Delft University of Technology

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DOI
10.4233/uuid:458a384f-6f8a-4fc3-8bc4-c01397b54b59

Publication date
2019

Document Version
Final published version

Citation (APA)
Li, Y. (2019). *A Systematic and Quantitative Approach to Safety Management*. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:458a384f-6f8a-4fc3-8bc4-c01397b54b59

A Systematic and Quantitative Approach to Safety Management

A Systematic and Quantitative Approach to Safety Management

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus Prof.dr.ir. T.H.J.J. van der Hagen,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op vrijdag 15 februari 2019 om 15:00 uur

door

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Dit proefschrift is goedgekeurd door de promotor en copromotor.

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Printed by: Ipskamp Printing, Enschede

ISBN: 978-94-028-1364-7
An electronic copy of this dissertation is available at https://repository.tudelft.nl/.

Table of Contents

1 INTRODUCTION

1.1 Background

The term “safety management system” (SMS) combines three extensive domains: *safety*, *management* and *system*. Here *safety* is the acknowledged responsibility of the management of an organisation; *safety management* means ‘a systematic control of worker performance, machine performance, and the physical environment’ (Heinrich et al., 1980); to structure this systematic control, the *safety management system* combines all safety management activities in an orderly manner. An SMS is a practical concept, widely used in different industries. A model for SMS is a general model that depicts the uniform components and principles of SMSs.

Before the 1970s, safety management was mostly concerned with accident prevention in the view of both researchers and companies. After 1970, when system safety techniques such as fault trees and event trees, were established, they were widely applied to safety management. For the first time, the term “SMS” was proposed in a paper (Kysor, 1973). In the meantime, a number of safety-specialised organisations were set up, such as the Occupational Safety and Health Administration (OSHA), the Health and Safety Executive (HSE), and the World Safety Organisation (WSO). These organisations published laws and regulations, collected incidents information, and raised awareness of safety management. In the 1980s, many companies, such as Shell, ExxonMobil, and DSM, established their own safety management systems, which were actually the original versions of their formal safety management frameworks. After 1990, SMSs became more mature thanks to the improvement of a multitude of technologies that support their development. New computer techniques, for instance, helped to develop safety information systems, providing risk control and safety-related data analysis with advanced methods. In general, safety management has experienced three stages: individual risk management, intensive training and accident investigation; technology, regulations and incident investigation; business management approach to safety and routine collection and analysis of operational data.

1.2 Problem statement

However, current safety management systems still give rise to problems from different perspectives of companies, auditors, government, safety-specialised organisations and researchers. These problems stem from the original SMS no longer being effective for its context, a lack of models and principles for auditing, administration and guidance, and a vague understanding of SMSs.

Company view: SMSs at different stages of development

SMSs are used in different companies within different branches of industries. However, they are often at different stages of development: some are an integrated part of the management system, of which safety is a part of the overall aim of the company; some companies have independent management systems whereby SMS is one system among many. The developmental stages of SMSs are so different due to the fact that (1) the context of the SMS (e.g. state policy, safety culture) varies; (2) the industry players require different basic standards; (3) the overall situation of companies themselves limits the investment in SMSs. Therefore, even when applying the same SMS procedure, the actual stage of development could be different. Thus, how to set up an effective SMS and how to assess its effectiveness scientifically is becoming an increasingly demanding question.

Auditor view: too many different SMSs and SMSSs are difficult to audit

Auditors for SMSs generally conduct internal- or external audits. Internal audits aim to review and improve an SMS, while external audits aim to assess legal, regulatory, or certificate compliance. However, a company can operate more than one formal safety related management system (e.g. ISO 31001, ISO 45001); each management system contains a mass of information or a large number of documented sub-systems, even if some of these are redundant. The guidelines for auditing are thus critical because they need to explain how to assess the quality of an SMS in a relatively short period of time. As a result, auditing requires a systematical model and principles to guide the work.

Government and (safety-specialised) organisation view: lack of uniform guidelines to oversee different industries

Similarly, governments or organisations specialised in safety are concerned with the safety performance of a large number of companies in different industries or sectors. As we know, almost every company has an SMS or a package of safety management activities, which need to be reviewed and audited regularly. A uniform guideline is required to check compliance with safety laws and regulations and to inspect safety situations systematically. Organisations specialised in safety would like to publish standards so as to give guidance to the specific SMSs. However, to make the standards up-to-date and effective, they also need to do research. At this high authority level, the difficulty of establishing a uniform guideline or standard is due to a lack of common principles and approaches.

Researcher view: ambiguous models and uncertain approach

Describing and modelling a safety management system requires a common language (Hale et al., 1997). Based on different backgrounds, different projects and different researchers contribute to different terminologies, which causes confusion among readers. Although SMSs and safety management models have different meanings a proper definition of both is still lacking. Therefore, we have defined them at the beginning of this research.

The SMS concept is used everywhere and for anything related to safety. The above confusion pertains to (1) the definition of an SMS; the emphasis is on management activities or system frameworks or both. (2) The scope of an SMS; it is a system within an organisation because they operate it, or it includes society and the highest authority because they provide criteria for it. (3) The specific functions of an SMS; there are too many functional-specific systems, but in some literature they are regarded as SMSs themselves, e.g. an operation system, information system or risk management system.

The problem of the SMS model is that too many frameworks, theories, and even procedures related to safety (management) are likely to be referred to as safety management models or SMS models. First, it is difficult to distinguish whether a model is just for operational use or formed for the purpose of generic modelling. Second, a number of so-called SMS models only depict accident causation theories. Third, the models that depict the relationship between some organizational or human or management factors and risk only partially explain the full SMS.

How the organisations use their management to control safety risk is the most unclear part of many safety management systems. An effective SMS model should contain explicit management processes on safety. These processes should also function well in the SMSs. A systematic approach to modelling the safety management processes is required.

To achieve efficient safety management, many safety performance indicators have already been developed by both practitioners and researchers. Thousands of safety-related items collected in different companies not only waste managerial resources but also cannot easily to be usefully interpreted. A quantitative approach to them should produce a quantitative result which is simple, clear and convenient for safety decision-making. Therefore, quantitative methods, especially probabilistic methods commonly applied to safety management research. However, measuring organizational factors, such as behavioural factors, is difficult and uncertain. Moreover, the limited structural data and various industrial cases make it even more confusing. A quantitative approach based on a structured model is required.

We distinguish several steps to solve the problems. Firstly, we need to gain insight into safety management systems. Clearing all the confusing concepts around the SMS will help us find the essence of a functional safety management system. As this topic is broad, we need to complete not only a systematic overview but also a specific comparison of all the constituent elements of SMSs. After a theoretical analysis, we can find a model that describes complete SMSs. Secondly, based on this model, we explore more specific safety management processes. Systems thinking is applied, and we elaborate how safety management works on safety barriers to control the risk. This analysis is not only systematic but also quantitative. Thirdly, in order to develop a quantitative approach, the idea of delivering management to safety barriers should be carried out in an industrial risk scenario. The lifting risk is common in many industries, and the barriers to this risk control will be clarified. Fourthly, one of our delivery systems (e.g. competence in this study) will be broken down clearly and the connection to the barriers will be quantitatively studied. Consequently, we will develop a quantitative approach, which can be a universal approach to the modelling of safety management.

1.3 Research question

We found out the gap to complete the quantification of safety management system is still have so many uncertainties. In our research, we will address the quantitative improvement in the modelling of safety management. The main question of this thesis is formulated as:

Quantifying safety management systems: to what extent is it possible and how?

The former part of this question means: which parts of the model are still relevant to developing the quantitative approach? Indeed, we will have to look into all constituent parts of our generic SMS model, but since each part is a sub-system with its constituent elements, there is hardly any end to this. The level of detail may increase but not necessarily the relevance for safety management. So we must find out where to draw the line in accordance with certain criteria (to be defined). The main challenge of our research is to know the exact details of safety management delivery systems and how these parts work to control risks through safety barriers. In order to quantify this relationship, we analyse the competence delivery system as an example and connect it to the safety barriers for lifting risk. If we know quantitative relationships in a safety management system, we can achieve a better safety performance more efficiently.

The contribution of this study is the universal approach to modelling safety management systems. This approach will help us establish a generic model, which would provide principles for industry' and company' specific SMSs. The generic model will look into the constituent parts of the SMS and the details of those parts.

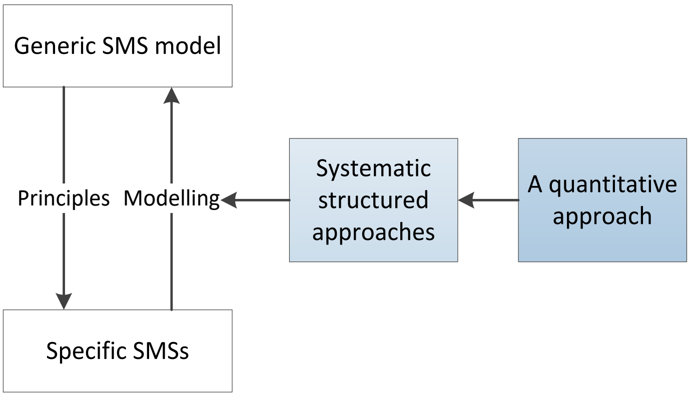

Figure 1.1 – A quantitative and systematic approach to safety management modelling

Safety management delivery systems are the focus of this research. We use them to model safety management processes. Normally, specific management factors are difficult to be modelled because the logic among these factors is vague. So to model how the management delivers in an organization and within the framework of an SMS is helpful to quantify them. We aim to develop a generalizable quantitative approach. Even if the risky environment changes, it is still applicable. Therefore, establishing the structure and details of the delivery system is the foundation for developing our quantitative approach.

My dissertation is original because of this systematic and quantitative approach to safety management. On the basis of a broad overview of SMSs, we distinguished the essence of models: a logical sequence of causal events, safety barriers and safety management. Since the causal events had already been widely studied for risk analyses, while the relationship between safety barriers and safety management was unclear, we develop an approach to explore this relationship. This approach models generic safety management delivery systems (DSs). These DSs can be decomposed into systematic processes, by a method with an input-activities-output framework. We also illustrate the connection between the output of DSs and the barrier tasks. These delivered safety management factors can be quantified not randomly but hierarchically. We considered the competence delivery system as an example and designed the initial indicators model (KSEA). By specifying the indicators in an industrial scenario (e.g. a lifting risk scenario), we establish the operational and managerial competence for safety barriers. An exciting result is a statistical relationship between the delivered competence and the performance of safety barriers. Our approach provides a universal way to model safety management systems from the generic management component to the specific factors and to quantify them the other way around. Methods such as data mining and machine learning are currently booming in many research fields. This approach fills the gap for a quantitative SMS and promotes future big data research in this field.

1.4 Outline of the thesis

Our research has a solid theoretic foundation, as it is based on a series of previous studies in safety management and risk control. We primarily reviewed SMSs from different perspectives, including their definition, history, modelling, purpose and elements. Then we proposed a complete SMS model as a benchmark and compared the elements with other SMSs by mapping method. Next, we improved safety management delivery systems and applied the SADT (structured analysis and design technique) method to analyse how an organization delivers a safety management to control risk. A risk is directly controlled by safety barriers, and barriers are managed by delivery systems. Therefore, a competence delivery system for safety barriers became the focus of this study. Then a lifting risk scenario was chosen as the basis of the quantitative case study. It was developed by the Bowtie model (which is an accident scenario method).

Based on the aforementioned scenario, we conducted a survey of competence for lifting safety and applied various statistical methods. We carried out a PCA (principal component analysis) to identify the key constituent factors of a competence delivery system; the quantitative relationship between delivered competence and safety barriers we modelled by a regression analysis. As a result of this case study, the aggregate barrier performance was statistically determined by the combination of operational and managerial competence. In this way, the other delivered safety management can be quantified as well.

Illustrating this overview, Figure 1.2 shows the outline of this thesis. From Chapter 2 to Chapter 6, this research progresses from generic safety management to a specific risk management process, whereas after the case study in Chapter 5 and 6, this quantitative approach based on the systematic analysis will become a generic approach again. The delivery systems will become a universal tool for both qualitative and quantitative safety management systems.

Chapter 2 provides a broad clarificatory overview of safety management systems. The SMSs are described with plenty of literature from different views. We consider and analyse the aspects of their definition, history, purpose, modelling and elements. We also summarize the logic among risk, barrier and safety management.

Chapter 3, more specifically, compares the elements of our benchmark model of SMSs with 43 other SMSs. These practical SMSs must contain all the managerial factors in different management levels. However, the emphasis of each SMS structure is different. By comparing them to the elements of our model, we can understand the weight of each element from the perspective of general SMSs.

Chapter 4 develops the details of safety management delivery systems (DSs), which explicitly model the relationship between management and safety barriers. The main part of safety management is risk control. Safety barriers are the practical countermeasures that control the particular risks.

Delivery systems are the management to sustain the function of safety barriers. In this chapter, the quantitative approach to the relationship between competence and barrier is proposed abstractly.

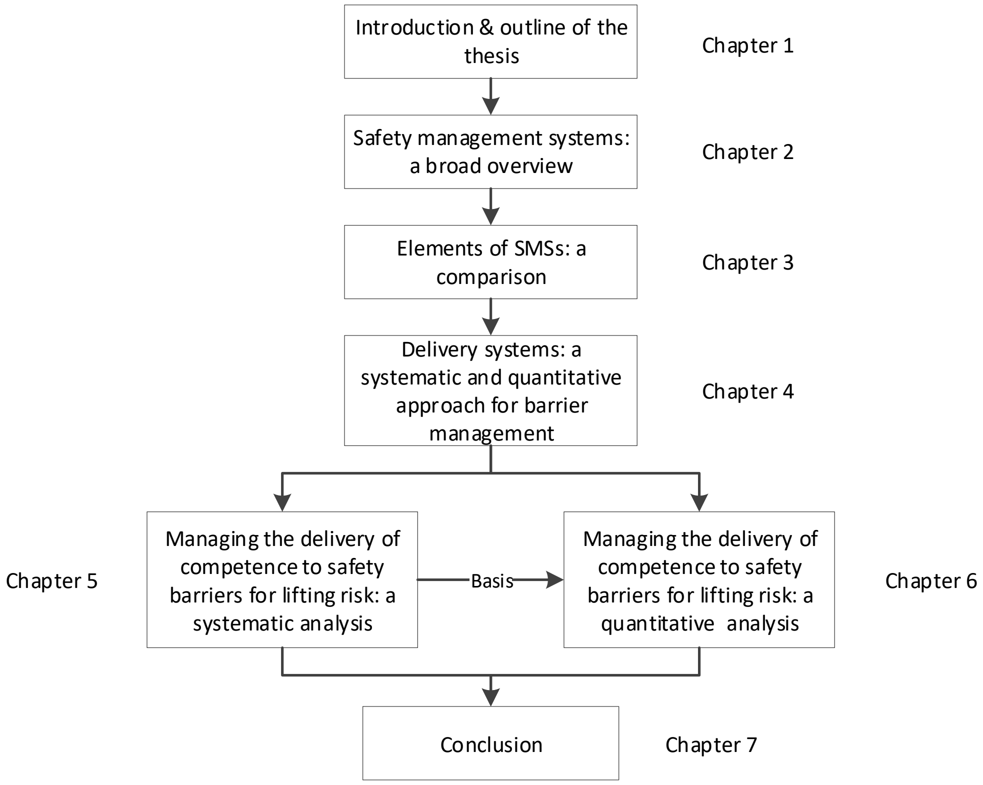

Figure 1.2 – Outline of the thesis

In Chapter 5 we implement a competence delivery system for safety barriers to control lifting risk. We analyse how the specific managing competence works on them. Specific barriers are identified in the scenarios of lifting risk (e.g. with centre event “object drop”), which is modelled by a Bowtie method. The managed competence is the output of the competence delivery system and is denoted as indicators based on a KSEA model. We explicitly model the relationship between the competence and barriers.

Chapter 6 is based on the application of Chapter 5 in the field via a survey. From the survey, we gain a large number of specific variables that represent the competence indicators, and we also obtain the performance of different barriers. By dimension reduction and aggregation, we discover the quantitative relationship between managing competence and safety barriers.

In this study, we reveal at which specific level of the model of SMSs safety management can be quantified and modelled properly. We develop the principles of this quantitative approach and expect to make it more widely used in industrial safety management systems. That is why this approach was originally based on systems control thinking and why the management is systematically structured. The specifics can be substituted, but the way of doing a quantitative management study can be reproduced in another delivery system or for another risk scenario control.

1.5 References

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2 SAFETY MANAGEMENT SYSTEMS: A BROAD OVERVIEW OF THE LITERATURE

Abstract

To begin this research, we will clarify the concept of a safety management system (SMS). This chapter covers five core aspects of SMSs: definition, evolution, models, purpose and common elements. An SMS implements management activities to achieve safety performance, so an overview of definitions of safety and safety management sheds light on its content. SMSs emerged from the concepts of risk and safety defences. Their development was boosted by research into safety, management and system theories, (safety) risk analysis techniques, audit tools, and related standards. Consequently, the study of SMSs became a multidisciplinary topic and by modelling them, a generic framework can be established to improve their effectiveness.

There are two main groups of models feeding into SMSs: (1) accident related models, and (2) organisational models. The relationship between these two is outlined in this chapter. Additionally, we show that SMS studies and models are developed for two main purposes: control and compliance. In other words, by implementing safety systems or subsystems, an SMS is able to control risks and improve continuously, as well as to comply with the appropriate standard management systems. As the key to creating a functional SMS is to carry out common managerial processes, we map the elements of various SMSs to a standard SMS for a better understanding of key components. This chapter thus determines and clarifies the facets of an SMS, in order to facilitate its modelling.

2.1 Introduction: overview approach and objective

A safety management system (SMS) is either a system that is used to manage and control safety or it is a management system specifically aimed at safety. Taking three perspectives, i.e. safety, management and system, an SMS is the intersection of these. How an SMS evolves over time depends to some extent on the individual progress of each of these three aspects. Safety primarily focuses on its opposite, i.e. accidents, loss or injuries, which are often described using models and metaphors (see Swuste et al., 2010, 2011). The terms management and system both have broad meanings: management involves planning, organising, leading and controlling functions (Robbins & Judge, 2012); the elementary principle of a system is input–process–output (Hale et al., 1997; Hammer, 1971; Waring, 1996).

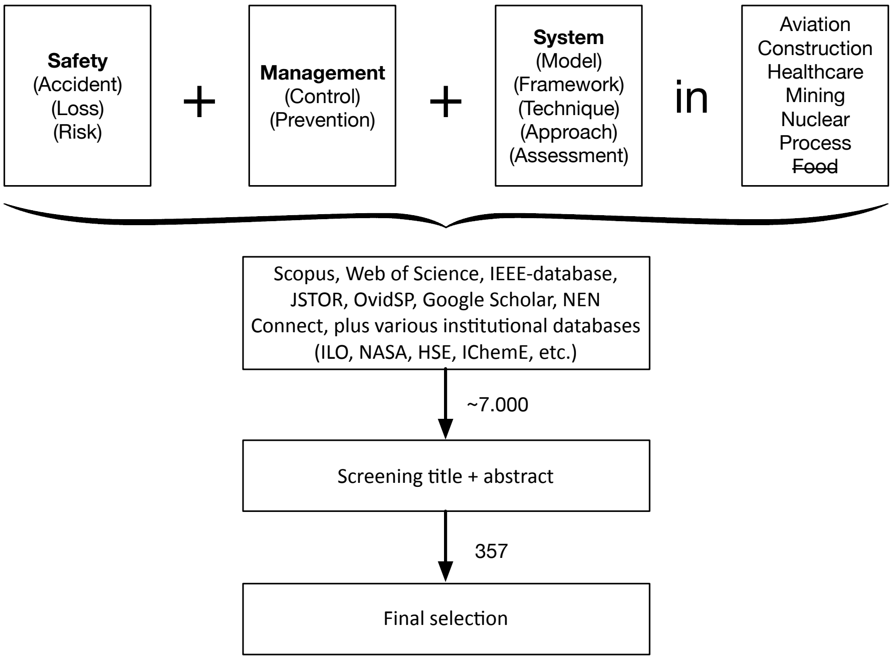


Figure 2.1 – Procedure for selection of literature for overview

The following steps were taken for this overview (Figure 2.1):

1. Select keywords and databases; initial keywords used were ‘safety’, ‘management’ and ‘system’;
2. Filter the outcome using the resulting titles;
3. Extract papers;
4. First bibliometric analysis of texts (e.g. abstract);
5. Refine overview sources.

Although the term SMS is widely used, its definition, scope, modelling and purpose still need to be clearly defined. To gain insight into the origins and development of SMSs, this chapter will focus on the following five questions.

1. What is an SMS? (Definition)
2. How does an SMS evolve? (History)
3. How are SMSs modelled? (Model)
4. What are SMSs used for? (Purpose)
5. What are the constituting elements of SMSs? (Elements)

According to Grote (2018) safety management systems operate within different contexts that influence the issues they particularly focus on. These contexts are:

1. The particular type of risk the SMS aims to control: risks associated with process safety or with personal safety. While both types of risks have some overlap, the focus on either one is different, though (i.e. preventing process accidents vs. preventing injuries).
2. The second context pertains to the way in which the SMS deals with uncertainty. Is uncertainty minimized by much standardization (of work processes, of competencies) that leave little room for improvisation? Or does the SMS aim to cope with uncertainty, providing employees with multiple options for discretionary action in less familiar or equivocal situations?
3. Finally, what is the regulatory regime in which the SMS operates? Is the regime primarily prescriptive, leaning on rigorous inspections and compliance, or is the regime leaning towards self-regulation, based on broadly defined safety goals?

The SMS discussed and developed in this thesis is basically generic, which means that it can, in principle, operate in any of these contexts. However, in order to operationalize parts of the SMS, we do have to make choices regarding these contexts. For instance, in Chapter 5, in order to identify the competencies needed for lifting, we build on personal safety data. And in Chapter 6 we collect data on how to perform a standard lifting operation safely. With regard to the third context, regulatory regime, we do not make any specific assumptions but given the fact that we collected most of our data in China, where a rather prescriptive regulatory regime is in operation, we can assume that our respondents provided answers consistent with this context.

2.2 Definition of an SMS

2.2.1 Definition of safety

Safety is a broad and abstract concept, which is best described in terms of a particular state or situation. This state is freedom from 'something' that could have negative consequences, such as harm to humans or animals, economic loss, or any other form of damage or loss. In other words, safety is the condition whereby unexpected events, such as accidents and incidents, are being avoided. In specific contexts, safety can be defined in more practical terms. For example, in a hospital, the safety of patients means keeping patients in a stable condition by avoiding the risk of adverse events (Shojania et al., 2001).

This thesis is concerned with industrial safety; hence, the unexpected events and risks arise within the context of industrial activities. However, a zero-risk situation, or absolute and unconditional safety, does not exist. Although some companies nowadays attain a zero accident or injury record for a certain period of time, it does not imply they are risk-free. Because 'risk is a measure of the probability and consequence of uncertain future events; it is the chance of an undesirable outcome' (Yoe, 2011, p. 1), while safety is, according to IEC 61508, 'freedom from unacceptable risk' (NEN, 2005, p. 13). We can therefore conclude that the safety of an industry is judged by its acceptable risk.

Whatever the context, the overall scope of *safety* can be divided into human, environmental and equipment safety (Dezfuli et al., 2011a, 2011b). The scope of safety, however, often depends on the context or on particular research views. For example, according to IEC 61508, defining the scope of safety is a step towards the building of automation and control systems (Novak et al., 2007), which is a definition focussed primarily on technology. In other words, the scope of safety refers to the particular objects that safety management focuses on.

2.2.2 Definition of safety management

Following the first workmen compensation act of 1908, which stated that 'in effect, that regardless of fault, management would pay for injuries occurring on the job' (Petersen, 1978, p. 11), safety gradually became a management issue. *Safety management* is the concept of 'the MANAGEMENT [capitals in original] of safety and uses the same concepts, principles and techniques as used in other areas of management' (DNV, 2012, p. 2). When comparing *safety* with *safety management*, the former refers to a state or condition, the latter is a process or a series of certain activities. Furthermore, *safety* is the freedom from unacceptable consequences, *safety management* is the process to realise certain safety functions. In this current context, the aim of (safety) management is safety, protecting human beings, the environment, equipment and property from unacceptable risk.

Managing safety is a comprehensive effort and needs an organisation to determine safety requirements (Strutt et al., 2006), design a safety management structure and process, and decide which activities need to be implemented in order to achieve pre-defined safety requirements. Harms-Ringdahl (2004) states that management actually tends to create a safety management system by combining the management process and activities into one system. But how can safety management activities be designed in a systematic and scientific way? This should be done by applying certain *techniques* (Leveson, 2011; Petersen, 2003), *approaches* (Dhillon, 2010; Petersen, 2001; Wu et al., 2010), and *models* (Gower-Jones & van der Graf, 1998; Hale et al., 1997).

