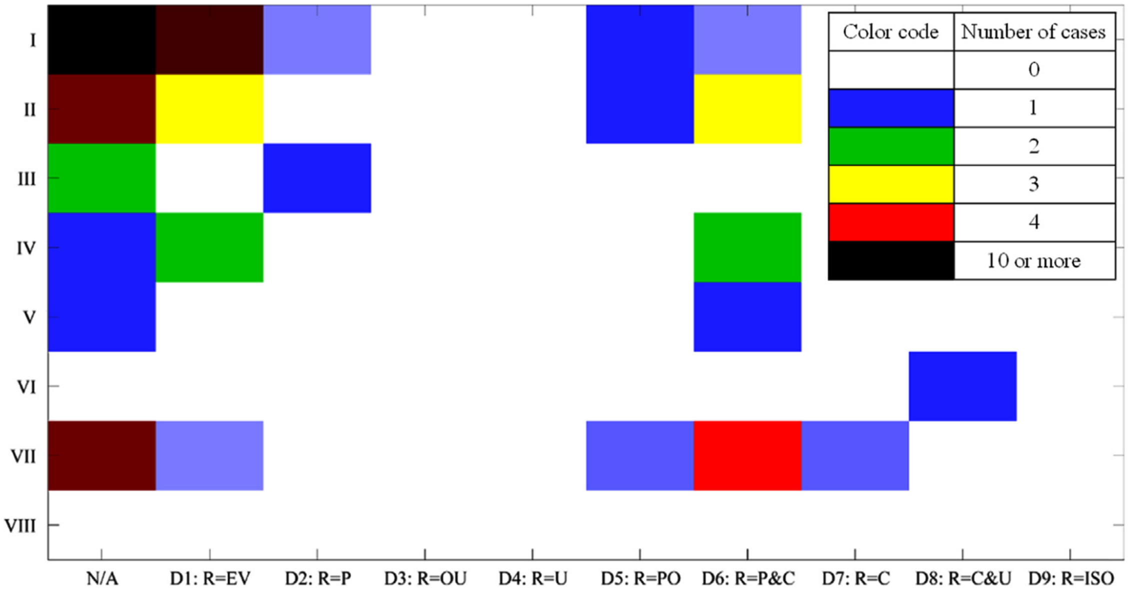


Fig. 4. Relation between applied risk definitions (Table 1) and adopted scientific approaches to risk analysis (Table 3) in applications of maritime transportation risk analysis, cases from Tables 4–7.

is made to a specific measurement tool, indicators (M36, M43) and fuzzy numbers (M17) are relatively more frequently found than in other definition classes.

It is furthermore observed that very few applications take a perspective where measures to assess the confidence in the analysis are considered, irrespective of the risk definition class. Only in the application where risk is defined through uncertainty (M56) a broad uncertainty assessment is performed. In some applications using probability-based definitions, uncertainty is considered through alternative hypotheses (M52, M54) or a broad uncertainty and bias assessment (M54). In definition classes D5 (R=PO) and D7 (R=C), the reviewed applications do not consider uncertainties or biases in the adopted risk perspectives.

Thus, it can be concluded that there generally is a very significant relation between the adopted definitions and the applied risk perspectives, which confirms claims that how one defines and understands risk to a large degree determines how one assesses it [55,117].

6.4. Risk perspectives in relation to approach to risk analysis science

In Table 9, an overview is shown of the applied risk perspectives in the applications of Section 5, grouped by the adopted approach to risk analysis science. This provides insight into how the application area has understood risk analysis, in light of the criteria outlined in Section 4.2, see Table 3.

In the strong realist approaches, risk perspectives consist exclusively of probabilistic risk measures (P_f^* and P_x). The evidence base for these probabilities consists exclusively of data or models. Probabilities of accident occurrences are calculated directly from observed frequencies (P_f^*, e.g. M19) or through probability models (P_x, e.g. M5). Uncertainties are not assessed, and the analysis is presented as a representation of a true underlying risk.

Moderate realist approaches show a more diverse spectrum of risk perspectives. While still dominated by probabilistic measures in terms of P_f^* and P_x, subjective probabilities P_s are also applied, e.g. in

Table 8
Analysis of applied measurement tools and tools for conveying confidence in analysis by risk definition as in Table 1, cases from Tables 4–7.

Risk definition	ID	Year	P_f^*	P_s	P_x	I_{QU}	I_{QL}	F	A	C	C^*	U_{QU}	U_{QL}	U_{AH}	B
D1: R=EV	M6	1998	x		x				x		x		[x]		
	M11	2002	x						x	x					
	M15	2005					x		x	x					
	M18	2008	x						x	x					
	M25	2010	x	x					x	x					
	M28	2010	x		x				x		x				
	M29	2010	x						x		x				
	M30	2011	x						x		x				
	M31	2011	x		x				x	x					
	M34	2012	x						x	x					
	M41	2012	x	x					x	x					
	M44	2012	x		x				x	x			[x]		
	M47	2013	x						x		x				
	M48	2013	x						x	x					
	M51	2013	x	x		x	x		x	x					
D2: R=P	M34	2012	x						x	x					
	M54	2014	x	x	x				x	x				x	
D3: R=OU	-														
D4: R=U	-														
D5: R=PO	M14	2005			x				x	x					
	M17	2007						x	x	x					
	M36	2012					x		x						
	M43	2012	x				x		x	x					
D6: R=P&C	M9	2001	x		x				x	x					
	M12	2002	x		x				x	x					
	M17	2007						x	x	x					
	M26	2010	x	x					x	x					
	M32	2011	x		x				x	x					
	M35	2012	x		x				x	x					
	M37	2012	x	x					x	x					
	M38	2012	x	x					x	x					
	M39	2012	x	x					x	x			[x]		
	M43	2012	x				x		x	x					
	M47	2013	x						x		x				
	M51	2013	x	x		x	x		x	x					
	M52	2014	x	x	x				x	x			x	x	x
D7: R=C	M17	2007						x	x	x					
	M43	2012	x				x		x	x					
D8: R=C&U	M56	2014	x	x	x				x	x			x		
D9: R=ISO	-														

M7, M10 and M37. However, they are used only as a supplement to applications and models otherwise strongly relying on data and models, and the analyses aim at representing a true underlying risk. Quantitative and qualitative indicators I_{QU} and I_{QL} are also used as measurement tools in risk perspectives. Such indicators are defined based on expert judgment (e.g. M33), but they are metrics derived directly from ship traffic data. Alternatively, they are judgments modeled based on experiments involving experts (M3). Uncertainties are typically not assessed, but some applications address some uncertainties (M39 and M44), or state that data or model-related uncertainties should be analyzed (M7).

In moderate realist approaches with uncertainty quantification, the focus is also on frequentist, subjective and/or modeled probabilities P_f^*, P_s and P_x, but quantitative measures of uncertainty supplement these. In M16, uncertainty is considered through Bayesian simulation, i.e. by sampling probability distributions about parameters of a probability model. In M50, uncertainty is quantified using the Dempster–Shafer evidence theory. In M54, uncertainty is considered in a Bayesian Network framework through the application of alternative hypotheses.

Scientific proceduralist approaches (M6, M8, M9 and M12) combine frequentist probabilities P_f^* and probabilities modeled based on expert judgment P_x, using a Bayesian paired comparison technique [20]. Alternatively, qualitative indicators I_{QL} are applied, based on judgments of experts of different stakeholder groups. Uncertainties are either summarily addressed (M6), or not considered in the analyses.

Moderate constructivist approaches show a rather scattered landscape of risk perspectives. Various types of probability are applied: P_f^* as derived from data (e.g. M21), P_s as degrees of belief of an assessor (e.g. M53) and P_x as modeled representations of experts' judgments (e.g. M23, M32), where judgments of an assessor are the predominant type of evidence. Compared with realist approaches, relatively more use is made of indicators (e.g. M43, M51) and of fuzzy numbers (e.g. M17, M58). Uncertainties are not considered beyond the probabilities, indicators and fuzzy numbers.

Precautionary constructivist and moderate constructivist approaches with uncertainty evaluation also apply the different types of probability. Judgments, data and models are combined in a model construct, which is supplemented with a systematic assessment of biases (M13), uncertainties (M56) or uncertainties and biases (M52).

7. Discussion: Risk analysis science and practice in the maritime transportation application area

In this section, a general discussion is given based on the findings from the previous sections. The following issues are addressed: (i) the need to clarify risk-theoretical issues in applications, (ii) the need to systematically consider uncertainty, and (iii) the need for further reflection on science and practice in the application area.

7.1. The need to clarify risk-theoretical issues in applications

A significant finding of the current research is that many applications provide little or no attention to risk-theoretical issues, concerning definitions, perspectives and scientific approaches to risk analysis. Risk is often not explicitly defined, and no attention is paid to how the risk concept is understood. Where risk is defined, the adopted definition is typically presented as if no alternatives exist, or no argumentation is given why the definition is taken. This practice may be problematic for several reasons.

First, the lack of clarity may lead to terminological confusion and definitional conflicts in risk communication [49,118]. Second, several authors have argued that the choice of a definition is not a value-neutral endeavor: including or excluding contextual attributes (voluntariness, fear, equity etc.) in the risk definition has a relation to normative commitments in risk management [119–121]. Third, even if contextual factors are excluded, different definitions can represent an opposing conceptual understanding of risk, from which important differences in risk perspectives can result. As found in Section 6.3, probability-based definitions D1 (R=EV) and D6 (R=P&C) commonly lead to probability-based perspectives, whereas possibility-based definitions like D5 (R=PO) are more frequently found with perspectives applying indicators or fuzzy numbers. Uncertainty-based definitions like D8 (R=C&U) lead to a broader risk perspective where other uncertainty factors (underlying the risk model or beyond the modeling scope) are assessed as well. The adapted terminology thus guides, supports, but may also limit which elements are considered in describing risk.

In the application area, there is typically no explicit attention given to the scientific approach underlying risk analysis applications, i.e. it is not clarified whether a realist or constructivist risk foundation is adopted. In fact, no work is found in the maritime application area where these distinctions are introduced or referred to. Nonetheless, as clear from Table 3, the differences are important, for several reasons.

First, considering risk analysis as a science focusing on a 'true', mind-independent underlying risk (realist approaches) or as a

Table 9
Analysis of applied measurement tools and tools for conveying confidence in analysis by scientific approach to risk analysis as in Table 3, cases from Tables 4–7.

Scientific approach to risk analysis	ID	Year	P_f^*	P_s	P_x	I_{QU}	I_{QL}	F	U_{QU}	U_{QL}	U_{AH}	B
I Strong realist	M1	1974	x									
	M2	1974	x									
	M4	1995	x									
	M5	1995			x							
	M11	2002	x									
	M14	2005			x							
	M18	2008	x									
	M19	2008	x									
	M24	2010	x									
	M27	2010			x							
	M28	2010	x		x							
	M29	2010	x									
	M30	2011	x									
	M31	2011	x		x							
	M34	2012	x									
	M46	2012	x									
	M47	2013	x									
	M48	2013	x									
	M49	2013			x							
	M55	2014	x									
II Moderate realist	M3	1995					x					
	M7	2000	x	x						[x]		
	M10	2002	x	x								
	M25	2010	x	x								
	M33	2011				x						
	M36	2012					x					
	M37	2012	x	x								
	M38	2012	x	x								
	M39	2012	x	x						[x]		
	M40	2012			x							
	M41	2012	x	x								
	M42	2012	x	x								
	M44	2012	x		x					[x]		
	M45	2012			x	x						
III Moderate realist with uncertainty quantification	M16	2006	x		x				x			
	M50	2013	x						x			
	M54	2014	x	x	x						x	
IV Scientific proceduralist	M6	1998	x		x					[x]		
	M8	2000	x		x							
	M9	2001	x		x							
	M12	2002	x		x							
	M15	2005					x					
V Precautionary constructivist	M13	2002	x	x								x
	M52	2014	x	x	x					x	x	x
VI Moderate constructivist with uncertainty evaluation	M56	2014	x	x	x					x		
VII Moderate constructivist	M17	2007						x				
	M20	2009			x							
	M21	2009	x	x								
	M22	2009	x		x							
	M23	2010			x							
	M26	2010	x	x								
	M32	2011	x		x							
	M35	2012	x		x							
	M43	2012	x				x					
	M51	2013	x	x		x	x					
	M53	2014		x								
	M57	2014					x	x				
	M58	2014						x				
VIII Strong constructivist	-											