2.2.3 Definition of safety management system

Since 1973, the safety management system has gradually developed into a main topic for safety science (Kysor, 1973). An SMS is commonly defined as the management procedures, elements and activities that aim to improve the safety performance of and within an organisation. 'Modern SMSs could be defined as an arbitrary collection of activities that were deemed necessary actions to discharge responsibilities under the new age of the delegated responsibility of self-regulation' (Thomas, 2011, p. 3). *Safety management* means ‘a systematic control of worker performance, machine performance, and the physical environment’ (Heinrich et al., 1980, p. 4). To structure this systematic control, the *safety management system* bundles all safety management activities in an orderly manner. An SMS is a very practical concept, widely used in different industries (Table 2.1).

Table 2.1 – Safety management system definitions

Authors	*Industry*	*Definition*
Kysor, 1973		*A Safety Management System (SMS) can be defined as a planned, documented safety program that incorporates certain basic management concepts and activating elements into a well-organized safety system. The safety activity areas and supporting elements that comprise this system act and interact on one another to help achieve the desired safety level or risk level. A total safety management system consists of objects: parameters such as input, process, output, and feedback control; attributes: properties of parameters such as the external manifestation of the way in which an object is known, observed, or introduced in a process; relationships: bonds that link objects and attributes in the system process.*
Carrier, 1993	Offshore	*ADCQ's Safety Management System (SMS): a system designed to cover a broad band of safety activities and provide positive management control.*
Waring, 1996	General	*Functionalist/engineering world view: a set of documented procedures or people using such a set of procedures.* *Interpretive world view: a human activity system including control monitoring communication, operational and other elements as well as complex human factors.*
IAEA, 1999	Nuclear	*The safety management system comprises those arrangements made by the organisation for the management of safety in order to promote a strong safety culture and achieve good safety performance.*
Mitchison & Papadakis, 1999	Legislation (directive)	*A Safety Management System (SMS) is defined in the Directive (Seveso II) as including ‘the organisational structure, responsibilities, practices, procedures, processes and resources for determining and implementing the major-accident prevention policy’, in other words the system for implementing safety management.*
Edwards, 1999; Hsu, Li, & Chen, 2010	Aviation	*A safety management system is no more than a systematic and explicit approach to managing safety – just as a quality management system is a systematic and explicit approach to improving the quality of a product to meet the customer’s requirement.*
DOE	Energy	*Safety Management Systems provide a formal, organized process whereby people plan, perform, assess, and improve the safe conduct of work. The Safety Management System is institutionalized through Department of Energy (DOE) directives and contracts to establish the Department-wide safety management objective, guiding principles, and functions.*

Ivan, Malenich, & Pain, 2003	Transport	*A highway Safety Management System (SMS) is a systematic process designed to assist decision makers in selecting effective strategies to improve the efficiency and safety of the transportation system.*
ERA, 2007	Railway	*Safety management system means the organisation and arrangements established by an infrastructure manager or a railway undertaking to ensure the safe management of its operations.*
ICAO, 2007	Aviation	*A safety management system (SMS) is an organized approach to managing safety, including the necessary organisational structures, accountabilities, policies and procedures.*
Stolzer, 2008	Aviation	*A dynamic risk management system based on quality management system (QMS) principles in a structure scaled appropriately to the operational risk, applied in a safety culture environment.*
Waddington, Lafortune, & Duffey, 2009	Aviation & Nuclear	*Safety Management System (SMS) approach aimed at harmonizing, rationalizing and integrating management processes, safety culture and operational risk assessment.*
Thomas, 2011	Transport	*Modern SMS could be defined as an arbitrary collection of activities that were deemed necessary actions to discharge responsibilities under the new age of the delegated responsibility of self-regulation.*

According to the definitions in Table 2.1, apart from *safety*, *management* and *system*, several other key words characterise an SMS, such as *activity*, *approach*, *control*, *operation*, *process* and *procedure*. Although these definitions are provided in various contexts, they represent the broad meaning of an SMS and its common understanding from users. In this chapter, we will explore with which aspects and words SMS have been described in the literature.

Apart from the broad definitions coming from different industries, the concept of an SMS sometimes gives rise to confusion when compared with other similar terms. Some of these concepts are discussed below.

2.2.3.1 The concept of risk management system

As safety management focuses on managing risk, the structure of a risk management system sometimes represents a rough SMS, but actually is only a part of a complete SMS. Following Greenwood and Spadt (2004) a risk management system consists of a policy, a risk data system, and a risk system for assessing and evaluating risks. Risk not only pertains to safety but also to economics, i.e. financial risk. However, the principles are similar for any kind of risk management system (ISO, 2009). It means objects for risk management could be well beyond the scope of safety risk. At the same time, a safety management system is also more than a risk management system. There are many examples of SMSs in which a (safety) risk management system is an important component, despite the fact that some regard a safety management system a phase of risk management (Demichela et al., 2004). Safety risk management is a critical component in the SMSs proposed by the International Civil Aviation Organization (ICAO) and the Federal Aviation Administration (FAA). Hale's SMS also contains a *risk control system* as one of its two constituent components (2005). Although there are many other SMS frameworks of that do not have a risk management system as an actual component, they do identify, evaluate and control hazards, which also represent a way to manage risk.

2.2.3.2 The concept of control system

Control systems approximate the function of an SMS. Management Control Systems (MCSs) as defined by Anthony (1980) are the processes by which managers ensure that resources are obtained and used effectively and efficiently in the accomplishment of an organisation's objectives. This concept comes from systems engineering, which states that by applying control, an input can be translated into an output. Similar to a risk management system, a risk control system involves risk identification and assessment (You, 2003). 'A loss control system for an insurance classification plan has a policy holder database, a predictive apparatus and a derived actual loss ratio generator' (Zizzamia, 1999, p. 1). Working in insurance, Bird developed a loss control system and a loss control management concept. Loss control management 'provides ideas, tools and inspiration to help keep personal injuries, with the resulting human suffering and severe economic losses, to a minimum' (Bird, 1974; Bird & Loftus, 1976, p. iii). Several recent models also contain control loops, like Leveson's STAMP control loop for operating processes (2004) and the SADT technique Hale used for his SMS framework (1997). A risk control system is sometimes used for a specific engineering or management system at the worksite, where control is needed to achieve a certain reliability or safety level. Control is an important part of an organisational management system, focusing on hazards, risks and safety activities.

2.3 History of safety management systems

2.3.1 Development of safety management over time

As described above, the main purpose of safety management and its supporting system is to control risks and, by doing this, to prevent accidents. The history of SMSs therefore partly coincides with the history of accident prevention or, more generally, the history of safety science itself. As this history has been described extensively elsewhere (Swuste et al., 2010, 2011), we suffice here with a brief overview. Overall, we see two main impetuses for the commencement of safety management systems: work carried out at insurance companies and accident prevention efforts by industry.

2.3.1.1 The insurance perspective: analyse loss patterns and develop risk management

Accidents caught the attention of insurance companies as they can be costly. Insurance is a means of protection from financial loss, so researchers became interested in the analysis of loss patterns. Heinrich (1931) analysed a vast amount of industrial accident records from insurance companies and based his accident models and theories on these: the iceberg model, an accident sequence model (domino theory) and the 300-29-1 ratio injury model. After reconsidering many loss patterns, especially the causes of loss, in later versions of his book notions of organisational management and risk management are introduced (1980). Similarly, Bird (1974, 1976) also analysed insurance companies' accidents reports, and revised Heinrich's injury model ratio based on these analyses, which were then used as input for his version of loss control management. However, the connection between accidents and loss control was not yet fully matured at the beginning of the development of SMSs.

The concept of risk is a critical output of insurance studies that just demonstrates this connection. Modern risk management started in the mid-1950s, as large companies began to develop self-insurance against risks. 'Self-insurance covers the financial consequences of an adverse event or losses from an accident' (Dionne, 2013, p. 149). As mentioned previously, risk management is a constituent part of safety management systems. Derived from the financial field, it offers methods to identify, assess, and mitigate risks, and subsequently to reduce loss. Industrial safety management has benefited to a large extent from the methods and techniques used in risk analysis.

2.3.1.2 The industry perspective: prevent accidents and develop safety defences

From a company's perspective, safety means that no accidents happen in factories, plants, or projects. Accident prevention is the primary task for safety management because accidents cause not only financial loss but also reputation damage. A safety goal (e.g. zero-accidents) is much more clear-cut than any risk acceptance levels in organisational management; zero accidents simply means no accident. In order to achieve such a straightforward goal, safety defences are used to prevent accidents, which includes safety equipment, devices and many behavioural activities. Even though the concept of defences (also called barriers) has been elaborated further in several theories and models (such as the Hazard-Barrier-Target model and Reason's Swiss Cheese model) they are indeed the practical safety management devices, developed and delivered in companies before formal SMSs emerged.

Safety equipment or devices are the hardware defences that prevent or protect against any harm. Setting up 'the installation of safety devices as complete a system of mechanical safeguards as possible' could indeed prevent accidents. These basic safety appliances, checked by a safety committee in London from 1917 on, led to a reduction of accidents (Vernon, 1919, p. 51). The introduction of *system* *safety* techniques in the 1950s improved their reliability and effectiveness further. System safety is primarily concerned with engineering reliability using quantitative methods. It helps decrease failures of components and systems of machines and installations; it also reinforces safety hardware systems.

In parallel, safety behavioural activities were developed for the prevention of accidents. In the early 1900s, with the introduction of legislation for workers, companies began to pay more attention to safety management activities such as the introduction of an accident recording system, individual safety measures, i.e. personal protection equipment, and safety measures on the shop floor. For example, in 1912 DuPont started to maintain a full record of accidents and introduced basic safety training. Another example of individual safety activities is the FAA-programme for carrying out accident prevention responsibilities. It briefly describes the activities of a maintenance system, fire warning, air traffic control, flight checking and training, accident investigation and hazard identification as separate activities. All these activities are the safety defences in the aspect of *management* above.

2.3.1.3 The commencement of SMSs: merging the risk concept with safety defences

A first glimpse of safety management systems appears when risk management is applied to loss control and safety defences are developed to prevent accidents. As a matter of fact, the frequency of use of the term risk has increased significantly since the 1960s, which roughly coincides with the use of the term *safety management system* (data obtained from Google's Ngram viewer). Statistically and logically, (safety) risk plays an important part in safety management systems. As safety defences become more advanced and complicated along with the improvement of technologies, management systems are required to implement, maintain and update these. In general, risk analysis and safety defences provide management with both strategical and practical information.

2.3.2 The period 1970–1990

2.3.2.1 Accident theories as driver for the development of an SMS

Following Heinrich's accident causation sequence (1959), various accident causation and prevention theories – e.g. Haddon's 1973 energy transfer theory – were updated (Smillie & Ayoub, 1976). The general idea of cause-effect and consequence began to take shape (Nielsen, 1974). Bird's 'Management Guide to Loss Control' discusses the cause and effect sequence model (1974). In order to control hazards and prevent accidents, the concept of barriers was introduced. The term 'barrier' is one of Haddon's ten strategies of safety countermeasures (Haddon Jr., 1973). MORT (Management Oversight and Risk Tree) was developed for U.S. nuclear risk management as a safety assurance system (Johnson, 1973, 1980). Originally based on an energy transfer model, MORT extends this concept with (preventive and defensive) physical barriers that can be put in place to stop the transfer of energy.

In the same period, after Kysor (1973) had introduced the concept of an SMS, Adams (1976, 1977) proposed that accident prevention has the same function as a safety management system. He outlined a system, which is based on 'the philosophy that accidents in the workplace have their root cause in the management structure; the objectives of the organisation; how management is organised and how operations are planned and carried out' (Adams, 1977, p. 279). Later, Weaver (1980) compared and evaluated various safety management and accident prevention systems. He pointed out that cases of the early sequence model are beyond management control. As these cases are at the root of different accident causes, a series of ideas about safety management were proposed. The steps of the accident prevention model and a flowchart of the safety management process directed the causation and prevention theory towards a framework of SMS (Denton, 1980; Saari, 1984).

2.3.2.2 System safety, the socio-technical concept and the system theory in support of SMS

During the 1970–1990s, system safety techniques increasingly became a subject of safety management studies and contributed to initial efforts to establish SMSs (Collins & Dickson, 1989; Grose, 1971; Hammer, 1971; Holt, 1971; Lee et al., 1985; Pope, 1971; Weathers, 1982). System safety tools and techniques can be used to analyse, identify and display potential hazards. For instance, the International Atomic Energy Commission's General Design Criteria for Nuclear Power Plants Construction Permits (Seth, 1971), NASA's R&D operating system (Connors & Maurer, 1975), and the design phase of the Intermediate Capacity Transit System (ICTS) (Rumsey, 1980) are all applied system safety approaches despite their different safety purposes.

The socio-technical concept arose in conjunction with the first of several field projects undertaken by the Tavistock Institute in the British coal mining industry (1949). Between 1950 and 1970, the use of this concept also increased in other industries, such as the projects of 'The Shell Philosophy' and 'Coal Mining' (Trist, 1981). Socio-technical systems were then for the first time mentioned in relation to safety management as a methodology for organisational design (Robinson, 1982).

The system theory provides an SMS not only with an approach but also with mechanisms and structure. The 'Man-machine-environment-system' (MMES) was proposed in 1981 and combined with *cybernetics* used in safety actions systems, which include system analysis and preference synthesis (Kuhlmann, 1986). Kuhlmann claimed that cybernetics could clarify the elements of a system and the relationships between those elements and the environment. As a result of applying a system framework and its accompanying techniques to safety management, the development of SMSs became more practical and applicable.

2.3.2.3 Specialised organisations and legislation

In the 1970s and 1980s, three developments made safety management systems a topic of more general interest, namely 1) the increased demand for regulation in European countries; 2) official reports following major disasters and; 3) the introduction of international standards for quality management systems as a basis for SMSs (Hale et al. 1997). Kuhlmann (1986) also developed a scheme for standardised hazard protection, using three levels of enforcement namely, instrument safety law, administrative regulations and technical standards. Both Hale et al. and Kuhlmann emphasised that specialised legislation plays a pivotal role in safety management. To authorise these laws, regulations and standards, safety-related organisations and dedicated departments in government and industry were established.

To publish specific laws and regulations to improve safety management, specialised organisations are needed. At the beginning of the 1970s, a number of specialised safety organisations were set up, such as the Occupational Safety and Health Administration (OSHA) in 1970 the US, the Health and Safety Executive (HSE) in 1974 in the UK, and the World Safety Organisation (WSO) in 1975. These organisations not only published laws, regulations, and collected accidents and incidents information, but also raised awareness for safety management. These organisations provide a platform for safety professionals and update their information continuously.

The increasing awareness for safety and the occurrence of serious accidents lead to more laws, rules and regulations. In the chemical industry, after the Italian Seveso disaster in 1976, the Seveso directive (Directive 82/501/EEC) was published; the Indian Bhopal disaster (1984) resulted in the Seveso-II (Directive 96/82/EC), which was updated after the French Toulouse accident (2001). In the nuclear field, following the Three Mile Island accident (1979) and the Chernobyl disaster (1986), 'a joint protocol forming a bridge between the two existing international nuclear liability regimes was established' (NEA, 2006, p. 3). In oil and gas, after the Piper Alpha disaster (1988), the regulations for offshore safety management were improved (Singh, Jukes, Poblete, & Wittkower, 2010). To sum up, major accidents thrust the development of safety legislation forward.

A standard is defined as 'something used as a measure, norm, or model in comparative evaluation' according to the Oxford dictionary. There are international general standards, or industrial standards, issued by organisations such as ISO (general), ILO (general), HSE (general), ICAO (civil aviation), IAEA (nuclear), IChemE (chemical), IOGP (oil and gas), SPE (petroleum) and NASA (aeronautics and space travel). During this period (1970-1990) international standards for SMS were beginning to emerge. For example, in 1981, ILO published the Occupational Safety and Health Convention and Recommendation that established the principles for national policy and action (ILO, 1985). In 1987, ISO published a quality management system standard, which was built on the principles of a company QSM and formed the foundation for future SMS standards. Similarly, OHSA and HSE published a series of industrial regulations. All of them contributed to the foundation of international structural safety standards, which were developed during the next decade.

2.3.2.4 SMSs and applications

Major accidents and standards started to draw companies' attention to SMSs in a global context (Bowonder, 1987; Mcnutt Jr. & Gross, 1989; Tombs, 1988). Since the mid-1970s, Australia put efforts into developing EH&S (environment, health and safety) management and initiatives, such as 'contractor management, quarantine procedures, incident and injury reporting and investigation etc.' (Kegg, 1998, p. 441). What followed was a shift from individual initiatives to a systematic approach through the development of a safety management system (Kegg, 1998). Especially towards the end of the 1980s, some large companies (e.g. SHELL, ExxonMobil, DSM, etc.) established their first versions of an SMS. They put their safety management activities into a kind of management framework as principles or elements of the safety guidelines for the whole corporation. From then on, safety management systems are widely used in companies to control their risks.

2.3.2.5 Audit tools

Internal audits aim to review and improve an SMS, while external audits aim to assess legal, regulatory, or certificate compliance (ISO, 2011). Audit tools and the assessment of SMSs are studied along with safety management theories. Based on loss control theory, the 'International Safety Rating System (ISRS)' audit tool was developed in 1978. In order to establish the International Safety Academy (ISA), Bird put forward a management control system with four functions of management: planning, organising, leading and control. This is based on industrial hygiene, loss control, risk management and training of specialists (Bird, 1974; DNV, 2012, 2013). This audit system was then systematically applied to different industries for assessing an SMS.

Under the banner of self-regulation, companies gradually became responsible for devising, installing and monitoring safety management systems (Feyer & Williamson, 1998, p. 134; Hale & Hovden, 1998). By applying an audit system, the effectiveness of an SMS could be further improved (Ashburn & MacDonald, 1987; Wallace, 1990). To summarise, in this period audit tools with assessment methods were developed and used both nationally and internationally (Conrad, 1984; Eisner and Leger, 1988).

2.3.3 Post 1990

2.3.3.1 Multi-disciplinary techniques and models

After the 1990s, SMSs became more sophisticated and multi-disciplinary by making use of an increasing number of new techniques, audit tools and standards. These new techniques helped to expand the study of safety management modelling, whereby the models became comprehensive systems rather than just reflecting accident sequences. In particular, two kinds of models were applied: the *accident* model and the *organisational* model. As the study of safety management originally is concerned with the causes of accidents and incidents as well as their prevention, the causation model became more mature; the safety management system is part of an organisational management system, the essence of which is the organisation model.

Thus, modelling SMSs became an important topic with many issues involved. Sometimes, it pertains to more than one model, theory or method. All these models are related to the SMSs at any level, i.e. the theoretical, practical, and standard level. Reason studied complex systems and developed a safety causation and control model involving human factors and feedback loops (Glendon, 1995; Reason, 1990a, 1995a). Another causal model, the Bowtie model, combined with BBNs (Bayesian Belief Nets), were used to model complex systems (Ale et al., 2006; Ale et al., 2009). Furthermore, hybrid causal methodologies incorporating physical & social failure were also extended to management activities and models (Groth et al., 2010; Mohaghegh et al., 2009, 2012; Mohaghegh & Mosleh, 2009). These and other studies on causal models and techniques reflect the current approach to safety management.

Vice versa, multi-disciplinary subjects also provide methodologies and tools for the modelling of risk and management. AcciMap (Svedung & Rasmussen, 2002), Storybuilder (Bellamy et al., 2007a), BowtieXP (Aneziris et al., 2008; Lisbona & Wardman, 2010), and Phonix (Ekanem & Mosleh, 2014; Ekanem et al., 2016) are graphical tools that systematically analyse industrial accidents and hazards. Furthermore, system dynamics as a system engineering technique was applied to SMSs in order to model dynamic factors and their relations (Cook & Rasmussen, 2005; Marais, Saleh, & Leveson, 2006; Yang & Sun, 2010). Others applied the 'systems concept' to safety management and resilience control (Belcastro & Jacobson, 2010; Leveson, 2011b). Others applied a system control structure to the model of an SMS (Hale et al., 1997; Waring, 1996). Typically, these tools and models aim to control safety and its management.

Different contexts of SMSs also influence audits or assessment approaches differently. In this period, audit tools were widely used to evaluate SMSs (Bellamy, Wright, & Hurst, 1993; D. Cooper, 1998; Glendon, 1995; Hurst, Hankin, Bellamy, & Wright, 1994; Hurst & Ratcliffe, 1994; Nivolianitou & Papazoglou, 1998; Watson, 1993). There also appeared a number of audit tools only concerned with occupational health and safety (OHS) systems (Emmett & Hickling, 1995; Gay & New, 1999; Lindsay, 1992; Redinger & Levine, 1998). As these multi-disciplinary techniques and models provide methods to calculate potential risks, risk management and assessment is approached here more quantitatively.

2.3.3.2 Studies of management factors

During the second period (1970 – 1990), the man-machine-environment system was introduced and traditional safety management factors or risk influencing factors were developed based on these three aspects. After this period, psychological, sociological and organisational factors that influence risks or safety management performance start to appear (Bellamy et al., 2008; Bottani, et al., 2009; Makin and Winder, 2009; Øien, 2001; Skogdalen and Vinnem, 2011). Socio-technical factors can be mapped onto the hierarchical system developed by Rasmussen (1997). Having analysed the latent failures in defences, Reason (1995b) emphasised the importance of organisational factors and the need to incorporate these in SMSs and their assessment (Davoudian et al., 1994a, 1994b; Embrey, 1992). Especially human factors and behaviour in SMS became popular topics (Bellamy, 1994; Ranney, 1994; McCafferty, 1995). New methods and techniques also help to model human factors in SMSs (Mearns et al., 2003; Khan et al., 2006; Baranzini and Christou, 2010; Koornneef et al., 2010). Recently, Yang (2017) reviewed the current frameworks for (safety) risk influencing factors and the methods used. Studies of those factors and their influence on risks and SMSs can improve safety performance further.

2.2.3.3 Standards

Compared to the legislation developed during the second period, an increasing number of international general standards and guidelines have been published; Table 2.2 summarises some. Actually, different industrial sectors have their own specific standards and regulations, which are published by local and national governments, standard organisations and industrial associations. Although the standards listed in the table could be applied to different industries, the application of an SMS still involves compliance with specific industry safety laws and regulations. Also, these uniform standards are recognised and applied globally.

Table 2.2 – Standards for general safety management systems

Organisation	*Industrial sector*	*Name/Year*	*Aim for*
ISO	General	ISO 45001/2018	Occupational health and safety management systems
	General	ISO 9001/1987, 2008, 2015	Quality management systems
	General	ISO 14001/1992, 1995, 1996, 2004, 2015	Environmental management systems

	General	ISO 31000/2009	Risk management
EU (European union)	Chemical industry (also other industries)	Seveso Directive (Directive 82/501/EEC)/1982 Seveso II (Directive 96/82/EC)/1996 Seveso III (Directive 2012/18/EU)/2012	Control of major-accident hazards involving dangerous substances
	General	(Directive 89/391/EEC)/1996	Guidance on risk assessment at work
BS (BSI Group, British Standard)	General	BS 5750/1979	Quality management systems
	General	BS 7750/1994	Specification for environmental management systems
	General	BS 8800/1996, 2004	Occupational health and safety management systems
	General	BS OHSAS 18001/2007	Occupational health and safety management systems
OSHA (United States)	General	PART 1910 (Standards–29CFR)/since 2001	Occupational safety and health standards

2.3.4 Reviews over time

During the development of safety management and SMSs, literature reviews describe this topic from different angles. We simply group these into three levels: theoretical level, practical level, and standard level (Figure 2.2 & Table 2.3).

The theoretical level pertains to the justification, origin and purpose of SMSs. The theories reflect the researchers' perceptions of safety management. The theories and theoretical models support practical SMSs because the basis of an SMS comprises safety, management and system, each having its own theoretical roots. The safety aspect deals with unsafe outcomes and their causes; management in this respect pertains to organisational safety activities; the system provides the framework and the logic for modelling. However, the application of an SMS resides at the practical level.

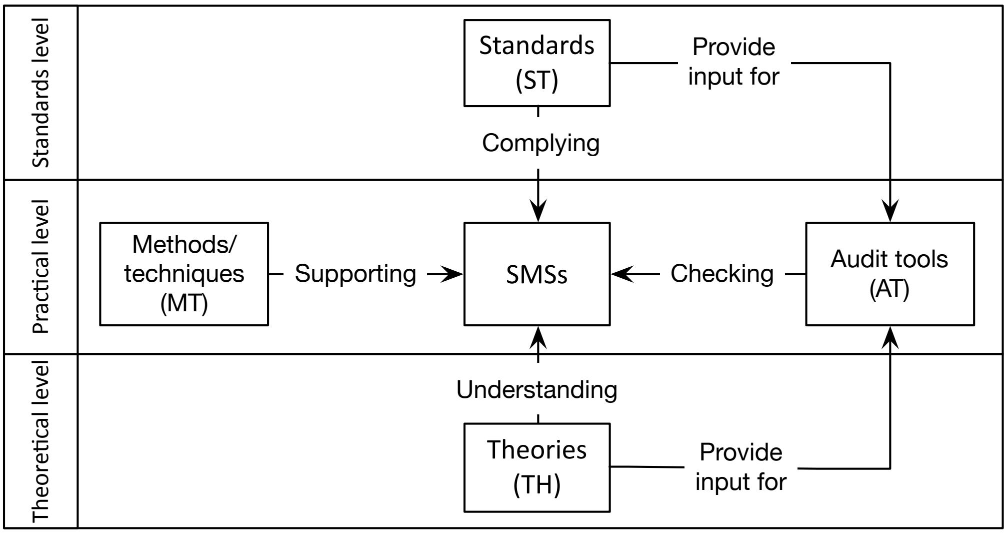


Figure 2.2 – Issues related to safety management

At the practical level, SMSs are more complex. Some are specific safety management systems, operated within a company or a particular plant. They have different functions, such as collecting information, maintaining (technical) systems or analysing risks. Some general SMSs, especially the SMS framework of large international companies, are also used at the practical level. The advantage is that these general SMSs can be applied in different contexts like in subsidiaries, different regions, and different types of industry. The SMSs at the practical level thus concern both generic SMSs and specific SMSs.