reflection of a mental construct (constructivist approaches) result in different risk analysis and subsequent decision making processes. In the former, risk analysis is a process of fact finding, i.e. an impersonal process governed by data collection and processing, and calculation of quantitative risk metrics using models from engineering and natural sciences. Decision making is strongly linked to the risk analysis, often using predefined risk acceptance criteria or mathematical techniques such as optimization or rational choice models, i.e. decision making is risk-based. In the latter, risk analysis can be understood as a process of problem finding, where judgments of a group of analysts are informed by data and models, possibly supplemented with uncertainty and/or bias descriptions, providing insight in the strength of evidence for making the judgments. Decision making here has a link to the risk analysis results, but it is an evaluative process in which apart from the quantitative risk metrics, uncertainties and contextual attributes such as public trust, equity and psychometric factors can be considered [38,42].

Second, the different commitments to risk analysis science possibly held by the different actors in a risk management problem (decision makers, analysts, experts, lay people) can lead to important challenges in communicating about risk. Hence, clarity about the foundations is of great importance for practical decision making [122].

Third, clarity about the different approaches to risk science is important from a scientific perspective as well, in relation to the scientific review process. As in risk communication, if the authors and reviewers do not share a common understanding of risk analysis as a scientific activity, this can lead to misunderstandings and misguided expectations. Thus, clarity on the adopted scientific basis is important to improve the reviewing process in scientific risk journals [6].

7.2. The need to systematically consider uncertainty

One significant finding of the review and analysis in Sections 5 and 6 is the lack of uncertainty treatment in the application area. Only three applications are found where uncertainty is quantified (M16, M50 and M14), and qualitative assessments of uncertainties and/or biases are equally rare (M13, M52, M56). However, in all three applications analyzed in more detail in Appendix A, important uncertainties which are not addressed in the actual applications, have been found.

In our view, the systematic consideration of uncertainty is a fundamental issue in risk analysis, which goes beyond the quantification of uncertainty of parameters or model structure. Two aspects are important. First, uncertainty related to the evidence for making statements about risk and for constructing the risk model should be considered, known as “evidence uncertainty” [30]. Second, uncertainty related to the occurrence of the events/consequences, in relation to the representation by a risk model should be considered. This is known as “outcome uncertainty” [30], and can be accounted for through a (qualitative) assessment of uncertainty factors beyond the model space.

Quantification and propagation of parameter uncertainty (as in M16, M50), or accounting for structural uncertainty through alternative hypotheses (M54) can provide confidence in the sense of bounding model-based uncertainties. However, it is questionable in how far such quantification can in practical settings account for all relevant evidential and outcome uncertainty. This would in principle require that a quantitative uncertainty measure is defined about all parameters and structural assumptions of the entire model, which are propagated over the entire model space [123]. Such a procedure is infeasible in practice, such that uncertainty is considered only about a selection of parameters (M16, M50) or about selected structural assumptions (M54). It is not clear in how far such uncertainty quantification adequately captures all decision-relevant uncertainty, because such procedures cannot account for uncertainties stemming from the omission of potentially relevant factors and because a purely quantified uncertainty analysis may fail to uncover the strength of evidential support for various model elements. We thus favor a broad assessment of the evidence base, as well as a systematic consideration of uncertainties beyond the model, as in [28,29]. Evidential biases, when present, can be assessed as well, as in [36,37].

Uncertainty treatment has been proposed as a validity criterion for quantitative risk analysis [124]. Another reason for the need to consider uncertainty is the responsibility of scientists to consider the consequences of error when informing public policy, which requires awareness and openness about the limitations in data and information, the inadequacies of models and opposing judgments [125].

7.3. Suggestions for improvement of the current situation

7.3.1. Clarity about fundamental issues in applications

As discussed in Section 7.1, it is important to provide clarity about the conceptual understanding of risk, the adopted risk definition and perspective, and insight in the scientific approach taken to risk analysis. Fig. 5 provides a schematic overview of concepts relevant for performing a risk analysis, which can be useful for clarifying the foundations in applications.

First, the risk analysis is embedded in a decision context, which sets the stage for the analysis by specifying the scope and focus of the analysis, but also by providing limitations in terms of resources (time, money, expertise) for performing the analysis. Where value judgments are required, the decision context can also inform the analysts to prefer conservative or optimistic inferences, so the decision context and the risk analysis are not necessarily independent [126].

Second, the risk analysis is conditional to a scientific approach to risk analysis as a science, and a reasoned choice is required between realist, proceduralist and constructivist approaches, as outlined in Table 3. There is potential for disagreement between various stakeholders in agreeing on the scientific approach, but a reasoned discussion on a philosophical rather than on a personal level may contribute to a decision. This can be facilitated by considering the relevant literature, see Table 3.

Third, the conceptual understanding of risk and the object of inquiry are considered. This means that clarity is needed about what risk per se is, how it connects to other concepts relevant in the analysis and what ontological, epistemological and normative implications this understanding has. As with the scientific approach to risk analysis, different conceptual interpretations of risk exist and disagreements may occur, but a reasoned choice can be made by considering the relevant literature, e.g. [4,27,49,52,55,120]. Similarly, an understanding of the object of inquiry is needed, to facilitate which aspects are relevant for the application.