Methods, techniques and audit tools are also developed at the practical level and applied to SMSs. These methods and techniques mostly support the implementation of SMSs. The audit tools are based on models of SMSs to assess the effectiveness or quality of an SMS. All in all, an overview of methods, techniques and audit tools provides insight into approaches to SMSs.

Table 2.3 – Overview of literature relating to SMSs

Group	*Issue*	*Title*	*Contents*	*Reference*
Theoretical Level	TH	*Accident causation theories: A simulation approach*	This paper reviews early age accident causation theories since 1919, including pure chance, biased liability, unequal initial liability, accident proneness, unconscious motivation, adjustment-stress, goals-freedom alertness, domino, epidemiological, specific variables and modelling.	Smillie & Ayoub, 1976
		The deviation concept in occupational accident control– I	This paper reviews the causation and control theories, models, and terms by the deviation concept and compares the phases of different process models of accidents.	Kjellén, 1984
		Models of accident causation and their application: Review and reappraisal	54 different accident causation models and sixteen methods of application are reviewed.	Lehto & Salvendy, 1991
		Accident prevention. Presentation of a model placing emphasis on human, structural and cultural factors	This paper systematically reviews safety interventions for accident prevention. Though it is not related to SMS directly, it shows the behaviour, physical factors of accidents and helps to discover the fundamental theories of SMSs and their influencing factors.	Lund & Aarø, 2004
		Highlights from the literature on accident causation and system safety: Review of major ideas, recent contributions, and challenges	This paper's angle is HRO (High Reliability Organising) theory, discusses literature on system safety and accident causation.	Saleh, Marais, Bakolas, & Cowlagi, 2010
		Safety metaphors and theories, a review of the occupational safety literature of the US, UK and The Netherlands, until the first part of the 20th century	This paper reviews occupational safety theories of three countries at the very early stage of safety science development. Some metaphors are used to show the investigation of accidents and the activities of safety management, for example, Heinrich's iceberg model.	Swuste et al., 2010
		Models of Causation: Safety	This paper summarises three kinds of models, which represent three distinct phases from 1920s onwards. They are simple linear models (Heinrich's Domino Theory, and Bird and Germain's Loss Causation Model), complex linear models (energy-damage models, time sequence models, epidemiological models and systemic models) and complex non-linear models (STAMP, FRAM and complexity and accident modelling).	Toft, Dell, Klockner, & Hutton, 2012
		Occupational injury and accident research: A comprehensive review	This paper reviews the five stages' development of accident causation theory: accident proneness, domino theories, injury epidemiology, system models, factors affecting injury; and briefly describes injury mechanism models and interventions.	Khanzode, Maiti, & Ray, 2012
		Analyses of systems theory for construction accident prevention with specific reference to OSHA accident reports	This paper reviews and classifies the studies of accident risks, based on Domino theory and OSHA data description.	Chi & Han, 2013
		Occupational safety theories, models and metaphors in the three decades since World War II, in the United States, Britain and the Netherlands: A literature review	After the 2010 review paper mentioned here above, this paper continues with describing the occupational safety theories after World War II and during the subsequent three decades, 'The hazard-barrier-target model' and the system method such as 'fault tree' were applied.	Swuste, van Gulijk, Zwaard, & Oostendorp, 2014
		A review of models relevant to road safety	This paper reviews safety related models and frameworks; and develops seven types of models.	Hughes, Newstead, Anund, Shu, & Falkmer, 2015

Practical Level	MT	*Rating accident models and investigation methodologies*	This report reviews fourteen accident models and seventeen different accident investigation methodologies in the selected government agencies.	Benner Jr, 1985
		Fault tree analysis, methods, and applications–*A review*	This paper reviews fault tree construction, application and evaluation including qualitative and quantitative evaluation.	Lee et al., 1985
		A causal model of organisational performance and change	This paper summarises the studies for the dimensions of the model, which is built for organisational performance and changes. It provides ten dimensions including leadership, culture, structure, management practices, etc.	Burke & Litwin, 1992
		Safety reviews and their timing	This paper aims to describe the approach of safety reviews but at the same time it summaries and compares some methodologies used in this field (e.g. CHAIR, CHA, PCA, PHA, HAZOP, FEMA, FTA, ETA, What if, PSMSA, PSAudit, Task, HAEA and QRA).	James & Wells, 1994
		Management and culture: the third age of safety. A review of organisational aspects of safety, health and environment	This paper reviews safety management related researches and their institutes or organisations.	Hale & Hovden, 1998
		Towards an evaluation of accident investigation methods in terms of their alignment with accident causation models	This paper reviews a series of accident investigation methods within accident causation models. It lists FTA, MORT, MES, CTM, OARU, AEB, SCAT, TRIPOD, ISIM, NSB, WAIT, HSG245, 3CA.	Katsakiori, Sakellaropoulos, & Manatakis, 2009
		A review: Advancement in probabilistic safety assessment and living probabilistic safety assessment	This paper summarises the methods of probabilistic safety assessment and living probabilistic safety assessment methods – ESSM (Essential System Status Monitor), DEM (Dynamic Risk Monitor), FTA, ETA, Markov analysis and Risk spectrum software.	Zubair, Zhang, & Aamir, 2010
		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	This paper specifically reviews methodologies used for risk analysis. Authors takes the angle of risk management and its technical uses.	Marhavilas, Koulouriotis, & Gemeni, 2011
		Safety management for heavy vehicle transport: A review of the literature	This paper reviews safety management interventions and measurements. It distinguishes three groups of relationships between the organizational characteristics and safety results.	Mooren, Grzebieta, Williamson, Olivier, & Friswell, 2014
		Risky systems versus risky people: To what extent do risk assessment methods consider the systems approach to accident causation? A review of the literature	This paper reviews the approaches to safety management, especially the methods and tools used for risk assessment. Aligned with Rasmussen's seven tenets., most qualitative and quantitative methods are discussed.	Dallat, Salmon, & Goode, 2016
		Risk influence frameworks for activity-related risk analysis during operation: A literature review	This paper reviews recent risk influencing frameworks explicitly. With models and methods, risk or safety influencing factors are analyzed. Most of them are project-based, such as MACHINE, SAM, I-RISK, ORIM and so on.	Yang, Haugen, & Li, 2017
	AT	*Safety management systems: Audit tools and reliability of auditing*	This paper reviews D&S, CHASE (CHASE-II), ISRS, SafetyMap and the MISHA audit method and presents a number of case studies.	Kuusisto, 2000

		Are organisations too complex with respect to technical risk assessment and current safety auditing?	This paper discusses how organisational issues affect safety auditing and reviews main theories and summarises the multi-dimensional perspective.	Le Coze, 2005
		Measurement properties of occupational health and safety management audits: a systematic literature search and traditional literature synthesis	This paper reviews audit tools on aspects of their conceptual basis, items and output. It contains descriptions of some international audit tools (e.g. D&S, ISRS, CHASE, AIHA ISO9001, SEM, AIHA universal OHSMS, Canadian Pulp and paper, MISHA and Construction Safety Index).	Robson & Bigelow, 2010
		Review of SMS Audit Techniques and Methods- Final Report	This VTT report gives specific information about audit tools used in recent years. It reviews a number of management systems of different industries and audit tools from different organisations.	Peltonen, 2013
	SMSs	*A Systematic Review of the Effectiveness of Safety Management Systems*	This paper reviews 37 safety management studies. However, not all of them are SMSs; most of them are dedicated studies and conducted in Asia, Australia and Europe.	Thomas, 2011
		Safety management systems from Three Mile Island to Piper Alpha, a review in English and Dutch literature for the period 1979 to 1988	This paper reviews the theories, metaphors and models in safety management during the period between 1979 and 1988. Especially, this paper shows the use of systems thinking in the development of safety management.	Swuste, Groeneweg, van Gulijk, Zwaard, & Lemkowitz, 2017
Standard Level	ST	*Occupational safety and health systems: a three-country comparison*	This paper reviews the OSHSs in Switzerland, the UK and the US based on legislation in different historical, cultural, economic and social terms.	Singleton, 1983
		Occupational Health and Safety Management Systems	This paper compares 24 national/state OHSMSs (standards) to a universal international OHSMS.	Dalrymple, 1998
		Safety management systems under Seveso II: Implementation and assessment	This paper reviews some safety performance measurements and audits for companies, approaches and some questions in this field. It also illustrates the weight of SMS elements in a different rating system.	Mitchison & Papadakis, 1999
		Regulating systematic occupational health and safety management: comparing the Norwegian and Australian experience	This paper reviews OHS-management systems in Norway and Australia, e.g. “the Scandinavian model”, “SafetyMAP in Victoria” and compares their implementation in the two countries.	Saksvik & Quinlan, 2003
		The effectiveness of occupational health and safety management system interventions: A systematic review	To understand their impact, this paper systematically reviews OHSMSs excluding those systems, which have no accompanying results for outcomes.	Robson et al., 2007

Safety management standards are the guidelines for SMSs published by the relevant authorities. They consist of both generic and industry-specific standards. Issues addressed in the literature are whether these standards are integrated into companies' management systems, whether the companies comply with certain standards and what the effectiveness of these standards is. To some extent, the standards form the basic reference for SMSs of small or medium-sized companies.

In this section, the literature reviewed roughly covers following issues: theories (TH), standards (ST), methods/techniques (MT), audit tool (AT), and SMSs. This overview also shows the historical development of safety management systems. In the beginning, accident theories, methods and techniques were applied most often. Then, standards and audit tools came into the picture. Nowadays, the systemic approach to safety management and the models studying the factors influencing safety or risk are garnering more research effort. However, the SMSs were reviewed from multi-aspects, which is also the aim of this chapter.

2.4 SMS modelling

2.4.1 Categories of SMS models

As mentioned previously, SMSs are essentially driven by accidents and incidents and the ways to prevent these. With regard to accident or incident analysis or investigation, there are *event models* that depict accident causation mechanisms and that could be used to develop accident scenarios with. These models can be extended further by the insertion of barriers. The term *barrier* comes from Haddon's ten strategies, and they can function as both hardware (physical) and behavioural (involving human action) defences. Barriers are used to prevent accidents and incidents or protect from unwanted consequences. However, event models and barriers are not the full story behind SMSs. *Management system models* are required to explain how to manage safety and how to control risks through the provision of barriers. The management of safety barriers is critical in an SMS, as safety barriers directly prevent unwanted events or mitigate the risk. Consequently, the risk is affected by management's safety performance; i.e. safety management controls the events related to the risk.

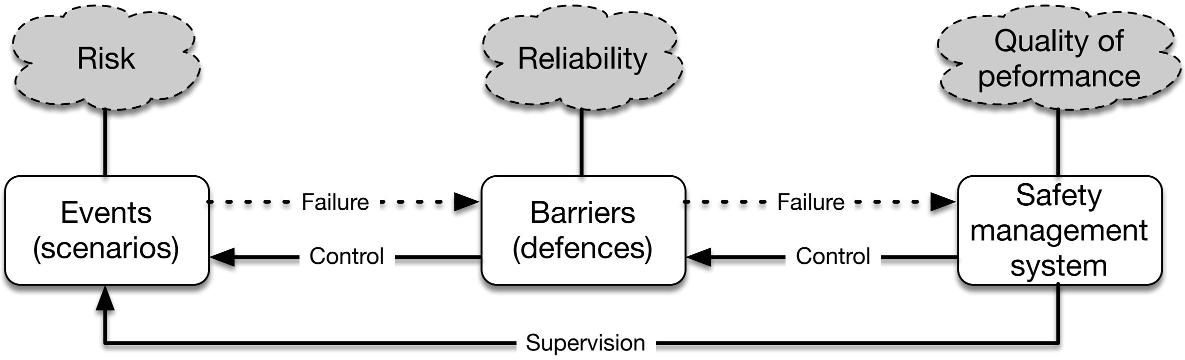


Figure 2.3 – The relation between scenarios, barriers and management

Figure 2.3 shows the relationship between scenarios, barriers and safety management and also represents the development of models to safety management. According to the definition of a model, the models for an SMS should answer questions about safety management processes. Event models provide accident scenarios, which illustrate the relationship between causes and consequences. In this group of models, the probabilistic analysis of events and consequences determines the risk of the hazards. If barriers are inserted to prevent unwanted events or harm, the extended accidents model emerges. Barriers have a risk control function, which is directly connected to the management system. The extensiveness and performance of barriers are determined by the safety management delivery processes. The management delivery processes are described in the SMS. Therefore, a complete model for an SMS should contain an events model, barriers and the management system. Accordingly, three categories of models of safety management can be identified. Their input and output are as follows.

1. **Events**: accident models and theories;

   The input is threats or hazards;
   The output is a risk inventory.

2. Events + **Barriers**: the extension of accident models;

   The inputs are risks;
   The outputs are barrier functions and risks.

3. Events + Barriers + **Management**: the models deliver management efforts;

   The inputs are barriers;
   The output is safety performance.

2.4.2 Events – accident theories and models

Accident models describe causes of accidents and subsequent events and help to develop accident scenarios describing particular risks. The identification of accident scenarios is important for efficient and professional safety management. 'Accident models affect the way people think about safety, how they identify and analyse risk factors and how they measure performance' (Hovden et al., 2010, p. 955). Although accident and risk are considered distinct topics, the study of accidents actually involves research into risks. Kjellen (2000) classified the concept of an accident into four aspects:

- Damage/loss: includes injuries and fatalities, material- and economic losses, reputation, etc.;
- Incidents: subdivided into type (fall, slip, explosion, etc.) and agency (machine, vehicle, tool, etc.);
- Hazardous conditions: covers defective tools, unsafe design, housekeeping, etc.;
- Unsafe acts: covers errors and omissions.

These categories imply that even if no damage or loss would occur, incidents, hazards and/or unsafe acts still remain topics for accident research. Table 2.4 shows that the literature mainly emphasises either one particular kind or part of accidents.

The accident models not only reveal the causes of accidents but also provide prevention control in the form of defences. The aim of analysing accidents or injuries is to take lessons from the past so as to achieve state-of-the-art safety management, which explains the relationship between those models and safety management. The history of accident models can be traced back to the 1920s and the models are grouped according to different opinions (Khanzode et al., 2012; Lehto and Salvendy, 1991; Toft et al., 2012). To classify accident models in terms of their contents, this section uses four mainstream groups (Table 2.4): (1) Simple sequence & complex sequence; (2) Epidemiology & energy transfer; (3) Simple system & social-technical system & complex system; (4) Human factor & behaviour & decision making. These categories are discussed below.

2.4.2.1 Simple sequence and complex sequence

Sequential models belong to the early structural accident causation models while the simple sequence model is a metaphor for accidents, described as 'the culmination of a series of events or circumstance' (Toft et al., 2012, p. 3). These simple sequence models are also called linear models. The Domino Model, a typical simple sequence model, originally represents ideas proposed by Heinrich (1931). It distinguishes five stages or factors in the accident sequence, namely (1) Ancestry and social environment (which means undesirable traits of character); (2) Fault of person (which means inherited or acquired faults); (3) Unsafe act and/or mechanical or physical hazard; (4) Accident and; (5) Injury (Heinrich et al., 1980, pp. 22-23). This popular model became the framework for later updated models. With the discovery that inherited characteristics are not useful causal events, Bird proposed the loss control theory by updating the Domino Model to include: (1) Lack of control; (2) Basic causes; (3)

Immediate cause; (4) Accident; (5) Injury/damage (Bird, 1974). Lack of control is concerned with management and is an improvement of the sequence models because ‘a function of professional management is optimised through five established steps that systematically produce the desired result’ (Heinrich et al., 1980, p. 24). This change also shows safety management emphasises the performance of organisational activities rather than finding the inherited shortcomings of humans.

Adams (1976) modified the Domino model that ‘retains the concept of operational error and introduces a concept of tactical error’, while Weaver (1980) expanded this causal chain by locating and defining the operational error. Besides, Heinrich’s book also introduced the *stair step cause and effect* sequence. This sequence model defined the acceptable upper and lower limits and showed step by step how things deviate and cause loss (Heinrich et al., 1980). Borys (2001) introduced the generalised time sequence model, which depicts a simple sequence while structuring the events into a time line. For decades, the simple sequence models have been discussed extensively and provide the foundation for complex theories.

Reason’s model, which gained significant popularity after 1990, forms a significant point of departure in the development from single to complex sequence models. The Swiss Cheese model reflects a simple sequence metaphor: an accident is the failure of defences aligned simultaneously in the sequence. Firstly, Reason’s model shows ‘the relationship between the various human contributions to accidents and the basic elements of production’ (Reason, 1990a, p. 479). The sequence encompasses fallible decisions, line management deficiencies, psychological precursors, unsafe acts and accidents. Secondly, he established ‘actual and potential feedback loops and indicators associated with each of the basic elements of production’ (Reason, 1990a, p. 479). Thirdly, his organisational accident causation model shows that the organisation, workplace, personal or team factors contribute to the occurrence of accidents (the latent failure path), which also illustrates that management decisions and organisational processes can be defences or barriers to prevent accidents (Reason, 1995a, 1995b).

Later studies using the Bowtie model, which can be considered an extension of the event sequence model, focussed on the relations between multiple causes and consequences. The Bowtie model ‘allows chains of cause-effect diagrams to be built with a specification of the barriers which can prevent passage from each cause to its effect’ (Hale et al., 2004, p. 612). The Bowtie model provides an approach for building accident scenarios; that is, causes, followed by a (potentially) large variety of critical events, one central event, resulting in multiple consequences (Hollnagel, 2008; Markowski, Mannan et al., 2009). Furthermore, the model provides a control mechanism in the form of barriers placed before unwanted events. Finally, the model connects barriers to (the) management (system) that has to control these barriers. The complex causal Bowtie model is more than just a causation model based on linear sequence thinking; it is associated with accident causation, prevention, control and management issues.

2.4.2.2 Epidemiology and energy transfer

Khanzode et al. (2012) put forward that injury epidemiology theory has a special feature, namely uncontrolled energy as immediate predecessor of accidents. Accidents could therefore also be considered an epidemic phenomenon (Heinrich et al., 1980). For example, Gordon (1949) analysed epidemic data of various areas in the US. He summarised the nature of injuries and identified the principal causes of death. And Suchman’s model described epidemiology as predisposition characteristics, situational characteristics, accident conditions, and accidents effects (cited in Heinrich et al., 1980). Haddon (1968, 1972) studied changing approaches to epidemiology and built the Haddon matrix. The columns consist of human (or host), agent, environment; the rows include pre-event, event and post-event. Its columns are often subdivided into physical and sociocultural factors (Phillips, 1970). Finally, Saari et al. suggested that epidemiology is introduced into the study of accident prevention with the following three aims: ‘description of the distribution and rate of accidents in human populations; identification of the etiological factors; provision of the data essential for the planning, implementation and evaluation of services' (Saari et al., 1986, p. 300).

Saari et al. (1986) also defined an accident as a series of consecutive events, always triggered by energy. His model consists of four phases, namely, the normal phase (work process is under control), the preceding phase (control is lost during the normal phase), the contact phase (injuring factors release harmful energy) and the injury phase (injury or harm inflicted). In Haddon's theory and other updated models, the agent (e.g. a car, a piece of machinery, a knife, etc.) represents the energy. The energy transfer theory assumes that all hazards involve energy whereby an unexpected energy transfer or release causes the actual accidents.

Gibson (1961) was the first one to propose the energy transfer concept. This concept also refers to the energy damage concept, which focuses on the need for energy to be present for any injury to occur (Borys, 2001). The unexpected energy derives from a destructive energy source or is caused by a lack of critical energy need (Heinrich et al., 1980). Johnson (1973) regards the energy transfer theory as a kind of sequential model. He combined the barrier concept with energy transfer and built the model 'energy and barrier tree' in the form we know as MORT. In this model, the barrier, as injury control mechanism, plays the prevention role that cuts off the unwanted energy transfer. Viner (1991) built an energy damage model to explain that a failure of the hazard control mechanism is equivalent to the loss of control of energy. His model introduced a space transfer mechanism, which brings the energy and the remote recipient together, whereby the recipient boundary is 'the surface that is exposed and susceptible to the energy' (Toft et al., 2012, p. 8). In summary, the epidemiology and energy transfer theory imply that a vulnerable target should be isolated from a harmful energy source (hazard).

2.4.2.3 Simple system and complex system

The simple systems theory of safety has different emphases: some consider the system objectives, some use the system control concept with consideration for its safety functions, others apply engineering techniques to management control. Firenze's system model (1971) is a man-machine system, composed of the physical equipment, the men who perform functions using the equipment, and the environment where the process takes place. The variables of this system are called 'stressors', which provide information for decision making, since they could lead from risk to accidents (cited in Heinrich et al., 1980; Wiegmann and Shappell, 2012). Rouse's (1981) human-computer interaction in the control of dynamic systems not only provides the structure of a dynamic system, i.e. with feedback loops, it also models the human factors comparably into interactive systems. Kuhlmann (1986) introduced the man-machine-environment system (MMES) in which complex technical systems and interdisciplinary safety tasks are modelled at local, regional and global effect levels. He also emphasises the control loop as an important of a (cybernetic) system. This circle loop consists of a controller, a controlled system and a monitoring device. Waring (1996) in particular explained the system concept in his book on safety management systems. His control paradigm shows the input, process and controller and also specifies Kuhlmann's loop model by applying it to offshore safety management. In the following year, Hale (1997) proposed to use SADT (Structured Analysis and Design Technique) for modelling a safety management system. SADT not only models input and output, but also adds criteria to the control processes, which determine whether a safety activity is successful. Furthermore, resources (nowadays called 'mechanisms'), as part of SADT, include both hardware and people. Based on the systems concept and modelling method, Hale's safety management system combines a framework (SADT) and safety functional logic.

The complex systems theory involves different views and approaches for preventing accidents, controlling risks and also improving safety performance. Leveson (2002) reckons that along with the fast pace of technological change and the changing nature of accidents, the system is becoming increasingly more complex by combining dynamics complexity with decomposition complexity and non-linear complexity. Based on the systems theory and socio-technical system theory, the System-

Theoretic Accident Model and Processes (STAMP) enforce safety constraints on system behaviour (Leveson, 2011). This structure follows Rasmussen's hierarchy model whereby the controllers use a process model with control actions and feedback loops (Leveson, 2004; Leveson et al., 2012). This model is used both for root cause analysis and for the dynamic accident process by applying system dynamics.

2.4.2.4 Human factors, behaviour and decision-making

Since Surry (1969, p. 17) wrote that 'pure accident research declined after 1940 and the study of performance influencing factors has flourished since' (cited in Toft et al., 2012, p. 2), we hardly separate human factors, behavioural or psychological factors and decision-making from actual accident causes. The accident proneness theory, which is commonly named as one of the earliest theories in the history of safety science, primarily shows that a personal trait is an important cause of accidents (Khanzode et al., 2012).

Greenwood and Woods (1919) tested three hypotheses regarding the occurrence of accidents: pure chance, true contagion (an individual who suffers one accident by chance may in consequence have his/her liability to accidents increased or decreased), and apparent contagion (some workers are from the beginning more likely to suffer accidents than others). They conclude that a varying individual susceptibility to accidents exists and that this individual trait can determine the distribution of accidents. Factors that underlie such accident proneness, are identified by James (1950, p. 772) as 'habits and skills, physical characteristics, psychomotor characteristics, mental characteristics and attitudes, and age and experience'. Statistical methods are often used to identify accident proneness at an early stage.

Until the control and modelling of behavioural factors became common practice, studies of the hypotheses of proneness shifted to systematic human factor studies, because efficient defendants are better able to prevent accidents than victims (James and Dickinson, 1950). Kjellén (1984) stated that the human factor theory concerns the probability of human errors that influence equipment, environment and task structure. Reason (1990b) showed underlying causes, intensified psychological research on error and behavioural explanations of error, and discussed approaches to decision-making and problem solving. He established a now popular organisational accident causation model, with performance shaping factors, that is, human factors. Gradually, the notion that human factors are not only individual causes but an integrated part of accident control, is becoming commonplace (Bellamy, 1994; Leonard et al., 2004; Maurino et al., 1995).

For in-depth research on human factors, behaviour-based safety (BBS) management became increasingly popular after 1990. Behaviour-based safety is more likely to be an important strategy of a safety management system rather than a causal factor (Fleming and Lardner, 2002; Nascimento et al., 2010; Salem et al., 2007). From this point of view behaviour research is more a by-product of major accident causation theories and in line with Rasmussen's observation: 'the convergence of human science paradigms toward models in terms of behaviour-shaping work features subjective performance criteria' (Rasmussen, 1997, p. 201).

The Surry model is a decision model, which shows the whole advance process of hazard and injury/damage: perception, cognitive processes and physiological response (cited in Heinrich et al., 1980). It illustrates, within a man plus an environment system, how decisions take shape to release danger. Similarly, the multinational vulnerability model applies the decision tree to get insight into the process underlying an accident in the chemical industry (Mcnutt and Gross, 1989). Since decision models address judgement, choice, and inference (Lehto and Salvendy, 1991), a simple decision model always contains yes/no questions, followed by a choice using a certain kind of (decision tree) operator and then predicts the result. As decision making is one important trigger of incidents, any behaviour or action will affect the safety decision-making in a logical way (Schröder et al., 2007). At present, more systematic methods are applied such as system dynamics, which could provide decision making based on the effect of organisational factors on safety.

Table 2.4 – Accident theories and models

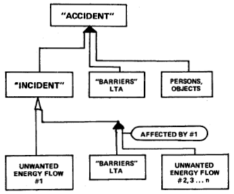
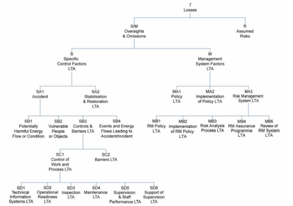
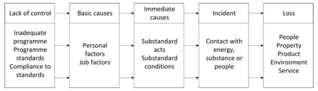
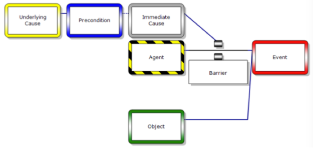
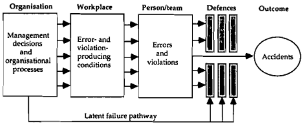
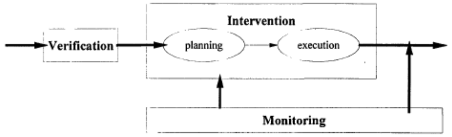
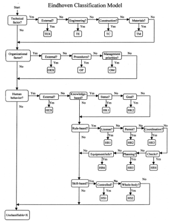
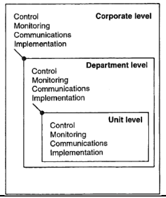
Theory group	*Kjellen's accident concept*	*Industry field*	*Theory or model name*	*Model*	*Method*	*Description of contents*	*Reference*
Simple sequence	Loss	General	Accident sequence model	Y	QL, QT	Develop the ideas, tools and inspiration to keep person from injuries and economic losses	Bird, 1974; Bird & Loftus, 1976; Wang, Feng, Gao, & Zheng, 1998
		Insurance	Injury level triangle	Y	QL, QT	Minimise loss and build new loss concept and causes analysis	(Sheriff, 1980)
	Incident	General (Insurance)	Domino sequence model	Y	QL, QT	Model of accidents causes and management factors	Heinrich, 1931; Heinrich et al., 1980
		General	Accident causation and the management system	Y	QL	Explore the causes to management philosophy	Adams, 1976, 1977
	Hazard	General	Use of cause-consequence charts in practical system analysis	Y	QL, QT	Outline the main steps of cause-consequence analysis based on the concept of critical events	Nielsen, 1974
		Offshore	The ILCI loss causation model	Y	QL	Provide the audit system management elements	Smith, 1995
	Unsafe act	General	Updated Domino Models	Y	QL	Human characteristics importance in causation model	Weaver, 1973, 1980, 2006
		General	Sequential model of accident occurrence	N	QL, QT	A behaviour-based safety management program focussed on specific work	Lingard & Rowlinson, 1997
& Complex sequence	Incident	General	The complex pattern of the Zeebrugge accident	Y	QL	Model dynamic events to analyze human factor and behaviour	Rasmussen, 1997
		General (Shell)	Tripod BETA incident analysis	Y	QL	Tripod BETA tree describes the incident mechanism in terms of hazards, targets and events	Gower-Jones & van der Graf, 1998; Turksema, Postma, & HAAN, 2007
		Construction	General model of accident causation; Pattern of Construction accident causation	Y	QL, QT	Identify distal factors and proximal factors	Suraji, Duff, & Peckitt, 2001
		Aviation	Schematic of the causal model	Y	QL, QT	Find causes of incidents and accidents and quantify of the probability	Ale et al., 2006
		General	Combined influence framework	Y	QL, QT	Investigate and understand construction accidents causes	Hale, Walker, Walters, & Bolt, 2012
		General	Accident sequence (phenomenology) and causal basis (etiology) of accidents	Y	QL, QT	Based on sequence events model for near-miss management	Gnoni & Saleh, 2017

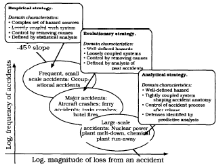
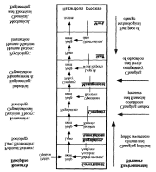
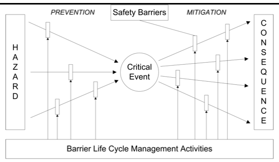
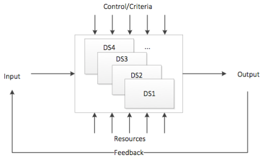
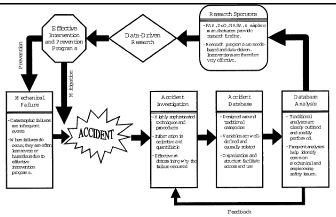
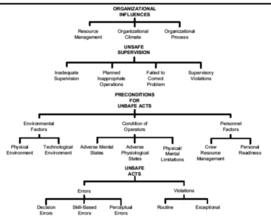
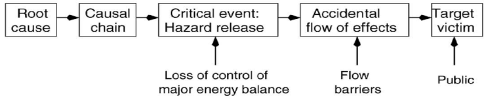
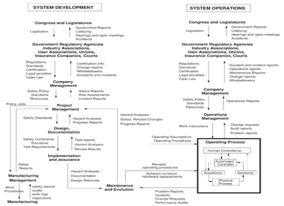
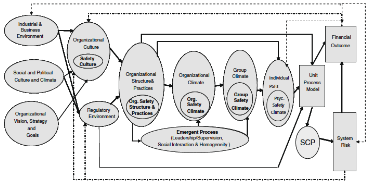
	Hazard	Healthcare	Reason’s Swiss cheese model	Y	QL, QT	Apply Reason’s model following analysis and comparison	Reason, 1990a, 1995a, 2000; Hudson, 2012; Perneger, 2005
	Unsafe act	General	The model bow-tie; PyraMAP, and other triangle MAPs	Y	QL, QT	Based on events model Bowtie, develop function models containing human, organisation, management factors	Bellamy & Geyer, 2007; Bellamy, Geyer, & Wilkinson, 2007
		Railway	Model of accident causation	Y	QL, QT	Model human failures, technical failures and external intrusions	Kim & Yoon, 2013
Simple system	Loss	General	The deviation theory and models	Y	QL	Define and model deviation by system thinking and then build information system	Kjellén, 1984, 1998; Kjellén & Hovden, 1993
		Equipment	The ‘ENKLA’ system for the management of information on accidents	N	QL	Aim to classify accidents in specific engineering systems by analysing the data	Backström, 1999; Backström & Döös, 1997; Laflamme, Döös, & Backström, 1991
		Chemical process industry	A simple model of incident causation; the Eindhoven Classification model of system failure	Y	QL, QT	Study failure system from near-misses reports	van der Schaaf, 1995
		Hospital	Dynamic safety model	Y	QL	Investigate systemic properties and its potential for creating accidents	Cook & Rasmussen, 2005
	Hazard	Road	The driver-vehicle-environment system	Y	QL, QT	Base on US road casualties, modelling for road accidents factors and mechanism	Kontaratos, 1974
		Aircraft	Hazard modelling research; causal loop modelling;	Y	QL, QT	Specifically model the aircraft hazard, error and unsafe behaviour	Ayres et al., 2013; Downes & Chung, 2011
	Unsafe act	General	Man-machine-environment system (MMES)	Y	QL, QT	Develop interactive system for safety management	Kuhlmann, 1986
		Aviation	SHEL (software, hardware, environment, and live ware) model	Y	QL	Examine the reasons for new human factors training requirements	Johnston & Maurino, 1990
& Complex system	Incident	Process industry	Socio-technical pyramid & Ideal management loop	Y	QL	The models combine the hierarchy of organizational safety and control loops	Nivolianitou & Papazoglou, 1998
		General	ATSB investigation analysis; AcciMap diagram format; etc.	Y	QL	Develop systems thinking models and techniques	Underwood & Waterson, 2013
	Hazard	Aviation	STAMP: system-theoretic accident model and processes; STAMP-VSM joint model	Y	QL, QT	Analyse accidents and control safety, based on systems theories and techniques	Kazaras, Kontogiannis, & Kirytopoulos, 2014; Leveson, 2002, 2004, 2011a, 2011b; Leveson & Dulac, 2005; Leveson et al., 2012
	Unsafe act	Offshore	The control and monitoring loop	Y	QL, QT	Model developed the control from operational level to management level	Bellamy, 1994

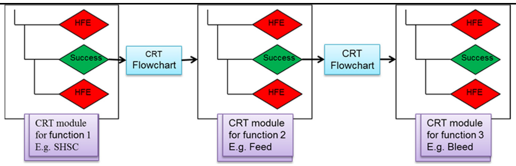
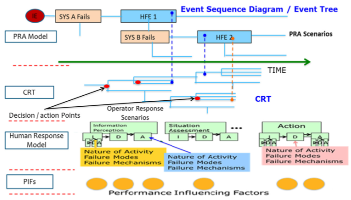
		Petroleum	Human factors activities in design	Y	QL	Integrate human factors and engineering into system design	McCafferty, 1995
		Social infrastructure	Conceptual systemic causal model of design error generation	Y	QL	Discuss the dynamic process of design error and causes	Love, Lopez, Edwards, & Goh, 2012
		Railway	Model of accident causation	Y	QL, QT	Model human failures, technical failures and external intrusions	Kim & Yoon, 2013
Epidemiology & energy transfer	Loss	General	General injury dynamic according Infor.Mo. model	Y	QL	The model emphasizes the energy transfer in accidents causal analysis.	Vallerotonda, Pirone, De Santis, Vallerotonda, & Bragatto, 2016
	Incident	General	The causation and prevention of industrial accidents	N	QL, QT	Discover the basic causes and set up the preventions	Vernon, 1919
		General (Public health)	The epidemiology of accidents	N	QL, QT	Discover the characters of disease and injury according to time	Gordon, 1949
		General (Highway)	Injury epidemiology and categories	N	QL	Develop systematic matrix to study the causes and the contributing factors	Haddon Jr, 1968, 1972, 1973, 1980
		Railway	Integrated framework for the in-depth analysis of HZSCC; HZSCC causation model based on MAERM	Y	QL	Causation analysis is based on modified accident energy release model	Zhou & Irizarry, 2016
	Hazard	Atomic energy	MORT–the Management Oversight and Risk Tree	Y	QL, QT	Present factors and improve system congruous with general system for management of high performance	Frei, Kingston, Koornneef, & Schallier, 2002; Johnson, 1973, 1980
	Unsafe act	General (light metal industry, printing industry, etc.)	Accident and disturbance in the flow of information	Y	QL, QT	Analyse the internal and external factors, and the mechanism of the information processing	Saari, 1984; Saari et al., 1986
Decision model	Incident	Chemical	Multinational vulnerability model	Y	QL	With yes/no questions, this model focus on the global management and operational factors.	Mcnutt Jr & Gross, 1989
& Behaviour theory	Incident	Construction	Accident causation model	Y	QL	Aim is to investigate the production factors that generate hazardous situations	(Mitropoulos, Abdelhamid, & Howell, 2005)
	Unsafe act	General (Standard)	Integrated behavioural safety framework; Information flow between behavioural safety and the HSMS; etc.	Y	QL	Improve SMS performance and feedback	Fleming & Lardner, 2002

Y – Yes; N – No.

Table 2.5 – Events +Barriers +Management models

Model Name	***+Barrier*** *Description*	 *Model shape*	***+Management*** *Main issues*	 *Model shape*
MORT (since 1973)	Energy trace and barrier analysis (and connect MORT analysis this way to the events of the accident).		- Barrier control and other controls - Safety management system - Risk management	
ISRS, also ILCI (since 1974)	Bird's domino theory and loss of control emphasizes safety management.	(no model shows inserted barriers)	- ISRS 15 key processes	
Tripod (since 1990)	Tripod Beta is based on cheese model; defenses (barriers) are inserted between the causal events.		- Latent failure defenses' control - 11 Basic Risk Factors (BRF)	
ECM, also PRISMA (since 1992)	The Eindhoven classification model (ECM) is based on Van der Schaaf's near-miss event model; the control shows the position of intervention.		- Technical, organization, human and unclassifiable factors - SRK-model - PRISMA	
Waring's SMS model (since 1996)	Based on system control, there are risk controls including engineering, organizational, procedural, behavioural, personal protection.	(no model shows inserted barriers)	- System resolution and 'nests' - Specific control models at the three levels	

Socio-technical model (since 1997)	Based on defense-in-depth protection, risk management strategies, such as empirical, evolutionary, and analytical strategies, are identified. 	- The hierarchy of safety management - Adapted socio-technical models applied to different cases 
Bowtie (since 1998)	Bowtie model based on Haddon's HBT-model and Tripod Beta; the barriers are classified and analyzed further. 	- ARAMIS - I-RISK - Hale's SMS Delivery systems: barrier management 
HFACS (since 2001)	Human Factors Analysis and Classification System developed four tiers of barriers, based on Reason's Swiss-cheese model of accident causation; barriers inserted for accident prevention and mitigation. 	- Emphasize the organizational factors - Four-tier system 
STAMP (since 2004)	Based on causal sequence model, 'protective barriers to control flow after release of hazard. Acceptable downtime according to predicted overall risk of major accidents.' 	- Socio-technical management model - Hierarchical control loop - Adapted STAMP applied to different cases 
SoTeRiA / Hybrid model (since 2009)	The causal part of this model is based on events sequence model and uses multiple analysis techniques. (no model shows inserted barriers)	- Model the safety influencing factors - Hybrid modeling technique - Start with the system risk 

Phoenix (since 2016)	Based on scenario development, the crew-plant interaction (CRT) actually is a kind of behavioural or socio-technical barrier. 	- Model for quantitative analysis - Performance influencing factors 

2.4.3 Extension models – barriers and/or management system

Accident theories and models are the foundation of safety management, so we discuss the barrier and management models based on the events model. Safety barriers are normally considered an extension of accident models, such as MORT, Tripod Beta, Bowtie and so on. However, the development, implementation, maintenance and update of barriers require a systematic management. So, the transition from an extension accident model to a management model is critical for barriers management.

2.4.3.1 Barriers prevent unwanted events

The barriers are functioning to prevent, control and mitigate both critical events and consequences. Some papers review and discuss barriers explicitly on definition, function, and classification (Bellamy et al., 2008; Hollnagel, 2008; de Ruijter & Guldenmund, 2016). Barriers indeed connect the events model to safety management. Table 2.5 illustrates the role of barriers in the events model and the management structure to control their performance.

In the MORT model, barriers can stop the unwanted energy flow in an event sequence or prevent the incident from intensifying. They are not only physical interventions separated in time or space but also procedures (Johnson, 1973). Even though more complex theories and techniques are used in barrier models, the position of barriers in events models never change. The Tripod Beta and Swiss cheese model just clear the layers of barriers and describe latent reasons for barrier failures, which are then related to their management (Reason, 1990a, 1995a, 2000; Groeneweg, 2002). The more specific barriers are mapped in the Bowtie extension model, which illustrates multiple ways of accident prevention (Duijm, 2009). Based on this model, barriers are modelled specifically in several projects. The Phoenix model describes three layers of defences. At the top layer, the crew response tree (CRT) directly connects to the control of risk. This CRT is also a method to model the barriers that involve human response (Ekanem and Mosleh, 2014; Ekanem et al., 2016). All in all, the position and function of barriers in the events model is obvious. While the barrier is a very practical and specific concept, how to model barrier systems still needs further study.

The risk is commonly defined in a scenario, which combines the severity of negative consequences and the likelihood of the accident pathway through (series of) unwanted events. To prevent unwanted events and consequences from occurring, safety barriers in the scenario should be functional. Safety barriers can mitigate risks by both decreasing the likelihood of the unwanted event and the severity of the loss. In this way, the management of safety barriers becomes essential for risk control.

2.4.3.2 The nature of management models

The management system purports to deliver the *management factors* to 'complete' the barriers, i.e. provide enough resources and controls to ensure their proper functioning. In the MORT model, the main branches are *specific control factors*, *management system factors* and *assumed risks*; the first two branches are the management components. The management system includes every factor that affect the performance of safety barriers. For instance, the Eindhoven Classification Model classifies incident or accident causes into technical, organizational, human and unclassifiable factors (van Vuuren et al., 1997). HFACS uses a four-tier organisational factors structure (Wiegmann and Shappell, 2001; Lenné et al., 2012). Also, based on the Bowtie extension model, Guldenmund et al. (2006) define seven management factors, also called delivery systems, to identify, implement and support barriers. All in all, the safety management system can and should ultimately control the operational risks.

Another important aspect of safety management models is their *hierarchical structure*. In Waring's SMS model, Rasmussen's socio-technique model and Leveson's STAMP model, the hierarchical structures of management form an essential part of their model (see Table 2.5). These structures are based on general organisational management systems, but clearly show the change in required safety information at the strategical, organisational and operational level. Evidently, safety management influences are expressed by both individual actions and organisational performance.

The combination with a *control loop* at each level typifies the function and processes of the SMS. Waring's model involves control, monitoring, communications and implementation phases from top to bottom. The STAMP model emphasises the control loop especially at the operational level. Guldenmund et al.'s delivery systems even use the SADT method, of which control is an essential part, to model both barrier and management functions. Control is a central aspect of management in a hierarchical structure.

The main function of a safety management system is to control hazards, by means of safety barriers. So, barrier management plays a pivotal role in safety management. As these practical barriers need their input, resources and controls mostly from higher organisational levels, management models are hierarchically structured. In other words, (generic) safety management is basically safety barrier management.

2.4.3.3 Factors that influence safety management

Research into accidents provides ample information for organisational safety management. Organisational safety studies in particular are meant to show organisational safety management factors and their interrelations. Some accident extension and management models address factors such as human factors, organisational factors, and other performance influencing factors. In current literature, these factors are not linearly related. They sometimes are one or a few latent causal factors affecting risks, barriers, safety performance or any other safety related issue, sometimes they are generic safety management factors that are used also in an audit. A general way of studying factors in SMSs can be summarised as follows:

1. Identify organisational model or factors;
2. Rate or weigh these organisational factors;
3. Design a propagation method or algorithm;
4. Choose modelling techniques;
5. Find the link to risk or other issues;
6. Conduct a case study or some specific application;
7. Improve the approach based on the study's feedback.

There is a series of projects that study how organisational factors affect risks, barriers or safety performance by using a probabilistic assessment method with weighting or rating approaches. The Work Process Analysis Model (WPAM) is a model that incorporates organisational factors for risk assessment (Davoudian et al., 1994a, 1994b). It combines an event tree with an organisational model and identifies a series of organisational factors, which are studied as part of the specific system. It uses an algorithm to study the influence of organisational factors on the safety system. The WPAM demonstrates the impact of organisational factors on a work process and has connected these factors to probabilistic parameters.

System-Action-Management (SAM) is a framework that addresses human and management causes of system failure (Paté-Cornell & Murphy, 1996, Murphy & Paté-Cornell, 1996). These researchers used a quantitative approach to illustrate how human and organisational factors affect the probability of loss. Also, the SAM framework, based on the (binary) event tree, makes use of probabilistic methods.

The Organizational Risk Influence Model (ORIM) applies organisational factors within an organisational model (Øien, 2001). A quantitative model has been built and its algorithm links the organisational model to the risk model (with a focus on frequency).

Studies of organisational safety factors are essentially based on latent accident causes and therefore contribute to the development of safety audits. Because the assessment of an SMS is related to a large number of indicators with information about the relationship between the measurable indicators of an SMS, these studies help to improve effective safety management. For instance, Tripod is based on Reason's accident sequence event model and distinguishes eleven basic (latent) risk factors (Hudson et al., 1994). Another example is the International Safety Rating System (ISRS), based on loss prevention theory, which is used extensively for safety management assessment (Guastello, 1991; Top, 1991). This system uses management factors and combines loss control theory with a management model. In addition, both I-RISK and ARAMIS were safety management and audit projects based on a Bowtie extension model (Papazoglou et al., 2003; de Dianous & Fiévez, 2006; Markert et al., 2013). They are founded on the same principles: a causal event model combined with an organisational model, which are connected through safety barriers. In both these models, management factors are defined through the use of 'delivery systems' (see chapter 4).

2.4.4 Safety, barrier and risk in a business process

Essentially, the safety management system is aimed at business services (Figure 2.4). In a business process, like a construction project, the input of raw materials is transferred into a designed construction which is the business output. During the process, risk control is necessary to assure output quality and integrated safety. All sorts of management delivery are an important resource or mechanism to this process. As risk control is important for the business process, the way to achieve a controlled risk has to be developed.

According to event models, risk control is ensured by safety barriers. The input to these barriers are threats or hazards and the output is controlled risk. These barriers also are supported by safety resources, such as human, organisational and technical resources. By using these resources, all stages of barrier functioning are carried out, which include installation, implementation, maintenance and monitoring of barriers. During these processes, controls and criteria are necessary to avoid the failure of safety barriers. All these aspects, i.e. hazards, safety resources, barrier controls and the barrier processes, are contained in the safety management system. As a result, risk is controlled like a business process. Figure 2.4 briefly shows the relationship between safety, barrier and risk in a business process.

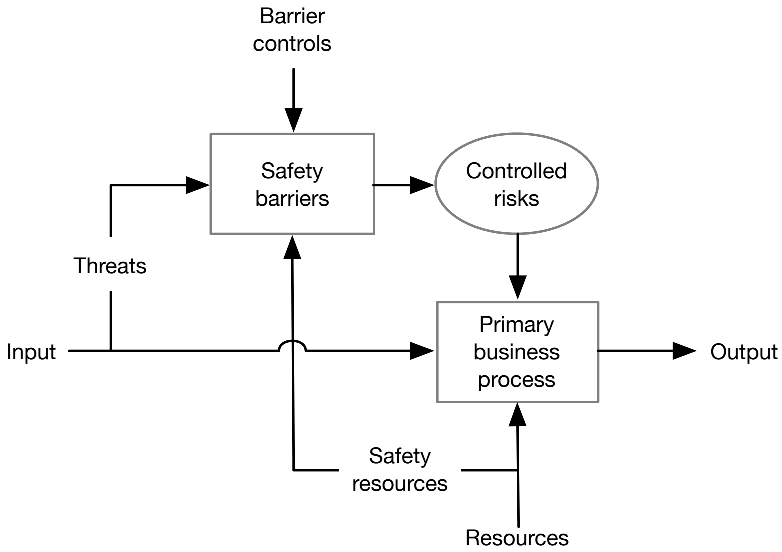


Figure 2.4 – Safety, barrier and risk in a business process

2.5 Purposes of safety management systems

2.5.1 Control perspective

The main purpose of a safety management system is *control* (Figure 2.5). As discussed in Section 2.3, the control of loss, accidents, hazards and risks is central to safety management (research), so the question arises as to what exactly SMSs have to control and by which means they perform this control function. Figure 2.5 illustrates the PDCA (Plan-Do-Check-Act) control process of an SMS and also gives its seven generic sub-systems. A PDCA-cycle is the most common feature of most safety management systems. Originally, the PDCA cycle was proposed by Deming in the 1950s. Since then it has 'evolved into an improvement cycle and a management tool' (Moen & Norman, 2006, p. 7) and is now widely used. Here, not only the management system but also its seven sub-systems use the PDCA-cycle to carry out and improve their functions continuously. Literature on these seven systems is given in Table 2.6. They are indicated by certain codes, which represent the function of these specific sub-systems and are explained further below.