Fourth, the risk measurement process is systemized. A risk definition stipulates specific features of the concept which are considered important in a specific application, and suitable risk measures are defined. A risk perspective is delineated, systemizing which measurement tools are applied, whether events or events and consequences are analyzed and how the confidence in the measurement is conveyed to decision makers, see Table 2. The risk perspective is thus the practically applied elements to describe risk, in line with the adopted conceptual understanding and definition. The operationalization of the object of inquiry specifies which features of the event and/or consequence are considered relevant for the specific application, i.e. the events/consequences are constructed in view of the intended use of the risk model [127]. When considered in the risk perspective, a method for conveying the confidence in the measurement is applied, e.g. using a qualitative uncertainty assessment [28], an assessment of the strength of evidence [29] or an assessment of biases in the risk model and evidence [36,37]. The measurement is conditional to an evidence base, which consists of data, information, models, expert knowledge and assumptions.

The outline of Fig. 5 is a simplification, but distinguishing the conceptual level of risk and its object, the measurement in a particular application, the evidence for making the measurement, the underlying scientific commitment to risk analysis as a science and the relation to a decision context are important aspects to more clearly articulate the foundations adhered to in a specific application.

7.3.2. Increased focus on foundational issues in the application area

Another finding resulting from the current work is that the maritime transportation application area would benefit from intensifying research on foundational issues, as well as increased reflection on proposed risk analysis methods. Various frameworks have been proposed for analyzing maritime transportation risk, e.g. [62,63,78,109]. Furthermore, many risk analysis applications have been presented in the literature, see Section 5. However, there has been very little scientific research and discussion on the proposed frameworks and methods.

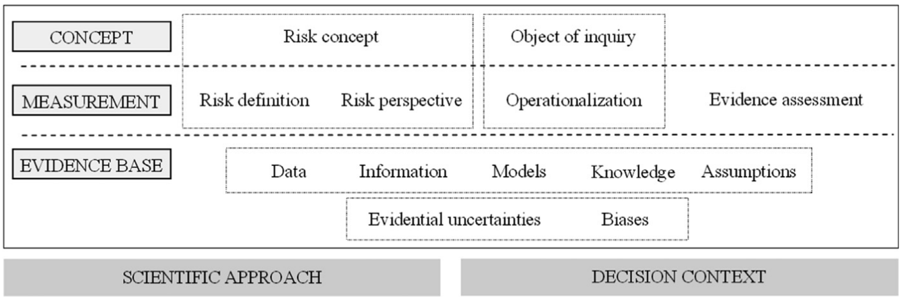


Fig. 5. Outline of concepts for clarifying the risk analysis applications.

A (non-exhaustive) list of issues requiring further scientific attention is given in [5], e.g. concerning research on the risk-conceptual basis, methods for assessing and communicating uncertainty and the causality of accident occurrence. Similar issues have been identified as requiring attention in revising the guidelines for Formal Safety Assessment (FSA), for decision making and rule development at the International Maritime Organization (IMO) level [128]. Thus, rather than being only academic exercises, research for strengthening the risk analysis foundations can also have repercussions for maritime policy.

8. Conclusion

In this paper, a review and analysis has been presented of risk definitions, perspectives and approaches to risk analysis science in the maritime transportation application area. A classification of risk definitions, an overview of risk measurement tools and tools for conveying information regarding the confidence in the analysis and a classification of scientific approaches to risk analysis have been used as a research method.

The main conclusions of this work are as follows. First, many applications lack clarity about foundational issues concerning the scientific method for risk analysis. Definitions for key terminology are often lacking, perspectives are not introduced and no attention is given to the scientific approach underlying the analysis. Second, the analysis of applications in light of the foundational issues introduced in Sections 2–4 shows that a large variety exists in the underlying principles for risk analysis in the application area. Definitions are mostly based on probabilities, but a minority of applications uses possibility- or uncertainty-based definitions. Many different risk measurement tools are applied, risk analyses focus either on events or on events and consequences, and uncertainties/biases are only in a minority of applications systematically considered. Applications are found across the range for scientific approaches to risk analysis, from strong realist over scientific proceduralist to moderate constructivist. Realist-based approaches are dominant.

Some suggestions are made to improve the current situation, focusing on the adopted terminology and principles underlying the risk analysis applications, and the need for a systematic consideration of uncertainty/bias in qualifying the risk measurement.

It is hoped that this work can increase focus on fundamental concepts and principles underlying future maritime transportation risk analysis applications, and that it can act as a catalyst for increased research and discussion for strengthening the scientific basis for risk analysis. To the extent our analysis and discussion has contributed to this end, the aim of this paper has been achieved.

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Appendix A. Example applications

In this section, a selected number of risk analysis applications are addressed in more detail to exemplify the differences in the adopted risk perspectives and approaches to risk analysis science. As it is infeasible to discuss all methods in detail, three examples are taken, representing the most commonly found approaches to risk analysis science, applying different risk perspectives. Focus is on the elements found in risk perspectives and the approach to risk analysis science. Furthermore, some uncertainties are identified in the methods (which are not addressed in the original applications) to show the relevance of uncertainty treatment, and the interpretability of the results is addressed. This last point has been raised as a concern for practical decision making: it should be possible to explain how to interpret the risk measurements [13,14].

Application M4 is represents the strong realist approach, see Table 3. A probabilistic estimate of frequency and consequences of collisions and groundings in a waterway is made. The method is recommended by maritime authorities and regulatory organizations [1–3], and has been influential to other work realist approaches (e.g. M10, M28, M34, M48), has been used in an uncertainty quantification approach (M50) and to estimate baseline probabilities in a precautionary constructivist approach (M13).

Application M33 is chosen to illustrate the moderate realist approach to risk science, see Table 3. Expert judgment is applied to define a set of quantitative indicators, which are measured directly from maritime traffic data. The method has sparked further work in M45. Indicators are rather rare measurement tools in the application area and hence are interesting to consider.

M23 is chosen to exemplify the moderate constructivist approach. The risk model is constructed based on expert judgments of the risk levels of vessel interactions, from which a probability-like measure is derived to measure the risk of collision in traffic data. Ordinal probit regression modeling is applied in this vessel conflict technique. This method has sparked further work, e.g. M45.

A.1. Method M4: $RA=I$, $R\sim(P_f, A, C)$

The method aims at estimating the collision and grounding frequency and consequences in a waterway, with a sequence of events as shown in Fig. A1. Three events are distinguished: ship–ship encounter, collision, and structural damage. The number of encounters N_G is measured using traffic data and an encounter detection method. The frequency of collision accidents is measured using a frequentist probability derived from accident data. Consequences are calculated using engineering models, but it is

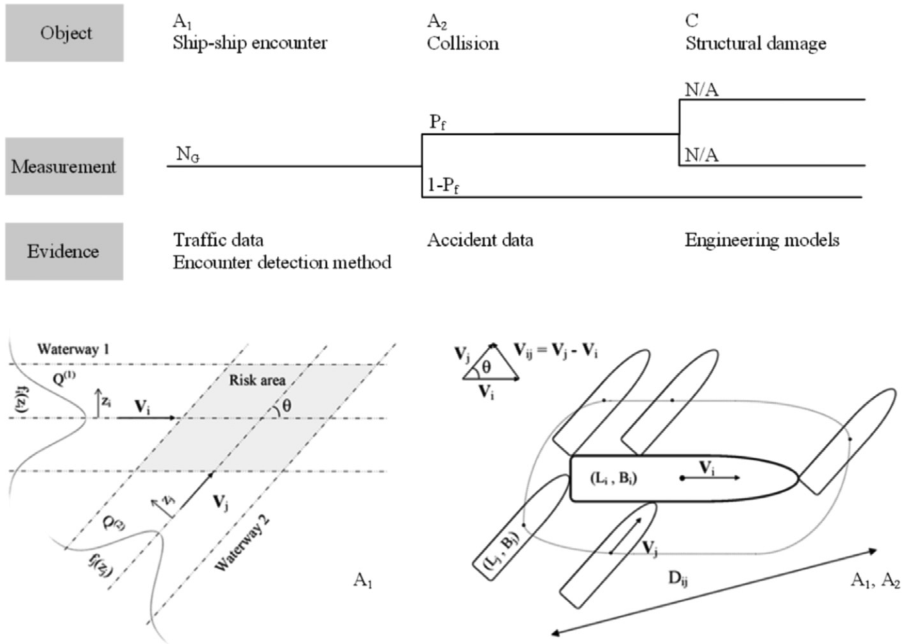

Fig. A1. Schematic overview of risk analysis application M4, based on [59].

not specified how exactly probabilities are derived. Here, focus is on the collision frequency f (involving A_1 and A_2 of Fig. A1), calculated as follows:

$$f = N_G P_C \tag{A1}$$

where N_G is the number of encounters in a waterway area and P_C the probability of accident in an encounter.

For crossing waterways, the number of encounters is calculated from the distribution of ship traffic in a waterway as follows, which is established using AIS data[2], see Fig. A1:

$$N_G^{CR} = \sum_i \sum_j \frac{Q_i^{(1)} Q_j^{(2)}}{V_i^{(1)} V_j^{(2)}} D_{ij} V_{ij} \frac{1}{\sin\,\theta} \tag{A2}$$

with V_{ij} the relative speed between the vessels and D_{ij} the apparent collision diameter:

$$D_{ij} = \frac{L_i^{(1)} V_j^{(2)} + L_j^{(2)} V_i^{(1)}}{V_{ij}} \sin\,\theta + B_j^{(2)} \sqrt{1 - \left(\sin\,\theta \frac{V_i^{(1)}}{V_{ij}}\right)^2} + B_i^{(1)} \sqrt{1 - \left(\sin\,\theta \frac{V_j^{(2)}}{V_{ij}}\right)^2} \tag{A3}$$

$Q_i^{(1)}$ and $Q_j^{(2)}$ are the flow rates of vessels of subclasses i and j. L and B represent ship length and width, V the ship speed and θ the angle between the waterways. The cross-waterway traffic distributions $f_i^{(1)}(z_i)$ and $f_i^{(2)}(z_i)$ integrate to unity for crossing encounters, but for overtaking and meeting encounters, the shape of these distributions affects the number of calculated encounters. The procedure is based on the assumption of blind navigation, i.e. under the premise that neither ship takes an evasive action prior to collision.

The probability of an accident given an encounter is calculated from accident statistics and is estimated as $P_C = 1.2 \times 10^{-4}$ [59]. This is a frequentist probability P_f^*, because it is derived purely from data, see Table 2.

The approach focuses on a true underlying risk, calculated using traffic-flow analysis (A_1), accident data (A_2) and engineering models (C). No expert judgment is applied and no uncertainty is assessed. Decision making is strongly linked to the risk model: "[…] it should be possible to derive *probability-based* codes for […]" ([59], p. 153). From this, it is concluded that a strong realist scientific approach to risk analysis is adhered to, see Table 3.

Focusing on the interpretability of the risk model, it is found that it is not straightforward to provide a meaning to the model elements. The measurement of event A_1 (ship–ship encounter) clearly is a strong simplification of a real encounter process, which is difficult to relate to actual encounters. The event A_2 (ship–ship collision) is likewise measured using a strong simplification, which is difficult to reconcile with actual collision accidents. In normal operation and in ship–ship collision accidents, at least one of the ships makes evasive action [129,130].

Interpreting the risk measurement tools also presents some conceptual challenges. The probability P_C has been explained as "the probability that an accident will occur if the ship is on collision course" ([97], p. 2). This seems intuitive enough, but assigning this probability to a model parameter (A_2, see Fig. 5) representing a blind navigation collision is inconsistent: in principle, the accident data should then only consider cases where neither ship made an evasive action. Moreover, interpreting the frequentist probability P_C is difficult, as such probabilities are defined through an infinite repetition and require a specification of what is understood under "similar" events [13]. It can be questioned whether a risk analysis should focus on mathematical constructs such as N_G and P_f [124].

Even though uncertainty is not addressed in M4, some important uncertainties can be identified, see Table A1. A simple uncertainty rating scheme is applied, proposed in [28] and briefly outlined in Appendix B. Each uncertainty factor is assessed using four criteria, leading to an overall uncertainty rating Table A1.