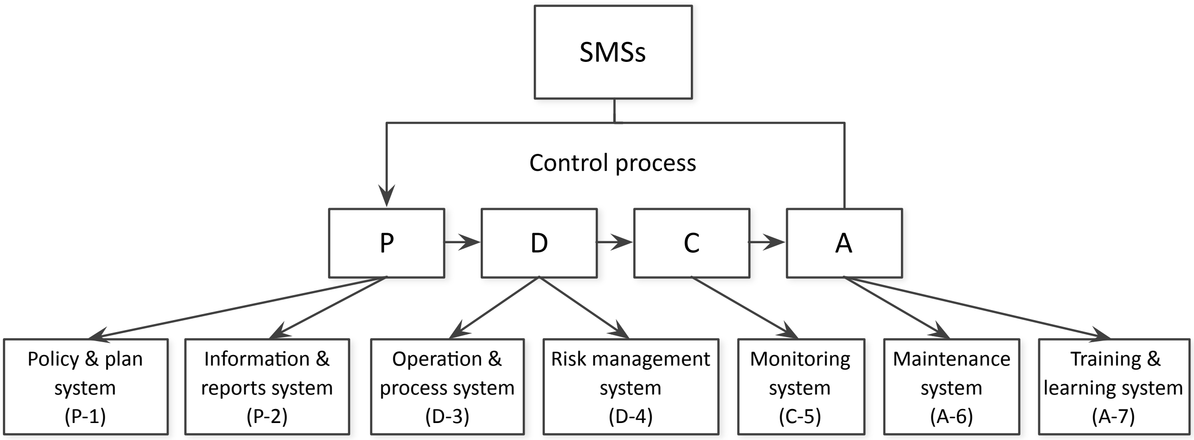


Figure 2.5 – Safety management systems from a control perspective

Policy and plan system (P-1): safety policy is an organisational strategy and the plan is the blueprint of an SMS. Although the policy and plan do not guarantee that the organisation will be accident or incident free, it shows the willingness and attitude of an organisation toward safety activities. Yet, there are few models that identify the safety plan as a separate sub-system, because safety is always a by-product of a project plan, or safety planning is a step in a management system. The safety planning and controlling function describes the processes and interaction between safety planning and safety control. It is proactive regarding measuring and monitoring safety performance (Saurin, Formoso, & Cambraia, 2008). That is, if safety policy is the aim, then safety planning is the designed way to achieve the aim.

Information & reporting system (P-2): the information system is supported by a comprehensive analysis capability using mathematical or statistical analysis tools to identify significant relationships between the data and possible risks in the system (S. Stewart, et al., 2009). The reporting system relies on the information system and varies amongst organisations, depending on the different aims and indicators. Some information and reporting systems are based on accident causation models like TRIPOD, such as the 'information flow model' that describes the sequence of sensing, perception, decision-making and action (Saari, 1984). Some of these systems are specifically built to assist a safety management audit system. For example, information from GUARD (Group Unified Accident Reporting Database) can be used to improve the audit system (Koene & Waterfall, 1992, 1994). Others are large data systems for international or industrial safety management, such as MARS (the European Commission's Major Accident Reporting System), PSMIS (Predictive Safety Management Information System), FSMIS (Flight Safety Management Information System) and so on (Table 2.6). Most information and reporting systems basically provide SMSs with past data to build scenarios and to quantify risks in the safety management system.

Operation & process system(D-3): the operating procedure is an element of a process safety management (PSM) framework (Shimada & Kitajima, 2010), as process activities are also the constituent parts of primary business operations. Studies of this function relate to either of the two aspects, operation or process. Indeed, PSM is a broad system and contains all elements with functions of an SMS in, for example, chemical process safety management. PSM provides methods to effectively solve dangerous situations and to prevent accidents within the process framework (96/82/EC). With the aim of safety control, the operation and process system focuses on actual process activities, procedures and operational performance of safety countermeasures.

Risk management system (D-4): risk management refers to the required architecture (principles, framework and process; e.g. ISO 31000) for managing risks effectively; while managing risk refers to applying that architecture to particular risks. This term has been discussed in Section 2.2 and defined as a component of SMS (Demichela et al., 2004). NASA distinguishes narrow-scope and broad-scope risk management. The former is concerned with hardware risks, the latter is more complex and involves multiple organisations (Dezfuli, Benjamin, Everett, Maggio, et al., 2011). Risk management, which involves identifying, assessing, controlling and evaluating safety risks, thus plays a pivotal role in any safety management system.

Monitoring system (C-5): monitoring aims to check or observe the state of the safety performance of an organisation. Real-time information of safety performance can be obtained and analysed during the monitoring process. By using sensors, the monitoring system can obtain certain values of parameters that tell us something about the performance of machines or operators (Zolghadri, 2000). For example, the Prevention Recovery Information System for Monitoring and Analysis (PRISMA) was originally developed to manage human errors in the chemical process industry. It incorporates an causal incident tree, the Eindhoven Classification Model (ECM) and measures for improvement (Dye & van der Schaaf, 2002; Snijders et al., 2009). This system also shows the relationship between information and monitoring. The monitoring system provides an SMS with actual information which is vital for continuous improvement.

Maintenance system (A-6): maintenance in this context always refers to mechanical maintenance. For the entire SMS it means that every component should be maintained regularly to ensure safety. Based on Juran's quality trilogy model (1999), maintenance includes planning, control and improvement. Tucci (2006) established the Deming cycle model for maintenance, introducing a process for maintenance, i.e. planning and execution, data feedback, data analysis and legal, technical and economic solutions. It is obvious that maintenance models emphasise the PDCA cycle; its process of continuous improvement keeps providing an SMS with control measures.

Training & learning system (A-7): training and learning are often regarded as necessary practices in a management system and an accident prevention strategy (Gherardi & Nicolini, 2000; Hale, 1984). Well-organised training and learning activities can also form an independent system. For the sake of safety, many companies actually do set up their own training programs, although some of them can develop into mature systems such as STOP at Dupont (1986). Other learning systems focus on incident learning for feedback and risk control (Chua & Goh, 2004; Cooke & Rohleder, 2006). Training and learning systems are therefore important for the quality of SMSs as they improve the organisation's and its workers' capability regarding safety.

All in all, these seven groups broadly describe the functions of safety management systems from a control perspective. Table 2.6 describes the literature using the following dimensions: industrial field, name of the system or study, function explanation, model, theory/method or technique and literature reference. The literature shows that a model or a system realises one or more functions of an SMS. They reflect the particular purpose of a control in safety management systems.

Table 2.6 – Safety management sub-systems for controlling

Group	*Industrial Field*	*System name or key words*	*Function explanation*	*Life cycle*	*Model and/or theory*	*Methods or techniques*	*Reference*
P-1	Construction	Supervising plan	HK government carries out 'supervision plan' to change the safety attitude and culture of construction practitioners.		The three-component model of attitudes by Roserberg et al. (1960);	Questionnaire	Tam, Fung, & Chan, 2001
	Construction	SPC – Safety Planning and Control model	SPC aims to implement an SMS with three principles (flexibility, learning and awareness); this model proposes proactive & reactive performance indicators.	Y	SPC model;	NG	Saurin et al., 2008
P-2	Light metal & printing	Information flow model	This paper compares two industries' information and based on their data discusses danger zones.	NG	The flow of information is dependent on several internal and external factors; error mechanisms in information processing	Probabilistic study	Saari, 1984
	Petroleum	GUARD – Group Unified Accident Reporting Database	The system is designed primarily as a safety management tool for Shell, whereby world-wide data will improve feedback to companies and as such influence the development of safety programs, policies, etc.	Y	Managerial safety control feedback loops; Accident feedback loop; Management of safety;	Computer techniques	Koene & Waterfall, 1991, 1992, 1994
	Nuclear	SAIA – Safety Analysis and Information system	By using a PSA event and fault tree, this information system sets up a probabilistic data bank.	Y	Integration of SAIA into the plant management process; functions, structure, and data models;	PSA (Probabilistic safety assessment); Fault tree	Balfanz, Dinsmore, Hussels, Musekamp, & Stuber, 1992
	General	MARS – European Commission's Major Accident Reporting System	MARS aims to 'collect information related to major industrial accidents in EU Member States in the context of the Seveso Directive'. This system comprises an accident report and data collection, with a special focus on near-miss reporting.	Y	Basic structure of the MARS information network; Model of human factors identification in MARS, Aviation maintenance check operations and key points of inefficiency; Scheme of the taxonomy (Rasmussen);	Computer techniques	Jones, Kirchsteiger, & Bjerke, 1999; Baranzini & Christou, 2010; Jacobsson et al., 2010
	Aviation (NASA)	IRIA – Investigation and Reporting of Incidents and Accidents	NASA's IRIA has four parts: organisational and system safety; classifying incidents & accidents; keynote address; software issues; reporting and tracking; analysis methods & results and Investigations.	Y	Aviation system risk model; Information flow chart; etc.;	HAZOP; FT; STAMP; etc.	Hayhurst & Holloway, 2003

	Aviation (NASA)	PSMIS – Predictive Safety Management Information System	This system reduces the time and manpower necessary to perform predictive safety studies by creating predictive SMS software.	Y	Barrier analysis; Risk analysis;	PHA; CHRDPM	Quintana, 2003
	Construction	A hybrid information and communication technology system	An advanced information and communication system used in the construction field for SightSafety management. To test the system, users and their interaction with the system were observed.	Y	Information flow for SightSafety	Micro-Electro-Mechanical Systems (MEMS) and smart sensors	Riaz, Edwards, & Thorpe, 2006
	Aviation	FSMIS – Fight Safety Management Information System	Developed by Taiwan Civil Aeronautics Administration (CAA), it uses quantitative methodology to study risk assessment and identify the influencing factors proactively.	NG	The hazard regression models ;	NG	Shyur, 2008
	Aviation	ASRS – NASA Analysis of Aviation Safety Reporting System	This system records accidents in categories and uses tools to analysis their causes. It is based on 'Loss of Control' (Project IRAC).	Y	Loss of control;	NG	Reveley, Briggs, Evans, Sandifer, & Jones, 2010
	Chemical Process	OSHA PSM Ontology Design	PSM information system incorporates the PSM elements into a computerised intelligent platform.	NG	NG	PHA (Process Hazard Analysis)	Tan, Yew, & Low, 2012
	Oil and gas	EHS MIS – Management Information System	EHS MIS meets the requirement of robust platform for management; it replaces the old incident management system.	NG	NG	NG	Heinrich, 2013
	Railway	Railway information system	This system improves near-miss data and combines safety data with GIS data.	Y	Data collection and analysis system; High-level recording process;	GIS	Wullems, Toft, & Dell, 2013
D-3	Aviation (NASA)	Safety management of a complex R&D	Safety management is developed for a complex R&D operating system and maintained under safety permit controls.	Y	Facility operations management; safety committees framework; elements involved in a comprehensive safety program	System safety tools and techniques	Connors & Maurer, 1975
	Port	SMS in marine operation	This SMS focuses on the barriers of specific operation systems.	Y	Bowtie; An integrated SMS	FT; ET	Trbojevic & Carr, 2000

	Oil and gas	PSM for risk management	Risk Management is 'for protection of environment and communities and prevention of major hazards'. This system introduces an effective approach used in PSM process.	Y	Process safety as a 'Three-fold' Issue	Process workflow	Petrone, Scataglini, & Fabio, 2010
	Subway	An operation SMS	This paper identifies the failure pattern of a subway operation system and factors affecting subway operation safety system.	Y	Subway operation mode map, Bow Tie subway system safety analysis model, subway operation system SMS framework	NG	Dai & Wang, 2010
	Aviation	NASA Safety Control	NASA integrates safety management into the aviation control system. It focuses on how to control the hazards of airplane systems; it also explains a whole hierarchy of management system.	Y	Socio-Technical Safety Control Structure; Safety Control Structure for ATSA-ITP (Airborne Traffic Situational Awareness – In-Trail Procedure); Control Loop for ITP Flight Crew during ITP, etc.;	NG	Fleming, Spencer, Leveson, & Wilkinson, 2012; Leveson et al., 2012
	Aviation	Location and consequence model	The technical safety model is based on accidents data; the work on the location and consequence models of airports specifically benefits operation safety.	NG	Location and consequence model	Statistics	Ayres et al., 2013
	General	MTOI – man, technology, organisational and information	This paper uses control metaphors for a safety management system.	Y	Control input-output model	NG	Wahlström & Rollenhagen, 2013
D-4	Construction	Feedback mechanisms model Risk assessment and control model	This paper reviews an incident causation model and gives the result of incidents or accidents' investigation; it aims to build risk assessment and control model.	Y	MLCM (modified loss causation model);	NG	Chua & Goh, 2004
	Process/ Petrochemical	Dynamic model of process safety management	Risk scenarios audit models are for risk analysis and show the scenarios and the barriers for protection.	Y	Map of scenarios risk process of the plant; Model that rep the process safety management audits;	NG	Neto, 2008
	Offshore	Hazard management (HSE)	This report discusses the risk management process with regard to aspects of competence and supervision.	Y	Bow-tie model, Barrier model, Socio-technical pyramid, Risk based scheme for balancing competence and supervision	NG	Trbojevic, 2008

	Aviation	NASA risk management system	This system consists of Risk-Informed Decision Making (RIDM) and Continuous Risk Management (CRM).	Y	RIDM, CRM, Coordination of RIDM and CRM within the NASA Hierarchy;	NG	Dezfuli, Benjamin, Everett, Maggio, et al., 2011)
	Aviation	FAA SRM	Consistent with ICAO, this system comprises five steps: describing, identifying, analysing, assessing and mitigation of risks.	Y	SRM & Safety Assurance Relationship;	Risk matrix	FAA, 2012
C-5	Aviation	Monitoring system for the controlled aircraft	This system is designed for aviation safety control, with two levels of mathematical models for major hazards.	Y	Monitoring system for the controlled aircraft; RCAM (Research Civil Aircraft Model);	NG	Zolghadri, 2000)
	Construction sites	DSS – Decision Support System	DSS assists construction engineers in monitoring and controlling the excavation conditions that could become hazardous.	NG	Disaster-reasoning model development process; Application model for instrumentation monitoring;	GIS; computer techniques	Cheng, Ko, & Chang, 2002
A-6	General	IMS maintenance system	This paper discusses maintenance activities within the integrated management systems, and how maintenance satisfies system certification.	NG	Maintenance engineering activities towards satisfying management systems certification;	NG	Bamber, Sharp, & Hides, 2002
	Gas	A Maintenance Management	A specific maintenance model for gas field safety management system describes the process of maintenance actions.	Y	Maintenance System Review; The Maintenance Deming Cycle;	FT	Tucci et al., 2006)
A-7	General	Safety training	The purpose is to promote safety-related training and measure the training performance.	Y	The training cycle and risk assessment;		Cooper & Cotton, 2000
	General	The incident learning system	This paper models a safety and incident learning system to explore its dynamics. The system is expected to move 'safety performance from normal accidents to high reliability'.	Y	High-reliability theory, The business and risk systems, 'Disaster dynamics' model, The productive organisational system, The incident reporting system, Safety leadership, etc.;	System dynamics	Cooke & Rohleder, 2006

Y–Yes; NG–Not Given (in reference)

2.5.2 Compliance perspective

Although the control of accidents, losses and defences is considered the main purpose of an SMS, this overview also pays attention to another purpose, namely *compliance* with standards, laws and regulations. For many companies, obtaining a certificate is important and is often a reason in itself to develop and improve SMSs. Some of the more general standards may not provide detailed features of specific operational processes but rather point to topics of significance in the management system (ISO, 2011). Others are industrial major hazard control standards or specific occupational safety standards. Laws and regulations are devised to specifically spell out the norms of safety actions and form a legal framework for acceptable risks. As a result, they provide a distinct view on the study of SMSs in terms of how to develop an SMS that meets the safety requirements set up by different governments, institutions or industries and how to make companies' safety management comply with certain standards.

The literature that relates to safety compliance has three main aspects (Table 2.7): *understanding, comparison* and *integration*. *Understanding* means by explaining certain standards or legislation, clues are provided as to how the organisational management system can comply with the standards. *Comparison* contributes to a general understanding by showing the pros and cons of certain standards. As different governments or institutions probably use different standards, a comparison could provide users with various views on their suitability. *Integration* means the organisation incorporates required standards or regulations into their own management system for a specific purpose. Beckmerhagen et al. (2003) defines the integration of management systems as 'a process of putting together different function-specific management systems into a single and more effective integrated management system (IMS) [but] the extent of management system "integration" may vary significantly from one company to the other, requiring some workable definition of this term' (p. 214). Normally, organisations can operate more than one formal management system and the above three aspects are all useful for the different development stages.

An integrated safety management system is (much) more advanced than an SMS solely set up for compliance or certification. SMSs started from individual management activities as described in Section 2.3. They evolved from individual management systems into integrated management systems as safety management is a core organisational issue next to other organisational management considerations. Regarding the form and results of simple *compliance* and *integration*, simple compliance refers to, e.g. an independent environmental management system, quality management system, occupational health & safety system, etc. (NEN, 2013), the indicators of which are to be considered and audited separately; while integration refers to a uniform system whereby indicators of all different aspects are included in the same information system because the quality of management has to be regarded as a whole (Beckmerhagen et al., 2003). Thus, it is evident that a good integrated SMS is more than just obtaining the appropriate certificates as it can, as a whole, improve organisational behaviour.

Moving from an independent safety management system to an integrated safety management system, two approaches are distinguished: one is the integration of, originally, separate systems; another is an integrated system that is developed and implemented from the very start (Labodova, 2004). The first approach is based on traditional management systems, which were originally set up with different management targets. An advanced management system combines these systems into an integrated system with a collection of targets. The second approach means building an integrated management system from the very beginning with comprehensive aims that include safety, security, quality, health, etc. How to obtain an integrated system still depends on the company's actual context. Implementing a management system efficiently is more important than getting a certificate or achieving compliance with standards. Not an integrated system per se but the process of achieving a better safety performance is the aim.

From a compliance perspective, there are several models that describe how SMSs and standards are integrated or aligned, although the original idea comes from quality and environmental management systems (EMS). Adams (1995) introduced total quality safety management and compared traditional management with total quality management (TQM). He argued that safety is an attribute of process quality. Puri (1996) built a framework for integrated EMS/TQM and addressed three specific aspects: management responsibility, process management and support systems. Renfrew and Muir (1998) proposed a management systems evolution model, which outlines the process of integrating into their own management system some ISO standards and some single management systems. This kind of model tries to combine an OH&S management system and a company's management system in either a national or international context (Rasmussen, 2007).

Another group of models shows how to deploy particular standard systems to specific management projects or systems. For example, in order to structure regulations and support guidance, Nelson (1997) established a model with specific safety critical elements for a project SMS; to improve a certain company safety performance, Kegg (1998) deployed an EH&S management system; based on experience with contractors, Griffith and Bhutto (2008) built a model from best-practices for integrated management system (IMS) development, integrating certain ISO standards into business management processes. Another typical example in an operational context is shown in the SMS standard for gas transmission infrastructure and pipeline integrity management (PIMS), called 'architecture of a company management system of transmission system operator (TSO)'. This model illustrates the hierarchy of a company management system (CMS), the safety management system is a constituent part of the CMS, including the specific IMS for different high risk equipment, (design, construction, auxiliary) processes, emergency preparedness and response procedure (EPR), and so on (NEN, 2013). From top to bottom, the management systems actually all rely on technology, documentation and data, and organisation. In summary, from a compliance perspective, safety management systems are expected to contain standards and regulations with multiple aims in their respective fields.

Table 2.7 – SMSS studies and models from a compliance perspective

Group	*Industry*	*Contents*	*Original SMS or standard*	*Integrated or comparable standard(s)*	*Reference*
Understanding	General	TQM considers the quality program requirements of the ISO 9000 series of standards and the safety management principles embodied in OSHA's VPP and PSM guidelines to create a comprehensive safety management system.	TQ(S)M – Total quality (or safety) management	ISO 9000 series	Adams, 1995; Cooper & Phillips, 1995; Weinstein, 1997
	Drilling	This system contains four aspects: Safety case regulations; PFEER regulations (fire & explosion and emergency response); MAR regulations (fewer substantial implications for drilling contractors); DCR regulations (two main implications for drilling contractors)	UKCS – UK Continental Shelf Regulatory System	HSE regulations; UKOOA Guidelines; IADC Guidelines	Nelson et al., 1997
	General	This report explains the contributing factors and barriers to OHSMS. It compares QM (Quality Management) with this OHSMS.	OHSMS (NOHSC)	QM	Gallagher, Rimmer, & Underhill, 2001
	Energy	This system aims to provide uniform guide and activities to improve SMSs.	DOE G 450.4-1B ISMS – Integrated Safety Management System	DOE orders; CFR series;	DOE, 2001
Comparison	General	This paper compares SOHSM in Norway and Australia; Key objective of SOHSM is 'to promote and monitor programs of internal responsibility for OHS on the part of employer'.	SOHSM-systematic occupational health and safety management	ISO9000; OHS (USA, UK, NSW)	Saksvik & Quinlan, 2003
	Nuclear	This paper compares IAEA GS-R-3, which defines and improves the integrated management system, to ISO quality management system, which satisfies the requirements of the customer.	IAEA GS-R-3 (The Management System for Facilities and Activities)	ISO 9001 2008	Biscan, 2008
	General	Based on the type of industry and international standards, this paper addresses SMSs and electrical safety standards in North America including how they can be implemented effectively.	ANSI Z10 – Occupational Health and Safety Management Systems & CSA Z1000 – Occupational Health and Safety Management	NFPA 70E-2009; CSA Z462 – 2008; ISO 14001; OHSAS 18001; ILO OSHMS 2001; IEEE 902; IEEE 3007.3; etc.	Floyd, 2011
Integration	Petroleum	Safety improved by new initiatives such as STOP; new trend is to consider integrated system; change safety performance of WAPET.	WAPET individual EH&S initiatives	Integrated EH&S MS	Kegg, 1998
	General	Models describe how to integrate standards into a management system and how to make QMS, EMS, OH&SMS fit for management and business systems.	Overall management and business systems	ISO 9001; ISO 14001; BS 8800	Wilkinson & Dale, 1999a, 1999b

Nuclear	This system cares how to integrate standards into a system rather than compliance. For example, it models alignment of ISO 9001 and 14001 using the systems approach.	Management system (main elements)	AS/NZS,1999; Norwegian guideline NTS (1996); ISO9001 (ISO, 2000) and ISO 14001 (ISO, 1996); IEC 60300-1 (IEC, 2001a); IEC 60300-2 (IEC, 2001b);	Beckmerhagen, Berg, Karapetrovic, & Willborn, 2002; Beckmerhagen et al., 2003
Construction	This system aims to integrate standard systems into construction management.	QES – Quality, Environmental, and Safety	ISO 9000; ISO 14000; ISO 18000	Koehn & Datta, 2003
Maritimes	This paper discusses SMS registration and the integration of an SMS with other related management system standards.	International safety management (ISM) code	ISO 19001:2000; OHSAS 18001:1999;	Pun, Yam, & Lewis, 2003
General	This paper discusses the approaches on how to integrate individual systems (QMS–EMS–OHSMS) into IMS and how to build an IMS from start; it describes a model for IMS implementation.	Leonardo da Vinci project CZ/98/1/82530/PI/III.1.a/F PI 'Technological Training for SME's'	BS 8800 ISO series SEVESO II requirements	Labodova, 2004
General	This paper reviews papers discussing similarities and differences of SMSs at standard level and papers about IMSs (Integrated management system); it provides an effective implementation approach: a multi-level synergetic model.	A multi-level synergy model	ISO 9001; ISO 14001; OHSAS 18001	Zeng, Shi, & Lou, 2007
Process	This paper focuses on 'the integration of health, safety and environment in single management systems', but also discusses two kinds of HSE indicators and problems.	HSE (Health, Safety, Environment)	ISO-9000 (1994, 2000); ISO 14000 (2004); BS 8800 (1996) and OHSAS 18000 (2008)	Duijm, Fiévez, Gerbec, Hauptmanns, & Konstandinidou, 2008
General	This paper discusses the standards, methodologies of IMS; compares companies' QMS & EMS & HSMS in Italy; and finally lists the elements and activities to implement an IMS.	QMS & EMS & HSMS	ISO 9000:2000; ISO 14001:2004; OHSAS 18001:1999; SA 8000:2007 BS 7750; BS 8800 French AFNOR 30-200 Spanish UNE 77-201 and 77-802 Italian UNI 10641	Salomone, 2008
Shipping operations	This paper describes approaches to explore the compliance of ISM (International Safety Management) as well as to assist the ship's management.	IQSMS – Integrated Quality and Safety Management System	ISO 9001:2000	Celik, 2009
General	This paper gives a guideline on and examples of how to integrate certifiable management systems for companies.	SMSs of companies	ISO 9001; ISO14001; ISO 18001	De Oliveira, 2013

2.6 Elements of SMSs

2.6.1 The basic elements – Hale's SMS model

SMSs have many common characteristics in that they are systematic, proactive and explicit (Hsu et al., 2010). Generally, safety management systems refer to a set of procedures connected by logical links. SMSs have general elements in common; they may be used in different industries while their elements are similar; and they are the result of continuous improvement following their life cycles. Figure 2.6 shows a complete safety management system following Hale's (2005) model, which is also a generic SMS as these elements can be applied in various industries or organisations.

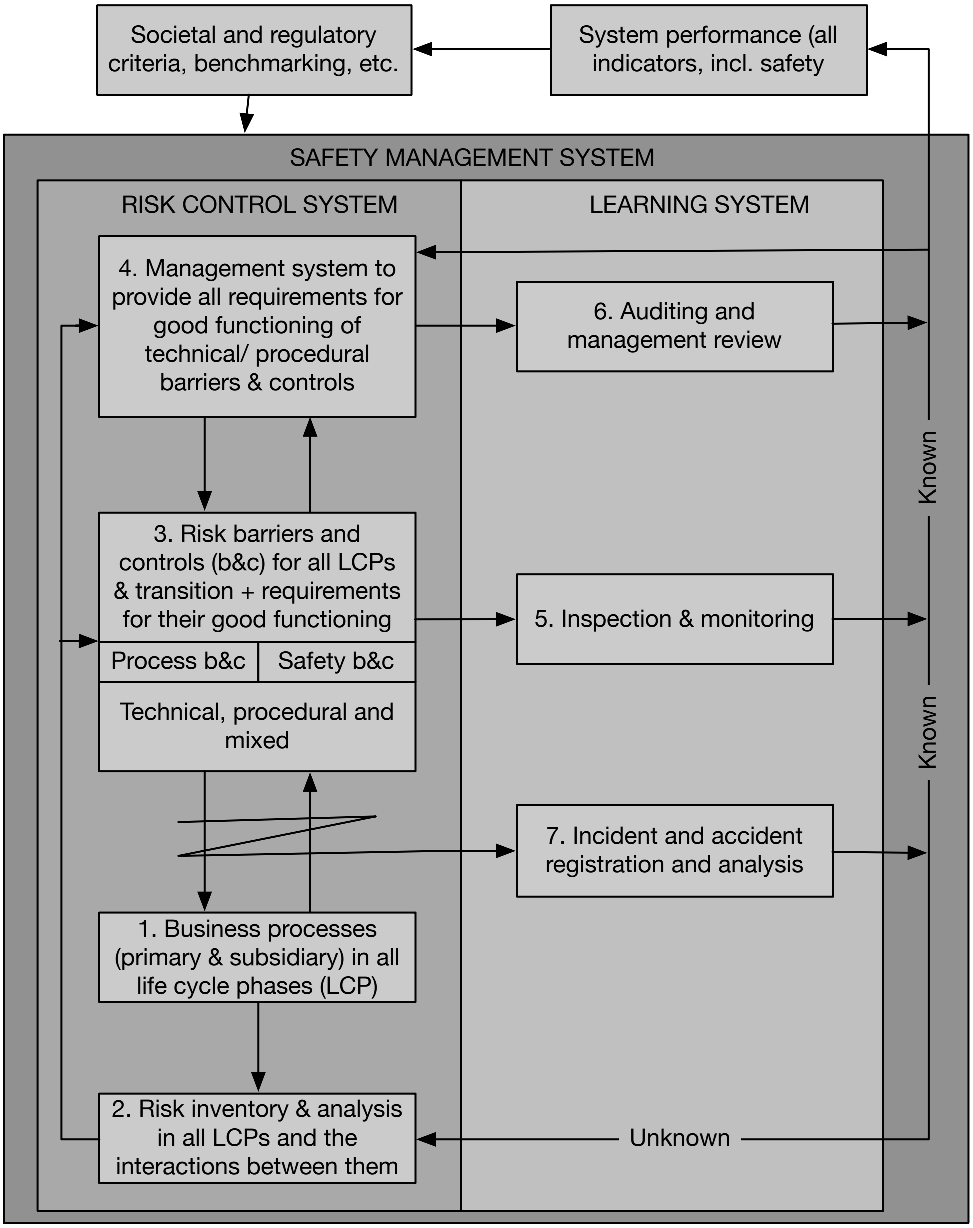


Figure 2.6 – A generic SMS framework (Hale, 2005)

The generic SMS consists of two main elements: the risk control system and the learning system, each of which can be unpacked to reveal several sub-elements. The generic SMS is influenced through feedback by its own system performance and the societal context in which it operates.

The *risk control* system consists of the following sub-elements or management processes:

Box 1. The *primary and subsidiary business processes* describe the safety management system covering all life cycle phases (LCP) and as such it is responsible for the design, the construction and the technology of the organisation and its output(s).

Box 2. *The risk inventory and analysis in all LCPs and the transitions between them* is concerned with identifying and examining the organisation's hazards, understanding how these can become manifest and can be controlled.

Box 3. *The risk barriers and controls for all LCPs and transitions, plus requirements for their good functioning* is concerned with the implementation of risk barriers and controls. It describes the management system within its particular context and its proper functioning.

Box 4. Finally*, the management system to provide all requirements for good functioning of technical and procedural barriers and controls* contains the so-called delivery systems, which deliver the safety barriers and controls.

The *learning system* consists of the following sub-elements or management processes:

Box 5. I*nspection and monitoring* is the process that receives real time information from the actual risk controls and checks these.

Box 6. The *auditing and management review* is concerned with the assessment of safety management and their performance, to make continuous improvement possible.

Box 7. The *incident and accident registration and analysis* is the end and also start box in an SMS, as this process is aimed at the identification of hazards and that provides critical information for the management of safety in the organisation.

Box 4 affects both *audit and review* (Box 6) and *risk barriers and control* (Box 3). As for the zigzag line between Box 1 and 3, it indicates that things can go wrong in this process but, at the same time, can be controlled also. So, the system needs *incident & accident registration & analysis* (Box 7), which process evaluates each incident or accident. If they occur, barriers might have failed and *inspection & monitoring* (Box 5) should be carried out more intensely. Otherwise, barriers should be put in place (Box 2, 3 and 4). *Auditing & management review* (Box 6) examines the quality of the delivery systems (Box 4).

Again, Box 4 can be unpacked to show the various *delivery systems* that together should provide barriers and their operators with sufficient controls and resources to function as specified.

4a. Competence and suitability of people;
4b. Commitment and conflict resolution;
4c. Communication, coordination of groups or teams;
4d. Procedures, rules and goals;
4e. Hardware and spares;
4f. Interface and ergonomics
4g. Availability and planning of people and hardware.

2.6.2 A comparison of the generic SMS to 43 other SMSs

Normally, the number of elements of an SMS determines the level of detail of a safety management system. Some organisations enter elements into a framework hierarchy of different levels. For example, Lees (2005) built an SMS with twelve main elements and 48 more specific sub-elements. This category of SMSs has thus two levels of elements. However, with respect to the dimensions of this overview, the number of elements do not indicate the effectiveness of these SMSs, but rather show the specification of elements or factors within the framework of an SMS.

SMSs are different from each other for several reasons: (1) as different industries have different safety management problems, their SMSs are based on specific industry criteria and rules; (2) some SMSs or standards are different from SMSs for specific companies because the former are (more) generic and focus on management consistency, while the latter concern a plant, its project management, etc.; (3)

the same element in different systems may have a different meaning and scope as a result of different interpretations of particular keywords.

By comparing the elements of different SMSs, their diverse features show the difficulty of modelling an effective generic SMS. An SMS is judged by its efficient and effective implementation. However, how to judge whether one system is better than the other is a thorny issue. Since Hale's SMS is systematic, understandable, applicable, and its elements are developed without any overlap, Figure 2.7 uses Hale's model as a benchmark for a series of SMSs.

From the percentages of use of each element in other SMSs (Figure 2.7), we can see that the 'Interface and ergonomics' (4f) does not feature in many SMSs and the same holds true for 'hardware and spares' (4e). However, in practice human and machine interfaces, software and hardware are very important for safety. For example, considering the various models of safety management, the MMES and SHEL models indeed emphasise these two elements (Table 2.4). But based on what has been found in the literature on SMSs, these two elements do not receive much attention.

While accident analysis (Box 7) and risk barriers and control (Box 3) draw much attention from academia, they are overall less deliberated by companies. Indeed, accident registration or analysis and practical measurements for controlling risks may not even be listed as important management elements in some SMS frameworks.

'Audit & management review' (Box 6) is included in most SMSs since it allows for the assessment or evaluation of the effectiveness of a whole SMS and it is therefore more distinct and independent than other elements.

In fact, a complete SMS contains all the elements shown in Figure 2.6 but the importance attached to them as well as their position in an SMS framework differ. Figure 2.7 shows the percentages with which these elements are used in other SMS models; the full comparison is discussed in a forthcoming chapter.

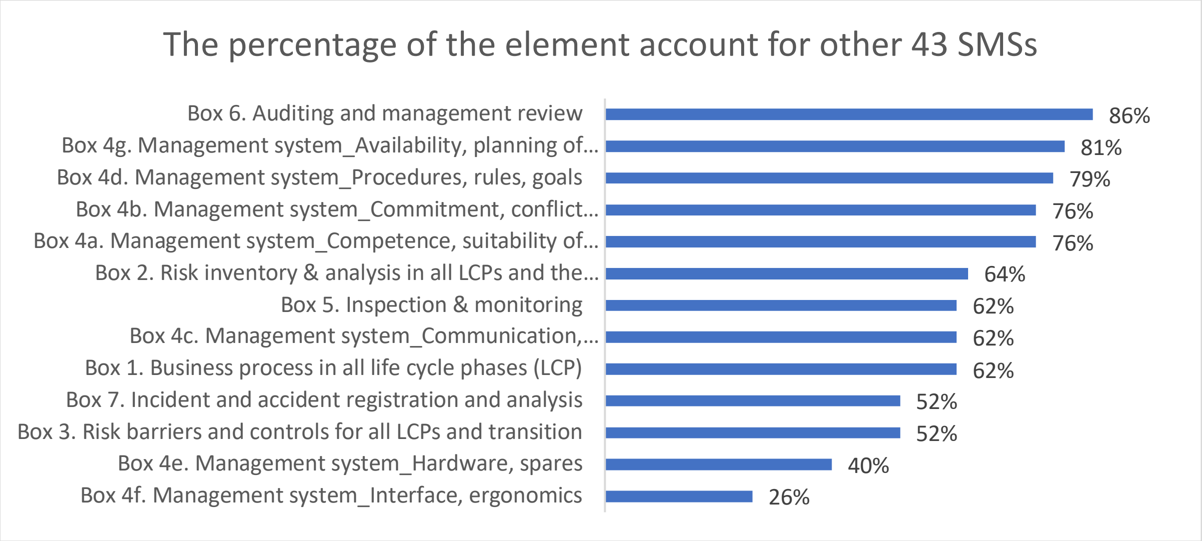


Figure 2.7 – SMS elements compared to Hale's model

2.6.3 A discussion of system performance

2.6.3.1 An SMS provides an assessment framework

In order to assess the effectiveness of the SMS, a clear list of indicators needs to be developed based on the framework of SMSs. The effectiveness of a general SMS is evaluated by a *compliance audit* and a *performance evaluation*. The compliance audit is based on the standardized SMS and its audit methods. It is a way to check if the organisation has the required elements in place and complies with a standard system. This generic audit can hardly use information from operational safety performance because the indicators are too general. However, a good thorough audit requires an effective performance evaluation.

A performance evaluation is difficult for the practice of safety management as key indicators of an SMS are not easy to identify and monitor. There are no principles on how specific a safety indicator should be. The 43 SMSs in section 2.6.2 show that generic indicators and specific indicators are both used. However, for some key indicators it cannot be demonstrated that they are actually useful for safety evaluations. Real-time performance information is not fully available or accessible. Regarding the performance of hardware, the failure or success mode of a particular component does not directly express the safety performance of a complex system. The more complex the system, the more affected factors are involved. So, it is hard to judge which barrier failure or barrier absence is critical in a whole safety system. Except for machine indicators, information on some other safety indicators is acquired through peer review and expert judgement. Using these methods requires accurate criteria, which are not easy to develop. In general, the performance evaluation of safety and its management is still a challenging topic.

The traditionally used indicators are the rates and nature of accidents, incidents, injury and other losses. Almost every company reports them in their annual safety report. The traditional outcome measures do not properly indicate the current SMS performance. Nowadays, a thorough analysis of risk, barriers and safety results in more frameworks of indicators. Robson et al.(2007) reviewed the effectiveness of occupational and health safety management system (OHSMS) interventions through the evaluation of three outcome changes: *implementation*, *intermediate outcome* and *final outcome*. The intervention framework is provided by the OHSMS while the indicators are based on the three outcome changes, such as OHSMS implementation over time, safety climate, injury rates and disability-related costs. Haas and Yorio (2016) reviewed performance indicators of health and safety management systems and carried out a survey on SMS elements and practices. They identified three categories of indicators: *organisational performance*, *worker performance* and *interventions*. These kinds of indicators are widely used in the evaluation of many other SMSs as well.

Considering the evaluation of safety management, elements of an SMS are often regarded as indicators, such as insufficient or improper procedures, leadership, commitment, competence, and so on. If one cannot be obtained directly, some other parameters and heuristics are identified when they can represent these general indicators.

An SMS can provide the framework for indicators, which includes every aspect (Øien et al., 2011a, 2011b). The problem is that the general elements sometimes cannot be used as safety indicators. Each element contains complicated control processes and these can affect each other. With various parameters to be monitored in the processes, the key indicators are mostly extracted at an operational level. The more specific the description of an indicator is, the more useful data it generates.

2.6.3.2 Three kinds of operational assessment in terms of performance indicators

A complete SMS consists of three parts: the events model, barriers, and the management model. Safety performance, therefore, is related to these models. The assessment of the performance can be classified in the following three groups; they contain the key indicators for overall system performance.

INDICATOR GROUP 1 – RISK: Risk assessment based on scenarios

In Hale's SMS, the risk inventory and analysis is an important start for risk control and this information is based on past incident and accident registration and analysis. The analyses apply the event models and techniques. As the original hazard scenarios and risk inventories are critical for an SMS, many specific operational indicators have been developed around these hazards and risks.

INDICATOR GROUP 2 – RISK': Risk analysis after inserting barriers

Modern risk analysis is based on the scenario after safety barriers, defences or interventions are inserted or put into effect. The calculation of event probabilities and consequence severities is with the inclusion of safety barriers. The failures of safety barriers influence the risk level of the basic scenarios. In Hale's SMS, inspection and monitoring focus on the performance information from dynamic barriers and controls, but which also provide (additional) safety performance indicators.

INDICATOR GROUP 3 – MANGEMENT: Delivery systems affect barrier performance

The performance of safety barriers is directly affected by the management systems, i.e. the delivery systems. Good condition of barriers demands a good performance of an organisation on seven aspects (Boxes 4a-4g in Hale's model). Although the assessment of management contains both operational and organisational information, the management is delivered through safety activities and tasks. Management performance is another group of performance indicators for SMS performance.

2.7 Conclusion

Depending on the perspective taken, there are multiple definitions of a safety management system, but its definition is always concerned with three core issues: 'safety', 'management' and 'system'. *Safety* refers to its opposite: accidents, losses or risks. *Management* connects accident causes to organisational control and actions. *System* refers to a systematic framework or models that provide the logic of safety management. To sum up, an SMS means a system containing management principles and activities for controlling risks and preventing accidents.

Depending on their background, SMSs are either narrowly or broadly defined and developed, each with its own pros and cons. Some provide a definition that is directly based on their own industrial activity or even operational SMSs; their angle is practical and meant to achieve the desired safety performance or meet specific safety policies. Others are more abstract in their definitions of an SMS whereby its constituent parts are elaborated along the lines of traditional management systems directed at the continuous improvement of safety performance. Despite the fact that the content of SMSs always pertains to activities, processes, documented procedures or functional control systems, a clear delineation of an SMS is imperative for its implementation as it determines the required resources as well as the responsibilities of the SMS. An SMS is essentially a mechanism that can be designed in different ways apart from its environment, such as (safety) culture or a certain industrial context. In our overview, the definition of an SMS makes it possible to distinguish it from other such management systems.

Safety management developed along with the improvement of safety theories, practices and standards. An SMS is primarily driven by accident analysis and prevention. Even laws, regulations and standards are prompted by accidents because their consequences raise the public's awareness of safety and their acceptance of risk: as low as possible in a practical sense. The history of safety management also shows increased attention for economic reasons with respect to the development of SMS. Indeed, an effective SMS plays an important role in the assessment of a companies' creditworthiness and its ability to control risk (e.g. through insurances). The overview of the history of SMS development has shown that safety management systems can significantly contribute to the improvement of organisational management as a whole.

The theoretical modelling of SMSs can improve the effectiveness and efficiency of SMS developments. Overall, there are three main groups of models. (1) Accident theories and models describe the events and cause-effect relationships. They provide the means to develop scenarios for risk analysis. (2) Safety barriers inserted in the event sequences are the connection between the accident model and the management model. The barriers show the elaborate ways that safety management systems have for controlling accidents. (3) The management models are important as they show how the safety barriers are to be managed. Subsequently, the risk is controlled. The hierarchical models only show the framework of management, but it is difficult to make sure that the safety systems and barriers are functioning as designed. Therefore, factors that influence risk or barrier failure receive increasing research effort. In terms of a complete SMS, the events model, the events model with barriers inserted and the management model are the three stages for modelling and still three important topics for safety management research.

In accordance with the purpose of setting up an SMS and carrying out research into it, control and compliance are critical. Either at a theoretical level or at a practical level, SMSs are designed to control unwanted events with a high probability or loss. The PDCA control loop is a central idea applied in safety management systems and all its sub-systems. Controls, techniques and data analysis are the main concerns in these sub-systems. In practice, SMSs are popular for their role in compliance management. This given explains why obtaining a safety certificate can sometimes motivate companies to continually improve their SMSs. According to the literature, an integrated management system is more advanced than independent safety systems, as safety is just one of the comprehensive organisation management objectives. In terms of purpose, control is the obvious aim of an SMS for which some functions to prevent accidents need to be fulfilled; a standard complied SMS is the necessary requirement in a global market. The demand for safety of companies ultimately determines the purpose of their SMSs.

Elements of SMSs have a bearing on the definition of safety management, modelling and the actual purpose of an SMS. They can explain the contents of an SMS and the processes of its implementation. Hale's SMS is a comprehensive and well-structured system, which makes it suitable for a comparison with other SMSs. This model provides a tool for assessing the completeness of an SMS. The performance of safety management system can be derived from three groups of indicators: the initial risk based on incident or accident scenarios, the risk' after insertion of safety barriers, and the delivery management for the barriers and controls. These three groups of indicators are not only present in Hale's SMS, but also correspond to the three groups of SMS models.

Throughout the overview, we concluded, grouped and discussed SMSs from five different perspectives: definition, history, models, purpose and elements. All five perspectives contribute to make the management of safety more tangible and efficient. Many SMSs, being a practical industrial topic, have not been elaborated theoretically, so this chapter fills this gap and also points out issues especially regarding modelling and the insight into particular SMS elements. Finally, current shortcomings in safety performance assessment have to be solved in a (scientifically) valid yet also practical way.

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3 THE ELEMENTS OF SMSS: A COMPARISON

Abstract

This chapter is an extension of the sixth section of chapter 2. Taking 43 SMSs into consideration in the previous study, we gain a brief understanding of their content, which is not sufficient to develop a concise, complete and functional safety management system. We will complete a further analysis of the elements of SMS to elucidate their characteristics.

This comparative analysis of SMSs focusses on the elements that contribute to their structure and function. The commonalities and differences of the elements are studied by using the mapping method. We clarify the three roles that elements play in an SMS both for practical and research purposes. We develop a four-layer model of an SMS, based on its functional elements. It shows how an SMS delivers management from the organisational level to the operational level through the development of elements. It reveals how the specific factors, safety activities and tasks make up an SMS via functional elements. Finally, we determine the principles of an effective SMS on the basis of relevant features of elements obtained from widely used SMSs.

3.1 Introduction

A functional safety management system is for safety control and compliance. From the perspective of control, an SMS must control risks, hazards, and maintain safety activities, thereby achieving the organisation's safety performance. Achieve compliance with various safety regulations is another purpose of an SMS. Standardised SMSs and industrial criteria are used for checking the performance of safety management. This check is carried out by internal and external auditors. Both purposes of SMSs require the full completion of a safety management process.

Safety management systems have been developed in industries since the 1970s. Safety authorities or organisations (e.g. HSE in the UK, OHSA in the US, etc.) were mostly established to define and regulate safety activities and best practices (Chapter 2). To that end, SMSs were widely used as a holistic framework for guidance and regulations.

Industrial institutes or organisations (e.g. ICAO for aviation, CCPS for process safety, DNV for certification, etc.) also supplied generic SMSs. These industry-based and standardized systems help companies to develop, implement, and check safety management tasks in their respective sectors. These systems provide elements with structures, requirements and methods that gradually aid the safety management delivery from organisational- to operational level.

At the end of the 1980s, a few major accidents prompted the further evolution of safety management. After the Piper Alpha disaster in 1988, safety management systems put larger emphasis on operational aspects, because safety 'can be achieved and maintained in design, construction and operation' (Department of Primary Industries and Energy, 1991, p. 2). Besides, Rasmussen's socio-technical system (1997) and Levenson's STAMP approach (2004) started to become used widely. These models and their application show that safety management includes not only authority and organisational management but also operational control.

Elements of an SMS can fulfil the safety management organisational requirements as well as operational control. Ideally, to define an SMS's elements appropriately, regulators, industrial institutes and companies should all be involved. Generic SMSs like the ISO standards series, provide a framework with generic elements. Sector-based safety management systems, such as the aviation safety management system developed by ICAO, the occupational safety and health management system of OHSA, the process safety management of CCPS etc., contain elements used commonly across industries. These standardised systems provide practical SMSs with developmental guidelines as well as a compliance framework.

Performing the functions of each SMS element at the operational level relates to employees and work tasks. The relationship between organisational elements (e.g. safety policy, risk control) and operational safety activities (e.g. use of a safety valve) is critical for carrying out safety management successfully. Elements provide principles to model specific safety activities and can be adapted for various applications in different contexts. Therefore, determining the characteristics of the elements for effective SMSs is of vital importance.

3.2 Framework of elements: an SMS

3.2.1 Structure of SMSs: the framework for elements

An SMS not only lists functional elements but also presents a structure to implement these elements in an organisation. According to the literature (see appendix), a PDCA cycle and continuous improvement are commonly used in most structures, although the connections between these elements may vary. Some structures are hierarchical or systematic; some elements are grouped or presented in parallel. Using a suitable structure improves the efficiency in performing safety management.

3.2.1.1 PDCA cycle and continuous improvement

The PDCA-cycle, also called the Deming circle, is a life-cycle of all phases – encompassing plan, do, check and act – for the implementation of a system. It stems from Shewhard's tricycle of phases, i.e. specification, production and inspection. Deming modified it to the PDCA's four steps, whereupon Ishikawa successfully applied it to quality control in Japan (Moen, 2006). Safety management systems, following quality management systems, integrate this cycle into their generic framework and even their individual elements.

The PDCA-cycle facilitates the implementation of an SMS because the phases all contain organising actions. This cycle is embedded in most international standardised systems, such as the international quality, environment, risk, occupational health and safety management systems (a.k.a. ISO 9001, ISO 14001, ISO 31001, ISO 45001). It is an easy and clear process for the implementation of safety management. For instance, the British Health and Safety Executive (HSE), also changed their standardised health and safety management system from a POPMAR-model (policy, organising, planning, measuring performance, auditing and review) to the PDCA cycle. This new model 'achieves a balance between the systems and behavioural aspects of management' (HSE, 2013, p. 7) so rather than being a stand-alone system, the PDCA-structure presents this OHS-system as an integral system of the general management system. As a result, the procedures related to this system are more concise.

By *taking action to continually improve process performance*, the PDCA-cycle of systems demonstrates a positive and dynamic approach to management (ISO, 2009). For instance, the International Labour Organisation's occupational and health (ILO-OSH) system provides a continuous improvement cycle to frame its elements. The elements of *planning*, *implementation*, *evaluation* and *action for improvement* match the steps of the PDCA-cycle. The last element, *preventive and corrective action* is to remedy insufficient safety activities (e.g. risk control), and *continual improvement* maintains the performance of relevant elements of the OSH-management system. Consequently, the system improves and will run its next round of the OHS-process (ILO, 2001). Hence, continuous improvement always follows the PDCA-cycle, and it is a typical feature of an SMS.

While some organisations do not apply the PDCA-cycle, their SMSs are still subject to continuous improvement, which is shown in an embedded feedback cycle or another improvement element. *Continuous monitoring* is also a useful element for improving SMSs. It is used to update information on hazards and review mitigation actions for compliance. In some other SMSs, continuous improvement of their framework is a function of a separate element. For instance, a risk standard management system contains such element that uses the results of monitoring and reviews as input (ISO, 2009). Obviously, continuous improvement is an essential characteristic of SMSs.

3.2.1.2 Hierarchical structure

A typical general framework of elements often has a hierarchical structure. There are two types of hierarchy. One is that the SMS is nested in a hierarchical organisation or context, but the constituent elements are the same or similar in the context of each level. In the second type, the general elements have sub-elements or even sub-sub-elements. These two types of hierarchical structures can both feature in one SMS.

The first type of hierarchical structure pertains to different levels of objectives. The hierarchy in Rasmussen's socio-technical system (1997) shows that governments, regulators, companies and even departments of companies all have a need to develop an SMS. For example, Waring (1996) proposed a model called 'recursive or nested structure of safety management systems' (p. 9). It contains SMSs for corporate, department and unit level. At each level, the system contains the same elements, such as control, monitoring, communication and implementation. The system at a lower level must fulfil functions for supporting some elements or activities at a higher level.