Take for example ME_3, the relation between the flow rate and the frequency of collisions. Based on traffic flow theory, the number of encounters is quadratic with flow rate, so it seems a plausible assumption. Given the use of the same assumption in other applications (e.g. M10, M13, M28, M34, M48, M50), but contested in others (e.g. M42, M56), the agreement about the model element is ambiguous. There is very little data supporting the claim that increases in traffic density in fact result in more

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[2] AIS is a system where navigational parameters are transmitted from ships to one another and to shore stations, allowing for improved situational awareness. It provides a rich data source for studies in maritime transportation, containing detailed information about vessel movements.

Table A1
Uncertainties underlying risk analysis M4.

	Model element	CR_1	CR_2	CR_3	CR_4	Uncertainty rating
ME_1	Encounter detection method	N	N	Y/N	N	M–H
ME_2	Collision probability equal for all encounters	Y/N	N	Y/N	N	M–H
ME_3	The relation between the flow rate and the frequency of collisions is quadratic	Y	N	Y/N	N	M–H

Note: CR_1=the assumptions are seen as very reasonable, CR_2=much relevant data are available, CR_3=there is broad agreement/consensus among experts, CR_4=the phenomena involved are well understood, Y=yes, N=no, L=low, M=medium, H=high.

collision accidents. Moreover, the phenomenon is not well understood in maritime transportation, with varying approaches to assess the relation leading to significantly different results [12]. Related research in road traffic has shown that the relation between traffic density and accident occurrence is complex, involving a heuristic balancing of economy, risk-taking behavior and comfort of road users. Areas with more traffic conflicts may even be safer due to increased awareness [131]. In maritime transportation research, an investigation on the relation between grounding accidents and traffic density has also shown that no clear dependency can be found [132]. For these reasons, ME_3 is considered to involve medium to high uncertainty.

A.2. Method M33: $RA=II$, $R\sim(I_{QU}\rightarrow A)$

This method uses three risk indicators to analyze the risk of collision in a Traffic Separation Scheme (TSS) area[3]. A speed dispersion index ($I_{QU,1}$), an acceleration/deceleration index ($I_{QU,2}$) and a vessel conflict index ($I_{QU,3}$) provide quantitative information regarding the possibility of a collision in a given area, as schematically shown in Fig. A2. The identification of indicators considered relevant to assessing collision risk is based on judgments of navigational experts. $I_{QU,1}$ and $I_{QU,2}$ are situational characteristics obtained directly from traffic data, whereas $I_{QU,3}$ is obtained from traffic data, using a ship domain model [88]. It is interesting to note that the event occurrence itself is not modeled, but its likeliness is inferred from the values of the indicators. Also, the risk perspective makes no reference to consequences of the collision accident.

The application is understood to adopt a moderate realist approach to risk analysis science. Even though expert judgment is applied in devising the indicators, the application is rooted in the idea that risk is a measureable property of the system. This follows from the reasoning applied for making the indicators: "[existing] risk reduction solutions are generally based on the qualitative and subjective judgment from experts. There is no existing study to quantitatively evaluate ship collision risks […]" ([88], p. 2030). Quantification is taken as an alternative to subjectivity, implying that the quantification provides better decision support than qualitative, subjective judgment. Even though expert judgment is applied to identify risk indicators, the analysis heavily relies on data. No uncertainty is assessed.

For the interpretation of the risk measurement tools, we consider the acceleration/deceleration index $I_{QU,2}$. This is introduced as follows: "[…] acceleration and deceleration happen under the condition that ships are about to cross, overtake, meet, or turn, namely, scenarios with collision potentials. Higher degree of acceleration indicates more frequent occurrence of scenarios with collision potentials." ([88], p. 2031). The indicator $I_{QU,2}$ in a traffic area k is calculated as follows, see Fig. A2:

$$I_{QU,2,k}=\frac{\sum_{i=1}^{I_k}\sum_{j=1}^{J_{i,k}}{a_{k,i,T_j}}^2}{I_k} \tag{A4}$$

where a_{k,i,T_j} represents the acceleration of a consecutive pair of data records, $J_{i,k}$ the number of records of vessel i in a TSS area k and I_k the number of ship trajectories found in TSS area k. The acceleration or deceleration of consecutive records for vessel i in leg k at time T_j is given by:

$$a_{k,i,T_j}=\frac{SOG_{k,i,T_j}-SOG_{k,i,T_{j-1}}}{T_j-T_{j-1}} \tag{A5}$$

where $SOG_{k,i,T}$ is the speed over ground of vessel i in leg k at time T. The AIS data contains the time T and the speeds SOG for the individual ships.

Interpreting $I_{QU,2}$ is not straightforward, but it is possible. The number represents the total acceleration/deceleration intensity of all ships in a given area in a given time period. The number itself is a mathematical construct, but it is an information carrier which refers to an object which can be given a meaning.

Even though uncertainty is not addressed in M33, some important uncertainties can be identified, see Table A2. The uncertainty rating scheme introduced in Appendix B is applied here as well, focusing on $I_{QU,2}$. It is clear that important evidential uncertainties underlie the risk model Table A2.

ME_1 addresses the fact that Eq. (A4) measures acceleration, which includes more navigational operations than collision avoidance. When ships are involved in collision evasive maneuvering, it is feasible that they slow down, either voluntarily or due to hydrodynamic forces in the turning maneuvers. However, acceleration/deceleration is not only because of collision evasive actions. Other reasons can be speed adjustments to meet the ETA[4] of pilot boarding or harbor entry, and involuntary speed fluctuations may occur due to tidal and wave action. In this sense, the indicator's specificity can be questioned as it obfuscates the relation between the indicator $I_{QU,2}$ and collision occurrence, leading to measurement uncertainty.

ME_2 addresses the fact that formula Eq. (A4) does not account for the unequal sizes of the TSS areas. An uncertainty results from this in relation to the number of AIS records in this area, as illustrated in Fig. A2. Consider a specific ship trajectory, which in AIS data is available as a set of points. If the number of data points in TSS area k_m is systematically more (or less) than the number in area k_n, because e.g. the areas are not of equal size, this means that the summation in Eq. (A4) is performed for a higher (or lower) number of data points. It follows that larger (smaller) TSS areas will result in a higher (lower) value for the indicator, not because of higher collision risk but because of the larger considered area. Eq. (A4) does not include a compensation mechanism for this, hence the values of indicator $I_{QU,2}$ are not dimensionally consistent across sea areas. This leads to uncertainty about the specificity of the measurement.

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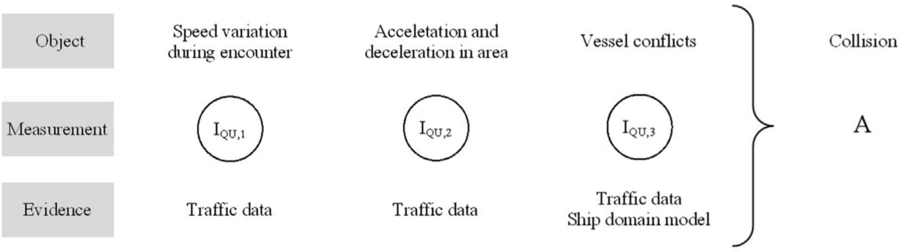
[3] A TSS area is an area where ship traffic is regulated, such that vessels are required to follow certain sea lanes.

[4] ETA: estimated time of arrival.



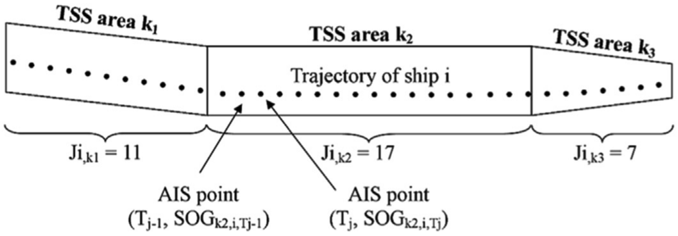


Fig. A2. Schematic overview of risk analysis application M33, based on [88].

Table A2
Uncertainties underlying risk analysis.

	Model element	CR_1	CR_2	CR_3	CR_4	Uncertainty rating
ME_1	$I_{QU,2}$ (Eq. (A4)) measures accelerations, not only collision-avoidance maneuvers	Y/N	N/A	Y/N	Y/N	M
ME_2	The areas k for which $I_{QU,2}$ (Eq. (A4)) is calculated are not of equal size	N	N/A	Y/N	N/A	M–H

ote: CR_1=the assumptions are seen as very reasonable, CR_2=much relevant data are available, CR_3=there is broad agreement/consensus among experts, CR_4=the phenomena involved are well understood, Y=yes, N=no, L=low, M=medium, H=high.

A.3. Method M23: RA=VII, $R\sim(P_x, A)$

This method uses a vessel conflict technique to analyze the risk of collision in a waterway area. The basic idea is that the severity of non-collision traffic encounters can be ranked, and that this information can be used to derive the probability of a collision. For this, a procedure schematically shown in Fig. A3 is used. First, a vessel conflict operator is constructed based on an ordered probit regression modeling of expert judgments. Experts are asked to assess the risk level in vessel interactions based on the proximity indicators DCPA[5] and TCPA[6], for day and night conditions and for different vessel sizes. The risk levels are interpreted as in Fig. A3, and a mathematical operator $C(t)|\boldsymbol{S}$ is defined. Second, this operator is applied in vessel traffic data for encounters involving a vessel conflict, and a measure C'_{max} is calculated. Finally, the collision probability $P_x(A)$ is mathematically derived from the fitted distribution $f((A4))$ to the empirical distribution $p(C'_{max})$. The threshold value τ_{HR} corresponds to the separation between serious and non-serious conflicts, i.e. based on the risk score RS_m corresponding to the "High risk" level. For details about the calculation procedure, see [78]. The application makes no reference to consequences of the collision accident, i.e. the risk perspective focuses on an event.

The application is understood to adopt a moderate constructivist approach to risk analysis science. While the method relies on data to determine collision risk, the basis of the method is a modeled representation of judgments by navigational experts, i.e. a mental construct of an assessor. The constructivist approach is also reflected in the proposed validation method. Considering the risk model to be used as an evaluative, diagnostic tool to assess the effect of changes in a traffic area, no demands are placed on the method to correlate with observed accident frequencies. Rather, the model results are compared with direct expert judgments of the risk level in different waterway areas, stressing the centrality of judgment in risk analysis. Uncertainties are not assessed.

Interpreting the risk measurement is difficult, as it is a derived measure from a fitted distribution based on data collected through running an expert judgment based model in traffic data. Even though an interpretation is given to the risk levels, see Fig. A3, this is not unambiguous. $P_x(A)$ is calculated using the threshold value τ_{HR}, corresponding to the action level "immediate actions needed", i.e. a level which does not per se imply a collision occurrence. However, $P_x(A)$ is calculated from serious conflict cases (with $C'_{max} > \tau_{HR}$), which are defined as "encounter[s] that may pose risk of a certain collision" ([78], p. 143). These definitions provide ambiguous information for interpreting the risk measurement tool: $P_x(A)$ claims to be the probability of collision, but it is derived from a risk level corresponding to "encounters requiring immediate action", also defined as "encounters which may pose risk of a certain collision". This circularity and inconsistency in the basic definitions obfuscate what precisely is measured, and what the measurement means.