Another, more common way to develop a hierarchical structure is by using a simple tree format. This tree branches out in more detail at each level downwards. Examples of such structures can be found with Gabbar's (2002) CAPE-SAFE (computer-aided plant enterprise safety management system) system, Saracino's (2012) new model of OHSMS, and Chen's (2012) or Chang's (2009) factors of SMS.

As described above, some display both types of hierarchical structures. For instance, there is a framework of safety management for nuclear power plants that distinguishes legislation, regulatory body, external and operating organisations. In this framework, safety management follows a similar differentiation. Within this SMS, safety management elements are also elaborated hierarchically. For instance, one generic element (component), the *definition of safety requirements and organisation*, includes two sub-elements, namely *statement of safety policy* and *management structures, responsibilities and accountabilities* (IAEA, 1999). Another example is Kazaras (2014)'s STAMP-VSM framework for safety assessment, which combines the hierarchical levels of the STAMP-model from legislation to operation. It integrates a socio-technical structure with five functional systems (e.g. policy implementation); the five systems also contain more specific elements (items). Using a hierarchical structure one can embed an SMS in a comprehensive organisation and decompose elements further with items or processes.

3.2.1.3 Group or parallel elements

An SMS consists of several elements, which may be grouped based on a certain classification. The early Dupont process safety management (PSM) addressed three groups of elements, namely technology, personnel and facilities (Burk, 1990). They are quite similar to the Nertney wheel's plant-procedure-people phases (Johnson, 1973). Another example of PSM shows that their elements can be grouped based on four aspects: *process safety commitment, hazard and risk understanding, risk management* and *learning from experience* (Zhou, 2017). These groups are the basic (or core) safety management processes. However, hierarchical structure here pertains to hierarchical organizational levels, while group structure is based on practical considerations.

The most simple structure is one that lists the elements in parallel. Non-structured elements are also regarded as parallel elements because they are individually listed. These SMSs, which are mostly used in companies, only state their ingredients but never fully structure them. Some elements are based on standards (Pheng, 2000; Lee, 2005; Ariz, 2017); some are obtained from safety practices (Ho, 2000). Parallel elements are more independent than grouped elements. As elements are the bricks in the architecture of an SMS, we suggest using them in the form of structures.

3.2.2 The role of elements for safety management

According to a holistic system definition, 'a system is a set of two or more interrelated elements with the following properties: (1) Each element has an effect on the functioning of the whole; (2) Each element is affected by at least one other element in the system; (3) All possible subgroups of elements also have the first two properties' (Ackoff, 1981, p. 15-16). Therefore, elements are the functional sub-systems for the whole safety management system. In the life-cycle of an SMS, elements are carried out along with their definition, development, deployment, review and audit. They are the *functional components* of an SMS, also used for *key performance indicators* analysis, or identified as *accident causes* in accident investigations. Understanding the roles of elements in an SMS helps practitioners and researchers to improve safety management.

3.2.2.1 Functional components for safety management

To complete the life-cycle phases of an SMS, all its constituent elements should perform well. Specifically, they should function along with the life-cycle of an SMS, notwithstanding the fact that in different SMSs the structures and elements are designed differently. According to Sage and Rouse (2009) the typical life cycle of any system consists of the following four steps (Figure 3.1): *definition* of the system and its boundaries, *development* of the defined system, using the system (*deployment*) and improvement of the system based on performance and systematic *review*. Consequently, performing the functions of these elements makes an SMS function.

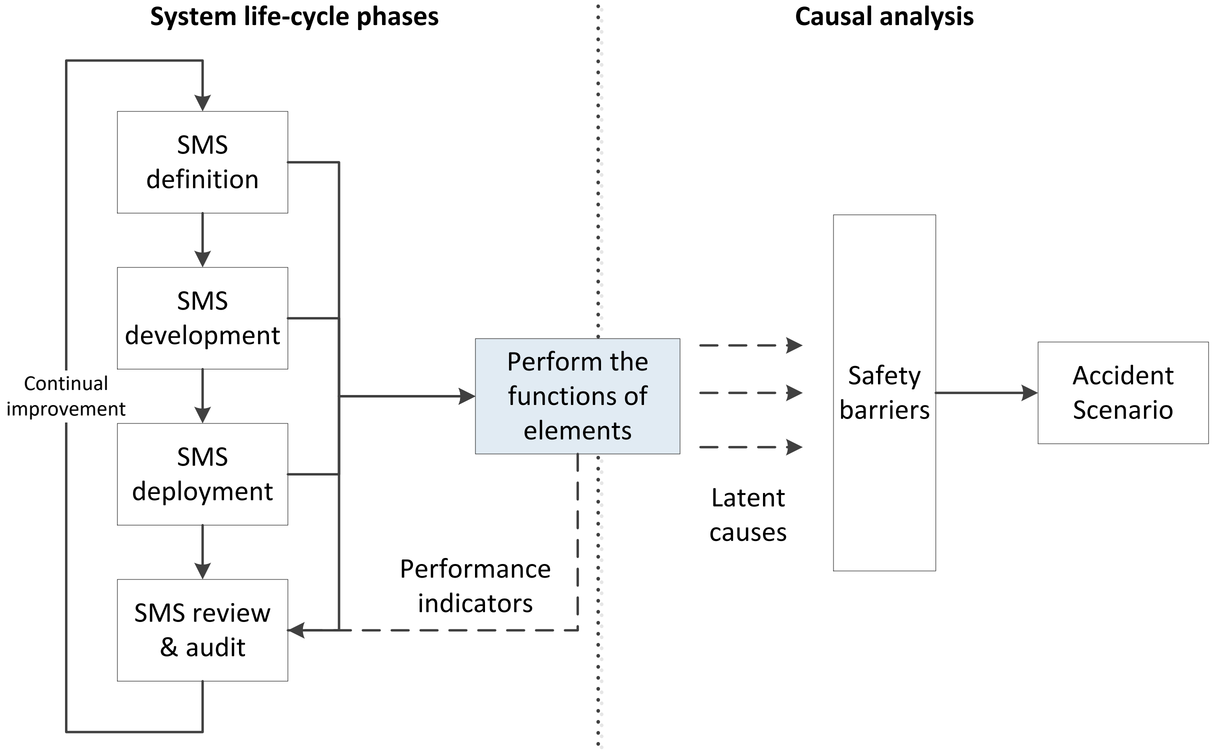

Figure 3.1 – The role of elements for safety management

3.2.2.2 Key indicators for SMS performance

Another role of the elements of safety management is providing key indicators of SMS performance. According to the literature, some elements are used directly as key indicators or factors influencing the performance of safety management. For example, Chen (2012) described general airlines' SMS by means of 37 items and extracted key indicators using factor analysis. Although extracting key performance indicators is not the purpose of designing functional elements of an SMS, it is still feasible. Whether elements function well determines the performance of an SMS; subsequently, the performance is fed back into the system for evaluation and improvement. Elements playing the role of indicators is the reason that safety audit systems can be the same as safety management systems.

3.2.2.3 Latent causes of accidents

Reason (1990) identified 'contributing conditions and latent failures' which make up management failure. As a result, the now prominent model of organisational accident causation was developed. It shows how management decisions and organisational processes lead to accidents via the failure of various (organizational) defences (Reason, 1995). Based on this model, many causal analyses of accidents indeed proved that the management factors are important causes of accidents or incidents (Bellamy, 2008; Hale, 2012). Since these management factors map onto the elements of SMSs they play the role of latent causes of accidents.

3.3 The feature of elements

A complete safety management system must contain all the required, functional elements. These elements may be named or structured differently, but together they should achieve the safety performance of a company, a plant or a project. This section will go into the common features of these elements.

3.3.1 Elements mapping with Hale's model

Hale's SMS model is hierarchical and systematic (Hale, 2005). Except for external factors and context, such as societal and regulatory criteria,the *risk control system* and the *learning system* are two constituent parts of this SMS. Risk control is the main task of safety management and learning from the process of risk control will help to improve this system. The two systems broadly represent components which define the scope of this system. For instance, in the aviation sector, ICAO-SMS contains four components, namely *safety policy and objectives*, *safety risk management*, *safety assurance* and *safety promotion* (ICAO, 2013). These components are made up of more specific elements. For instance, *training and education* and *safety communication* are the two key elements of safety promotion. By defining their scope as well as determining the constituent elements of the above systems will help clarify the systems' purpose. An organisation places all its safety management elements in these high-level components.

Elements stand for functions that pertain to specific safety management activities. They can be connected to form a complete management process; they can also be presented as individual items. When it comes to a process, elements interact with each other, and they are executed sequentially in a designated order. Even though some SMSs are modelled on individual items, these items are not run independently. Generally, drafting and imposing a safety policy is the initial element of any SMS; risk assessment and mitigation follow the identification of hazards; audit or system review forms the last element of any SMS implementation. To understand the mechanism of these elements, we will look further into them in different SMSs.

In our previous review of SMSs, we presented the result of the percentage of the elements in Hale's model accounting for 43 other SMSs (Section 2.6.2). We reckoned that Hale's model is an example of a complete SMS because it contains a coherent structure, comprehensive elements and all systematic processes of safety management. In this section, we present the result of a comparison of elements of SMSs by means of a mapping method (Table 1). This method, also called systematic map, is described as 'map out and categorise existing literature on a particular topic, identifying gaps in research literature from which to commission further reviews and/or primary research' (Grant, 2009, p. 94). We use this method to check if a certain SMS complies with all the elements of Hale's system, and which elements are present regardless of the type of industry the SMS is used in.

Table 3.1 – Generic SMS's elements mapping according to Hale's model

Name	Mapping elements												
	1	2	3				4				5	6	7
				4a	4b	4c	4d	4e	4f	4g			
Dupont PSM		×	×	×	×		×	×		×		×	×
ADCO's SMS	×	×	×	×	×	×	×		×	×	×	×	×
HSE best practice model		×		×	×	×	×			×	×	×	
HSE SMS	×	×	×	×	×	×	×	×	×	×	×	×	×
ILO OHS in forestry work	×	×	×	×	×	×	×	×	×	×	×	×	
IAEA	×	×	×	×	×	×	×			×	×	×	
Site safety in HK (Audit)	×	×	×	×	×			×	×	×	×	×	×
BOWEC regulations		×		×	×	×	×			×	×		
ILO-OHS		×	×	×	×	×	×			×		×	
CSMS	×				×	×		×	×	×	×	×	
SSMS (a Systematic SMS)	×					×						×	×
EPSC MS (1994)	×		×		×		×				×	×	
Alpha S&ESM (1997)	×	×										×	
Beta SME MS (1996)	×	×	×	×	×	×	×			×	×	×	×
CAPE-SAFE (Function Decomposition)		×	×				×	×		×	×	×	×
Integrated SMS system (NCHRP Report 501)	×			×	×	×	×			×			
CCPS (1989/7)	×	×	×	×	×	×	×	×	×	×	×	×	×

ICAO- & FAA- SMS		×	×	×	×	×	×			×	×		
An HSE	×		×		×	×	×					×	×
An SMS			×	×		×	×	×		×	×	×	×
New VPP	×		×	×	×	×		×		×		×	×
Functional SM	×	×	×		×	×		×		×		×	
ALSTOM transport	×		×	×						×		×	
General	×	×	×	×	×	×	×		×	×	×	×	×
Airport SMS		×	×				×			×		×	
Taiwan air transportation		×	×	×	×	×	×	×	×	×	×		×
Taiwan paint manufacturing facilities		×		×	×	×	×	×	×	×	×	×	×
SSMS (Systematic SMS)					×	×					×	×	
An SMS	×	×	×	×	×	×	×		×	×	×	×	×
OSHA/PSM		×		×	×		×			×		×	×
A Chinese coal SMS	×			×								×	
COMAH (Control of Major Accident Hazard)	×						×			×	×	×	
M.I.M.O.SA system	×	×	×	×			×			×	×	×	×
DuPont PSM	×			×	×	×	×			×	×	×	×
ISM model (Chinese coal mine)		×		×	×	×	×	×			×		
A Taiwan airline SMS	×			×	×		×			×	×	×	
Offshore OSHA's PSM	×	×		×	×		×	×	×	×		×	×
Offshore SEMP/SEMS	×	×		×	×		×	×		×		×	×
An HSE management system (MS)				×	×		×			×	×	×	
ISRS (audit)	×	×	×	×		×	×			×		×	×
A PSM		×		×	×		×	×		×		×	×
DuPont PSM		×		×	×		×	×		×	×	×	×
VSM (Viable System Model) functions	×			×		×	×				×		
Percentage	62%	64%	52%	76%	76%	62%	79%	40%	26%	81%	62%	86%	52%

Note: 1 Business processes (primary & subsidiary) in all life cycle phases; 2 Risk inventory & analysis in all LCPs and the transition between them; 3 Risk barriers & controls for all LCPs & transitions + requirements for their good functioning; 4a Competence, suitability of people; 4b Commitment, conflict resolution; 4c Communication, coordination of teams; 4d Procedures, rules, goals; 4e Hardware, spares; 4f Interface, ergonomics; 4g Availability, planning of people & hardware; 5 Inspection & monitoring (technical, behavioural); 6 Auditing & management review; 7 Incident & accident registration & analysis.

Hale's system shows a total of 13 elements of which 7 are 'management deliveries'; they define columns in Table 3.1. Management deliveries provide specific controls and resources for technical and procedural barriers or controls. This group of elements plays a critical role in safety management as it explicitly describes 'management'. The management elements of planning (4g), procedures (4d), competence (4a), and commitment (4b) all show high percentages of use in other SMSs: 81%, 79%, 76% and 76% respectively. These numbers show the importance of safety management deliveries. We have explained the reasons for the different percentages of the use of elements in Chapter 2.

A complete and functional safety management system must contain all these elements, even if their priorities differ. In a generic SMS, some elements are not present yet, since these become apparent when it is applied to a specific industry. For example, the management of hardware (4f) or interfaces (4g) is not shown in the elements of the British H&SMS or the ISRS (International Safety Rating System). Both systems are not industry-specific, so the development of elements do not focus on hardware, spares, interface and ergonomics.

However, these elements are necessary for safety management in many industries. For instance, the chemistry-based CCPS-SMS has one element, namely *process and equipment integrity* (Lee, 2005), which relates to hardware and interfaces included in chemical processes as well as their interactions with operators. Some other process safety management systems have similar elements, such as *mechanical integrity* (Aziz, 2017; Zhou, 2017), *safety instrumented system* (Charnock, 2007), etc. Overall, we think Hale's model contains all the necessary elements for an SMS.

3.3.2 Interaction or independence of elements

Hale's model is comprehensive also because it shows clearly how its hierarchical elements work together. These elements contain all (the) safety management activities without overlaps. According to the literature, a few SMSs present the relationships between their elements, while some others give a rather unclear description of the process of implementation. Yet, as we will explain hereafter, the interaction between, or the existence of, independent elements shows a mechanism for how to effectively use functional elements.

3.3.2.1 Interaction

When developing an SMS, some of the elements connect and interact with each other. The previous edition of the British H&SMS had a simple flowchart. Policy, organising, planning and implementing, measuring, reviewing performance and audit are connected in series by arrows (HSE, 1997). The flowchart clearly shows a control sequence. The audit is the last element of this SMS and also the central link of the information cycle, which means the element audit exchanges information with other elements, such as measuring and reviewing performance. The feedback loop is for safety performance improvement.

However, in the latest edition of their H&SMS, all its elements are integrated into the structure of PDCA (HSE, 2013). This process is more concise than the previous one, although elements and the feedback cycle have not changed. Another connection of elements within this system is the development of core elements (such as leadership, competence, legal compliance, etc.), which in particular allude to the attitudes and behaviour of people in an organisation (HSE, 2013). This system offers general PDCA-elements and core elements of managing health and safety. Similar to Hale's model, it is also comprehensive.

According to the H&SMS and also other SMSs, we distinguish two kinds of interacting elements: connected in a flowchart or within a PDCA-structure. The flowchart is a flexible method to link the elements as it represents a workflow. The elements for safety management can be regarded as general work process steps, and they are connected by arrows in a logical order. Sometimes this SMS flowchart is also called the process to implement an SMS. Many industrial SMSs use this method, such as IAEA-SMS, ICAO-SMS, etc. (IAEA, 1999; ICAO, 2013).

Likewise, PDCA-structured elements represent a process which is more fixed. As we mentioned in Section 2, this structure has a feedback loop for continuous improvement. Different SMSs have different elements in this framework, but the links are the same. All elements must match with the four steps i.e. *plan, do, check and act.* There are other examples that apply this structure: ILO-SMS, with the attribution of a hierarchical framework of safety management; and an HSE management system (ILO, 2001; Chang, 2009; Tauseef, 2012). A process to connect elements, either in a fixed PDCA-structure or a flexible flowchart, provides a general mechanism to put an SMS into practice.

3.3.2.2 Independence

Many elements are, however, independent, especially in non-structured SMSs. Elements are listed but not tied in (see Appendix). Lee (2005) offered some such examples, such as the eleven elements taken from Lord Cullen's report on Piper Alpha, the fourteen elements of the PSM-system, the eleven elements in yet another PSM-system (API RP750), etc. All in all, to combine independent elements is difficult. An SMS is sometimes just a package that contains the necessary elements to comply with international, national or industrial regulations. Therefore, some elements lack an actual order of execution or a systematic framework.

Some elements in a hierarchical structure are also independent. In this respect the structure only says something about the organisational level or the organizational group involved. Fernandez-Muniz (2007) proposed a six elements system using non-industry specific items. *Safety policy* includes four specific activities; *worker's incentives* are described with six items; *training in safety* even have nine aspects; etc. It seems like a complete generic system but its elements are listed mainly for the purpose of safety management research. Also in many other systems, the hierarchical elements are used as pertinent safety factors for reports or research (Su, 2011). In practice, however, these elements have little meaning.

Overall, many SMSs show weak relationships between elements. Despite their importance for operational safety management, the literature hardly discusses how to use these elements and in which order to control risks in an SMS. Except for a cycle of continuous improvement, generic links between elements are usually lacking. The latter makes it hard for SMSs to comply with safety regulations as safety risk control and safety performance improvement actually do require a crystal clear deployment of these elements. Therefore, a functional SMS, like Hale's, is an example of a reasonable order of elements.

3.3.3 Process and procedure of elements

Each element should have a control function to achieve its designated management goal because in a functional SMS each element must work well as explained earlier. Harms-Ringdahl (2004) defined that an OHSMS is a systematic way of managing the occupational health and safety risks of a company. This systematic way normally means modelling elements in terms of *processes* and *procedures*.

3.3.3.1 Process

In a management system, the process of a full cycle of implementation is always generic; but the process defined by each element contains specific activities or tasks. A general element is like a multi-function box. When you unpack it, you can find the process, documents, methods, and other resources. For example, according to British HSE regulations, the risk control system (process) contains *operational control*, *management of change* and *planning for emergencies* (Bellamy, 2007). With more specific safety activities and resources for these three sub-elements, this element can be modelled systematically.

Even for the same element, the process varies due to either different developers or having different purposes. For instance, in Hale's model (2005), risk control is described differently. The *barriers and controls for all life-cycle phases and transitions, plus requirements for their functioning* element plays a crucial role in the implementation of safety activities for risk control. They can be tailored to specific technical and procedural issues depending on the requirements of particular industries or sectors. Furthermore, the management of the barriers mentioned above is in another element, in the form of seven processes of management deliveries (Figure 2.6). Hale's system emphasises the safety barriers for risk control, while the HSE system focuses on safety *control* phases: design, operation, modification and emergencies. Hale's model is for research and applications; while HSE regulation is for guidance and compliance. When comparing the two, we found that even for the same element, the content can be developed in different ways.

Control theory and systems thinking are helpful for the development of safety management elements. The input-process-output control structure is an accepted way to describe the process of elements (HSE, 1997). Based on this, Hale (1997) suggested using a universal method for modelling safety management: structured analysis and design technique (SADT). This technique comprises input-activities-output, supported by resources and controlled by criteria. The processes of safety management deliveries by using SADT were developed in several projects (e.g. I-Risk and ARAMS). Shimada (2010) also used this method to model elements in a PSM system. He claimed that mapping specific activities systematically can make the PSM functional.

Another method to describe the process of an element is using a flowchart. Smith's four components system (2005) is similar to the ICAO safety management system. He modelled one of the four components, *the safety risk management in the national airspace system*, with a process of several sub-systems. They follow the (generic risk management) sequence of *describe the system*, *identify hazards*, *analyse risk*, *assess risk* and *treat risk*. These sub-systems, including activities, tasks and related tools, work together to achieve risk control. The development of elements reflects that functional elements require logically connected activities.

3.3.3.2 Procedure

The procedure describes what we need to do in order to accomplish a process. The details of an element may be structured as a process, but they are part of the procedure. Elements in SMS-standards are always described in guidelines or reports. They are usually published by industrial or government authorities, such as ISO, BS, HSE, ICAO, IAEA, etc. These SMSs provide strategies, steps, methods, and notes of elements. Making procedures for an SMS and its elements has many advantages: (1) Practitioners can understand how the SMS works in practice; (2) It helps organisations with completing a safety self-regulation or an audit; (3) Small- or medium-sized enterprises need (more) guidance to develop their own SMSs; (4) An industry or a sector can use common elements of an SMS to facilitate safety improvement.

How does the procedure describe the details of each element? ISO 45001, the international OHSMS standard, which is based on the British OHSAS-standard, ILO-OSH guidelines, and other ISO-standards, generally provide the aim, functions, framework, and contents. The definition of each element is stated as a seperate section of the standardised document; for example, coded as ISO 45001:2018. This document does not provide the specific criteria for OH&S performance, but provides the elements with common *requirements*, *recommendations*, *permissions*, *possibilities* and *capabilities*. This OHSMS is based on the PDCA-structure with six elements. The element of planning contains two aspects: *actions to address risks and opportunities* and *OH&S objectives and planning to achieve them*. Each of the sub-elements has more specific steps or processes, which are described in non-industry based universal contents, like requirements, planning actions, etc. (ISO, 2018). From this standard procedure, we can obtain the generic contents of elements. However, aligning these with a company's safety management activities will need more details on its actual operations.

A process safety management (PSM) procedure is an example involving an industry-specific context. Process sector here means the chemical industry, which uses groups of pipes and vessels containing hazardous materials. Therefore, more terms for process risk control are used in the procedures. The American OSHA published a series of PSM-procedures, which translate the elements for different contexts. The generic PSM (OSHA 3132), the PSM for small businesses (OSHA 3908), the PSM for Petroleum Refineries (OSHA 3918), etc. emphasise different elements in their procedures (Table 2). Considering common applications, elements in a general PSM are all useful; for specific purposes, the PSM focusses on some particular elements. Even though some PSMs share the same elements, they can have different criteria, methods, and requirements, because of the different context and purposes.

Apart from regulatory procedures, the industrial practice procedures explicitly clarify elements, which comply with these regulations. For instance, CCPS published rather elaborate guidelines for risk-based process safety with twenty elements. In accordance with a regulatory PSM, these guidelines provide valid and practical means to design, correct and improve a process safety management system; hereby, improving the safety performance effectively (CCPS, 2010). The PSM-elements in procedures indicate that documented procedures assist practical SMSs to comply with regulations.

Table 3.2 – Mapping the elements of PSM for different purposes

Regulatory Standards			*Non-Regulatory Best Practices*
PSM (2000)	PSM for Small Businesses (2017)	PSM for Petroleum Refineries (2017)	(CCPS) Risk Based Process Safety (2010)

Process Safety Information	Yes	Yes	Compliance with Standards
			Process Knowledge Management
Process Hazard Analysis	Yes	Yes	Hazard Identification and Risk Analysis
Operating Procedures		Yes	Operating Procedures
			Safe Work Practices
Employee Participation			Workforce Involvement;
			Stakeholders Outreach
Training	Yes		Training and Performance Assurance
Contractors			Contractor Management
Pre-startup Safety Review			Operational Readiness
Mechanical Integrity	Yes	Yes	Asset Integrity and Reliability
Hot Work Permit			Conduct of Operations
			Safe Work Practices
Management of Change		Yes	Yes
Incident Investigation			Yes
Emergency Planning and Response			Emergency Management
Compliance Audits	Yes		Auditing
Trade Secrets			
			Other elements

Note: Yes – the element corresponds to the generic PSM's element; elements filled in grey means this element is not shown in the procedure.

Whether in regulatory standards or companies' procedures, for an element to be functional it must involve a complete process. To this end, procedure and process together make an element functional in a certain way. The process describes the working mechanism for an element, while the procedure provides the requirements, resources, and other supports. An SMS achieving optimal performance relies on functional elements following the system design. As a matter of fact, not every element is expanded with a process or a procedure, especially when they are part of a provisional SMS for a project or a research paper.

3.3.4 The weight of elements

Weighing elements is common in the assessment of safety management systems. If the weight of each element is given, the algorithm for the evaluation of a whole SMS can be developed. However, it is almost impossible to complete this quantitative task because holistic elements relate to a large number of non-quantifiable issues. The application of elements in different industries bring more uncertain definitions, criteria and scopes of the issues concerned. According to the roles of elements in safety management, we roughly describe two ways to assign weights, evaluation of performance indicators and accident data analysis.