Even though uncertainty is not assessed, at least one important uncertainty can be identified. This relates to the structure of the vessel conflict operator, which assumes a linear combination of TCPA and DCPA:

$$r = \hat{\beta}_1 \mathrm{DCPA} + \hat{\beta}_2 \mathrm{TCPA} \tag{A6}$$

Here, DCPA and TCPA are instantaneous values of the spatial and temporal proximity indicators in a vessel interaction, and $\hat{\beta}_i$ $(i=1,2)$ are estimated coefficients based on ordinal regression modeling of questionnaire-based expert judgments. From research on vessel domain analysis, it is known that in practice, navigators allow a smaller or larger distance between the vessels depending on the encounter angle [133–135]. Hence, navigators interpret the collision risk not only in terms of DCPA and TCPA, but also in relation to the

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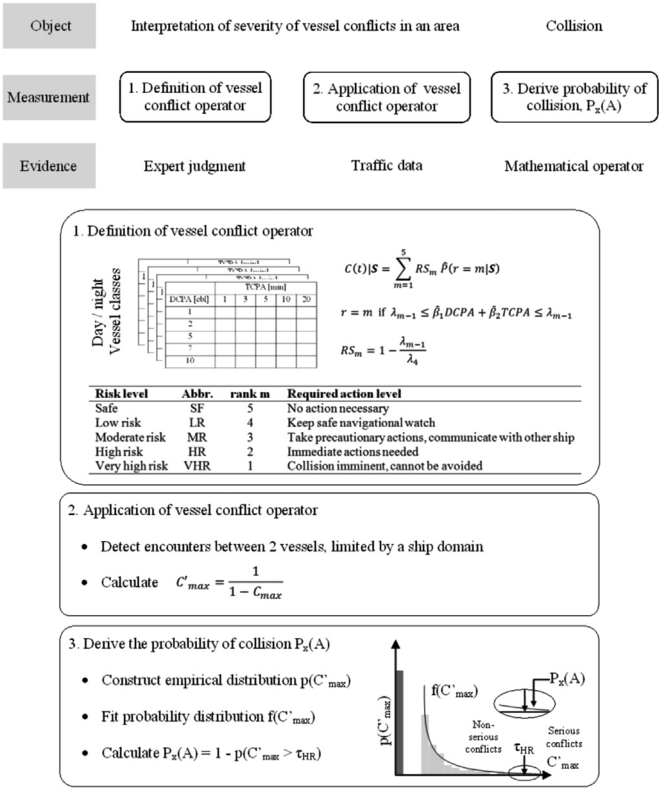
[5] DCPA: distance to closest point of approach.

[6] TCPA: time to closest point of approach.



$$C(t)|\boldsymbol{S} = \sum_{m=1}^{5} RS_m\,\hat{P}(r = m|\boldsymbol{S})$$

$$r = m \text{ if } \lambda_{m-1} \le \hat{\beta}_1 DCPA + \hat{\beta}_2 TCPA \le \lambda_{m-1}$$

$$RS_m = 1 - \frac{\lambda_{m-1}}{\lambda_4}$$

Risk level	Abbr.	rank m	Required action level
Safe	SF	5	No action necessary
Low risk	LR	4	Keep safe navigational watch
Moderate risk	MR	3	Take precautionary actions, communicate with other ship
High risk	HR	2	Immediate actions needed
Very high risk	VHR	1	Collision imminent, cannot be avoided

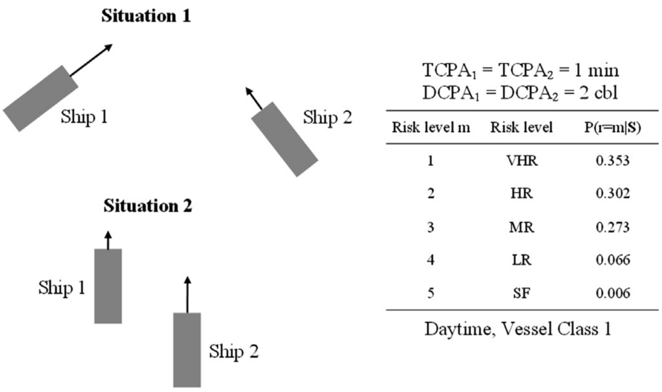
2. Application of vessel conflict operator

- Detect encounters between 2 vessels, limited by a ship domain
- Calculate $C'_{max} = \frac{1}{1 - C_{max}}$

3. Derive the probability of collision $P_x(A)$

- Construct empirical distribution $p(C'_{max})$
- Fit probability distribution $f(C'_{max})$
- Calculate $P_x(A) = 1 - p(C'_{max} > \tau_{HR})$

Fig. A3. Schematic overview of risk analysis application M8, based on [78].



$TCPA_1 = TCPA_2 = 1$ min
$DCPA_1 = DCPA_2 = 2$ cbl

Risk level m	Risk level	P(r=m|S)
1	VHR	0.353
2	HR	0.302
3	MR	0.273
4	LR	0.066
5	SF	0.006

Daytime, Vessel Class 1

Fig. A4. Two situations with equal risk level according to M23.

encounter angle. Take for example the situations in Fig. A4, with equal TCPA and DCPA. According to the regression model, the risk level is most likely "Very high risk", which means that collision is imminent, and that it cannot be avoided, see Fig. A3. For situation 1, this may be plausible. However, in situation 2, which is an overtaking encounter, this contradicts common navigational practice. It seems more plausible to rank this situation under "Low risk", i.e. requiring safe navigational watch but not evasive action. This implies that the vessel conflict operator may not appropriately rank the detected encounters, leading to uncertainty in the shape of distributions $p(C'_{max})$ and $f(C'_{max})$, and the calculated value for $P_x(A)$.

Appendix B. Uncertainty assessment scheme

Flage and Aven [28] propose a method to assess uncertainties in a risk analysis application. A direct grading of the importance of the uncertainty is performed through a judgment of an assessor of four criteria. A justification for the assessment of each criterion can be provided.

The knowledge is weak (uncertainty is high) if all of the following conditions are true:

(a) The assumptions made represent strong simplifications.
(b) Data are not available, or are unreliable.
(c) There is lack of agreement/consensus among experts.
(d) The phenomena involved are not well understood; models are non-existent or known/believed to give poor predictions.

The knowledge is strong (uncertainty is low) if all of the following conditions are met:

(a) The assumptions made are seen as very reasonable.
(b) Much reliable data are available.
(c) There is broad agreement/consensus among experts.
(d) The phenomena involved are well understood; the models used are known to give predictions with the required accuracy.

Cases between these two extremes are classified as involving medium knowledge (medium uncertainty).

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