3.3.4.1 From the perspective of key indicators for SMS performance

Elements sometimes are denoted with indicators or factors. Weighing elements is always based on perceptions and judgements of experts. For example, the analytic hierarchy process (AHP) method is used to evaluate hierarchical elements. This method typically uses experts' judgments about the relative meaning and importance of elements (Dagdeviren & Yuksel, 2008; Podgorski, 2015). Sometimes the evaluation is for some particular elements or relies on limited information. Papazoglou et al. (2003) assessed the influences of eight delivery systems on selected basic events in safety management. Although several basic events cannot represent the full safety management, Papazoglou et al. proposed a quantitative way to roughly weigh management deliveries. From the perspective of key performance indicators, weighing safety management elements is difficult, and since the data are limited we therefore rely mostly on expert judgement.

3.3.4.2 From the perspective of latent causes of accidents

Another method to determine the importance of elements is by analysing a large number of accidents. Organisational factors have commonly been identified as important causal factors (Vredenburgh, 2002; Tam, 2004; Aneziris, 2008). Safety management factors that contribute to accidents can be tagged as elements; then the number of accidents ensuing from each factor can be determined. Thus, we obtain the percentage of each element that contributes to all accidents in total. For instance, Aneziris (2008) attributed 9187 accidents to the failure of management deliveries, based on Hale's model. The ratio of failed management factors represents the weights of different delivery systems for risk control and safety management.

3.4 Elements for an effective SMS

Studies of the effectiveness of SMSs are usually discussed at a general management system level. Gallagher (2001) proposed four attributes of an effective OHSMS. The type of system should be customised to the organisation's needs; senior management commitment should involve both motives and methods; OHS should be integrated into the general management system of an organisation; management should consult employees. These suggestions show that effectiveness needs the involvement of both senior managerial and operational management. They all relate to the structure and features of elements, such as a continuous improvement structure, the arrangement of safety commitment, etc. Therefore, to understand the mechanism of an SMS, the following sections provide insights into its elements.

3.4.1 A four-layer framework for elements

According to the structure of an SMS and its elements, we can sketch a simple framework of a complete SMS, which contains all the functional elements (Figure 3.2). Each element has its own processes and procedures to fulfil its function. These processes and procedures are carried out in a specific context, like safety activities or tasks. The activities are related to many issues, which may influence the safety performance. Accordingly, we distinguish four layers of an SMS and its elements:

Layer 1: *organisation's safety management.* Here, an SMS for the organisation is developed. It is generic as it should be easy to apply to different projects or plants.

Layer 2: *universal elements for safety management.* Elements have already been structured when the generic SMS is developed. These elements together perform safety functions. Usually, they are of a general nature so that they can be well adjusted to various specific contexts.

Layer 3: *procedure or process for the safety activities or tasks which are being carried out.* Procedures and processes are described in more detail than the general elements of layers 1 and 2. No matter which safety aim is going to be achieved, only managerial and operational safety activities and tasks can fulfil the functions of the elements.

Layer 4: *indicators/factors influencing elements via activities and tasks in a specific context.* Safety management does not merely control activities, it also includes an analytical review and continuous improvement. Therefore, indicators and factors that influence safety performance should be identified and updated for improved control.

3.4.2 Development of elements

3.4.2.1 Define SMS and structure elements

Safety management is a systematic approach to deliver management from top to bottom in industries or projects. Admittedly, none of the existing safety management systems is universal and fit for whatever context (Salmon, 2018). However, considering standardised or industrial regulated guidelines/guidance as a framework for elements is a common and effective way to develop an SMS for an individual organisation. Moreover, the PDCA-cycle, continuous improvement, and the hierarchical structure are also helpful when designing an SMS. Defining the scope of safety management of a particular business can help users to structure elements in this context.

3.4.2.2 Establish functional elements and their relationships

In an organisation, we need universal elements or approaches for risk control of all operations. The PDCA-cycle is a typical way to connect all the safety management elements, but there still are other logical links that can help achieve safety goals. According to Hale's SMS, for example, to decrease the number of incidents, it starts from accident analysis; after that, risk analysis and control are completed by safety barriers; these are put into use by means of management deliveries; finally, organisations review this process and learn from it. There are common, generic elements and connections even though industries have their own specific requirements.

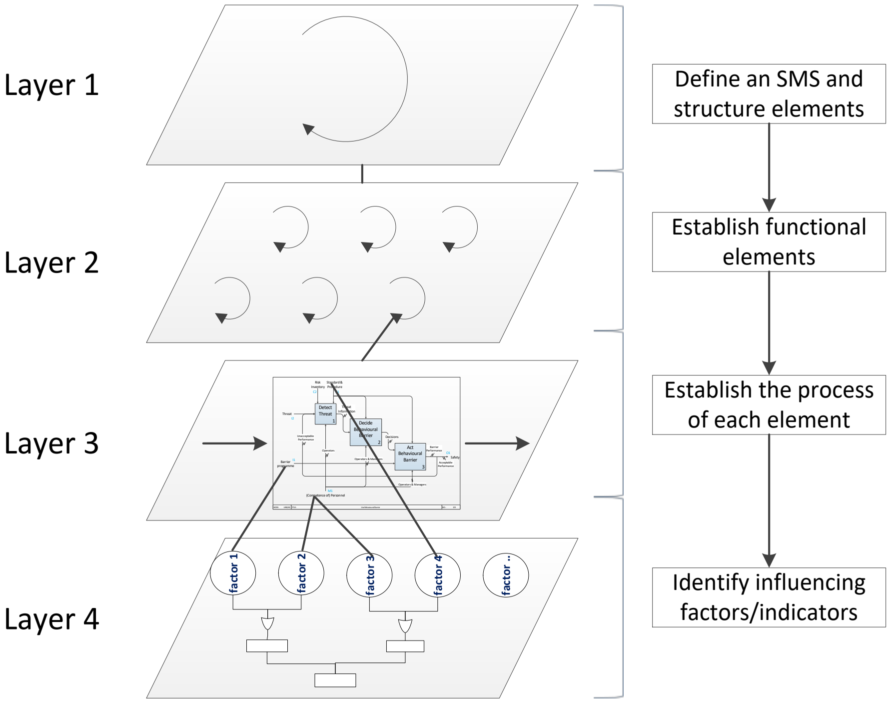

Figure 3.2 – The four layers of an SMS and the development of elements therein

3.4.2.3 Establish the process (IO) of every element: essential idea is control

A process of an element involves specific activities and logical connections between them. Researchers commonly apply systems control, i.e. an input-activities-output structure, to model them. Procedures describe how the processes of elements can be put into practice by detailing the necessary resources, principles and requirements. The essential idea behind modelling these elements is control.

3.4.2.4. Identify the indicators/factors influencing the elements in a specific context

During the execution of safety management activities, key performance factors that have been defined, affect the performance of elements. Some of them function as pure safety key performance indicators, others are meant as safety management influencing factors. They may contribute to one particular item which is critical for safety. For example, safety training affects people's competence to perform safety tasks, which in turn influences (the) safety management performance. These indicators or factors need to be customised to the particular industry or particular scenarios. For example, the training of how to use a brake system of a particular vehicle affects this barrier's performance.

3.4.3 Judgement on effectiveness

The effectiveness of an SMS is judged through safety auditing or the monitoring and reviewing of each of the SMS's elements with various performance indicators. Akyuz (2014) developed nine key performance indicators (KPIs) to measure the effectiveness of the implementation of a safety management system. Although these indicators have been derived from literature rather than structured elements, they are related to the performance of most elements. For instance, the indicator *number of the near-miss reports* is associated with the element *accident investigation;* the indicator of *audit judgement* is the result of the element *audit*. However, question remains why just these particular indicators determine the effectiveness of an SMS and not others? Hochleitner (2017) claims that functional safety audits evaluate the management system and procedures specifically, which keep safety controls effective. Therefore, regarding all the elements as functional systems and looking for their key performance indicators is a practical way to judge the effectiveness of an SMS.

This is also the reason why safety audit tools always cover a complete SMS framework using multiple elements. For instance, the international safety rating system (ISRS) contains eleven elements to cover all aspects of an SMS; INTEGRA, developed by DNV, is a modified ISRS; the I-RISK audit approach is based on Hale's SMS model, etc. Kjellen (1993) defined a safety audit as "a systematic and independent examination of a company's safety management system" (cited in Inge, 1998, p. 13). Either in a generic external audit or specific internal audit, the safety management performance must be evaluated (or judged) by auditors using comparable criteria for each indicator. The processes of the elements provide the parameters for the judgement (see Layers 3 & 4 in Figure 3.2). Elements are therefore crucial for the judgement of an SMS.

3.5 Conclusion

An organisation implements an SMS with a series of functional elements, which together form a logical framework. The PDCA-cycle or an adapted PDCA is necessary for continuous improvement of SMSs. In addition, a hierarchical structure is the most commonly used structure as it is both systematic and practical. Grouped elements or elements aligned in parallel are used as well, especially in a provisional SMS, e.g. for a project. A suitable framework for the elements reveals a clear-cut plan of an SMS.

Connecting elements, which is like using lubricant on gears, facilitate the safety management functioning. With connections between elements, safety management becomes a process. Furthermore, elements contain activities and tasks, involving equipment or employees. Within the framework of each element, activities are linked in a certain way as well. The requirements for implementing the element are recorded in a procedure, which can be either general or specific depending on the context. Connections, processes and procedures are all used to construct elements.

According to the literature, elements can play three roles in an SMS, namely principal functional components, key indicators of SMS performance, and the latent causes of accidents. The first role is distinct as safety management is modelled as a system. Sometimes the elements represent key performance indicators because their performance determines safety management. Causal analysis of accidents will reveal the elements involved. Therefore, either a positive or negative performance of elements will provide useful information for safety management and research.

Hale's SMS model gives a standardised framework, a complete system with functional elements. Mapping various SMSs onto Hale's model shows the importance of each element from the perceptions of SMS users. Most SMSs are known for their risk control function. The importance of management here is obvious, especially on the aspects of planning, procedures, competence and commitment.

Mapping the PSMs used for various purposes points to different uses of elements. When an SMS is applied in an industrial sector or for a project, the appropriate processes and requirement of each element become more explicit. It is noted here that for the same industry branch, SMSs can consist of different elements, as long as they function well.

We have developed a four-layer model to understand the development and role of elements in SMSs (Figure 3.2). It provides a generic approach to develop functional elements. This model shows that the general elements must fit into a continuous improving SMS; the process of safety activities and tasks fulfil the function of each element; the output of the elements provide critical factors, indicators or parameters that influence safety performance (or accidents); monitoring, reviewing or auditing can be used to assess the effectiveness of the SMS. In conclusion, SMSs fully rely on the well-functioning of their elements.

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4 DELIVERY SYSTEMS: A SYSTEMATIC APPROACH FOR BARRIER MANAGEMENT

Abstract

Having considered the generic SMSs and their constituent elements in the last two chapters, we model the important aspects of safety management in this chapter. How the safety management to keep safety barriers functioning was unclear. This intention is to show how such management can control and quantify safety barriers.

Safety management systems usually follow specified formats, as required by standards and other procedures. The quality of such systems is often assessed at the ordinal measurement level. This chapter introduces a barrier-based safety management system coupled with a quantitative approach to safety management modelling. The risk control part of this system is composed of so-called delivery systems, which describe the management processes that manage barriers. The proposed approach aims to determine how the delivered management factors affect risks by influencing the functioning of barriers. Taking the competence delivery system as an example, people's competence are delivered to carry out the tasks of barriers, and these tasks guarantee the barriers' effectiveness. In this research, barriers are grouped into five types. By quantifying competence indicators and the performance of each type of barrier, the link between a delivery system (competence) and the barriers is established.

This proposed approach is still theoretical. However, on this theoretical basis, we expect that other delivery systems can be quantified in a similar way, meaning that safety management systems will work more efficiently with such monitoring. In addition, this quantification can be used as input for audits, by making assessments more transparent.

4.1 Introduction

Safety management systems (SMSs) are commonly defined as the management procedures, elements and activities put in place to control and improve the safety performance of an organisation. Safety management has general aspects and mechanisms that can be modelled. The aim of this chapter is to present a systematic and potentially quantitative approach for modelling safety management factors of the safety barriers as a starting point.

Accident prevention theories provide information for safety management. In the development of hazard scenario models, control and prevention play a pivotal role in improving safety performance. Following the reasoning underlying linear, epidemiological or systematic causal models, the basic idea of management and control is to provide the means or measures preventing unwanted loss. For instance, the Bowtie model was derived from Haddon's Hazard-Barrier-Target (HBT) model, that describes potentially harmful energy flows (Haddon, 1973). Barriers are devised and inserted in the Bowtie model to prevent, control and mitigate critical events and their consequences.

Firstly, we will introduce the concept of management delivery carried out by delivery system processes. Then we will zoom in a particular delivery system, the competence delivery system, which delivers competence to all people dealing with safety barriers. The concept of safety barriers and their classification will be analysed next, and we indicators assessing the quality of competence and of various barriers will be proposed.

4.2 Delivery systems model

4.2.1 Approaches to safety management modelling

In terms of safety management modelling, quantitative approaches will enhance the validity of a safety management system and provide a means to assess their effectiveness and quality. Several approaches have been developed in a series of projects, e.g. frameworks like the Work Process Analysis Method (WPAM) (Davoudian et al., 1994a, 1994b), System-Action-Management (SAM) (Paté-Cornell & Murphy, 1996; Murphy & Paté-Cornell, 1996) and Organisational Risk Influence Model (ORIM) (Øien, 2001). These quantitative approaches for safety management modelling can be summarized as follows: (1) develop a (generic) model or framework for safety management; (2) weight or rate its major management factors and (3) study their effects on risks and SMS quality.

The SMS-model resulting from the WPAM-project incorporates organisational factors in an overall risk assessment (Davoudian et al., 1994a, 1994b). This model combines an event tree with an organisational model. A series of organisational factors were identified and their effects on a specific safety system were assessed. This model demonstrates the impact of organisational factors on work processes and connects these organisational factors to probabilistic parameters of barriers, such as failure rates, available time to recover etc.

The System-Action-Management (SAM) approach provides a framework for human and management effects on risk (Paté-Cornell and Murphy, 1996; Murphy and Paté-Cornell, 1996). SAM proposed a quantitative probabilistic approach to calculate the influence of human and organisational factors on the probability of loss.

Finally, ORIM, which is based on leak event reports, also applies organisational factors (Øien, 2001). Within this study a quantitative model and an accompanying methodology were developed and the resulting algorithm linked organisational factors to leak frequency. Using leak events data, a quantitative methodology for assessing the effect on risk (leak frequency) is supplied. All these researches explored the relationship between organisational factors and risks with certain probabilistic methods. A generic model and suitable approach for all cases is expected in a different context.

4.2.2 Delivery systems development

Delivery systems (DSs) were originally defined for the I-RISK model (Guldenmund et al., 2006; Papazoglou et al., 2003). They are principal management systems that influence and ensure the continuous functioning of barriers (Duijm, 2009; Markert et al., 2013), i.e. both hardware and behavioural barriers.

Originally, Hale (1997) globally defined safety management as: input-process–output and feedback (Figure 4.1). Input consists largely of information or documentation (plans, designs, calculations, assessments, etc.). Resources are hardware, people and the organisational efforts required to carry out safety activities. Criteria are the requirements or standards that determine, monitor and control the delivery system's processes and evaluate its output. The delivery process itself is the transformation of input(s) to the delivery system. Eventually, the delivery system's output determines the performance of barriers. The output is used as feedback, which is processed and evaluated to make improvements to the input. In the I-RISK project, delivery systems were studied qualitatively using a specific case, basically a technical model with parameters (Papazoglou et al., 2003). Within the ARAMIS-project a probabilistic approach for barriers was designed along with weighted delivery systems (Duijm, 2009; Duijm and Goossens, 2006). The subsequent WORM-project connected the failure of barriers to delivery systems with data from Dutch occupational accident records (Aneziris et al., 2008; Aneziris et al., 2012). In the CATS-project (Ale et al., 2010) bowties and delivery systems were applied for aviation safety. A semi-quantitative approach was used to weight delivery systems and the authors explored how some particular factors in delivery systems affect barriers (Ale et al., 2010; Lin et al., 2008). However, complete generic delivery systems and management factors, as main contributors to the effectiveness of barriers, still have not been fully studied.

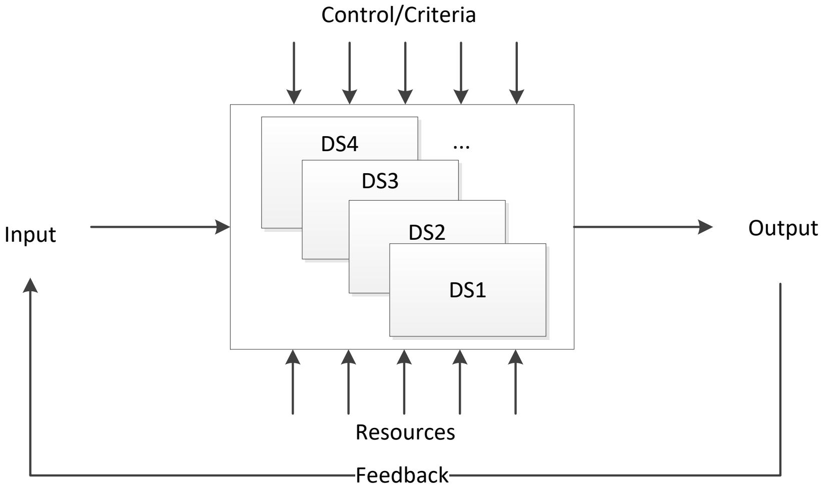

Figure 4.1 – The framework of delivery systems (DSs)

4.2.3 Delivery systems for safety management systems

Delivery systems are not only management systems to deliver functions of barriers and controls but they can also be used for auditing, and they have been applied as such in both I-RISK and ARAMIS projects. The previous studies and projects, to some extent, explored the relationship between barriers and delivery systems, or even between hazard scenarios and delivery systems. However, what is the precise role of delivery systems in a safety management system?

A delivery system is a part of the risk control system within a generic model of a safety management system, according to Hale (2005) (see Figure 2.6). This SMS contains all processes and their relations. Various business processes (Box 1, in Figure 2.6) implement the safety management system covering all life cycle phases of the plant and is therefore responsible for the design, construction, and the technology used in controlling safety. Box 2 involves identifying and examining the hazards, understanding how they become manifest and how they should be controlled. Activities in Box 3 define the risk barriers and controls. It devises the management system according to the context and its proper function. The elements in Box 4 constitute the set-up of the system. These are the delivery systems, supporting both Box 6 (audit and review) and Box 3 (risks barriers and control). As for the zigzag line between Box 1 and Box 3, it simply indicates that things can go wrong in this process but, at the same time, they can also be controlled. So the system needs input from incidents and accidents (Box 7) to learn and improve. If mishaps do occur, barriers and controls should be in place. Finally, regular inspection and frequent monitoring (Box 5) always have to be carried out in the management of barriers and controls.

All the delivery systems defined in Hale's SMS support the overall management of barriers. Barriers can be classified as not only hardware- and software-based, but also as requiring knowledge-, rule- and skill-based cognitive effort, or as requiring more active or passive behaviour from the operator's part (Duijm, 2009; Guldenmund et al., 2006) (again, these terms will be explained in detail below). Delivery systems are designed for these multiple demands in delivering the barriers' functions. Hale's SMS shows the following delivery systems, which all deliver to the whole lifecycle of barriers:

A. Competence, suitability of people;
B. Commitment, conflict resolution;
C. Communication, coordination of teams;
D. Procedures, rules, goals;
E. Hardware, spares;
F. Interface, ergonomics;
G. Availability, planning of people & hardware.

4.3 The delivery system "Competence of personnel"

4.3.1 Definition of competence for safety management purposes

Competence is an old term stemming from French and denoting an individual's ability to do some kind of job. Nowadays, competence is defined as a process of activities (Ritter and Gemünden, 2003). Stracke (2011) states that competence is 'the ability that cannot be observed directly but only by activities to adequately and successfully combine and perform necessary activities in any context to achieve specific tasks or objectives' (p. 35). Thus the process of competence for safety management shows the activities delivering competence to accomplish tasks required for the operation, maintenance and monitoring of barriers.

Competence has various dimensions depending on the perspective taken, such as: intelligence, problem solving and knowledge; skills, ability and attitude; cognitive, content and literacy aspects; abilities and knowledge, etc. (Kauertz et al., 2012). Competence is also defined as a cognitive asset used to solve problems which led Djaloeis et al. (2010) to distinguish between personal, professional and social competence. No matter which classification is used, competence can be cognitive, technical, integrative, context-dependent, relationship-focussed, or affective as well as moral habits of mind (Epstein and Hundert, 2002).

Safety competence for risk control systems is shaped by knowledge, experience, training and skills (KETS) (Lovell and Hill, 2013). Bain (2009) considered safety competence as the combination of training, knowledge, experience, ability and common sense, the latter meaning judgement and attitude. Next to these elements, Ebrahimi (2010) argues that certification should be included as well, because it will also indicate some ability. People having safety leadership roles should be competent with regard to this aspect too, as leadership reflects on safety excellence (Carrillo, 2002). In the European ARAMIS-project, competence was defined as the knowledge, skills, and abilities of first-line and/or back-up personnel for the safe execution of safety-critical tasks related to barrier functioning or management. Competence then covers the cognitive aspects of behaviour, which can be learned through training, experience and practice (Betten, 2004).

Employees in different positions, departments, industries, etc. have their own required level of knowledge, skills and experience. This kind of professional competence to some extent determines work performance and barrier tasks performance. The UK regulation highlights competence assurance, which requires duty holders to follow the competence management system (CMS) as a guideline for the Control of Major Accident Hazards (COMAH). CMS commonly incorporates 'recruitment requirements, site induction materials, training courses, risk assessment tools, human error analyses and training needs analyses' (Lovell and Hill, 2013, p. 1). This system provides an approach and criteria for the inspection of a competence management system. Competence is therefore the ability to undertake responsibilities and perform safety activities whereas competence management means arrangements 'to control in a logical and integrated manner, a cycle of activities within the organisation that will assure', and develop, competent performance (COMAH, 2011, p. 8).

4.3.2 The process of competence delivery system

The delivery system for competence is primarily concerned with providing competence to personnel working for the successful operation of barriers. Therefore, competence pertains to both physical and cognitive qualities of workers. On the one hand, competence is necessary to carry out the steps of the hardware life cycle, because the success of hardware barriers depends on correct adjustment, inspection, testing and maintenance of (hardware) barriers. On the other hand, with regard to cognition, competence is expressed as the necessary knowledge of rules and procedures and skills, required for behavioural barriers. The output of this delivery system is competent workers with adequate situational awareness who can handle the safety-critical tasks they are assigned to, in routine operations, or highly critical situations during unplanned or unexpected situations.

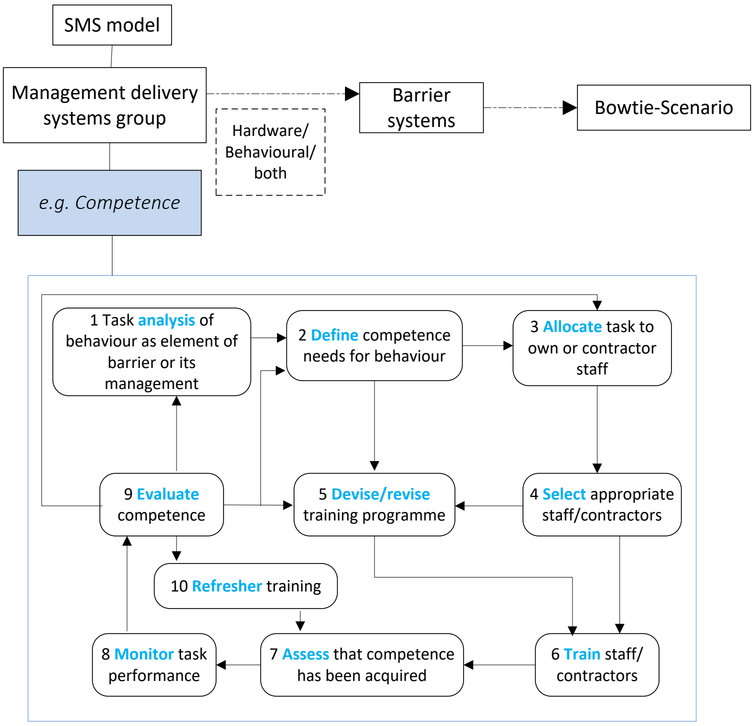

Figure 4.2 – The process of competence delivery

The process of competence delivery is shown in Figure 4.2. Task analysis of behaviour is based on barrier analysis, which specifically describes the activities that are required for the barrier operation according to specifications. The behaviours required for proper barrier functioning determine the necessary skills and knowledge delivered by the Competence delivery system. According to these needs, managers allocate tasks to qualified staff. However, the selection of suitable staff is not enough, because an effective barrier not only requires the right person but also well-organised training programmes related to various aspects of the barriers. These steps, presented in Figure 4.2, succinctly illustrate the competence delivery process.

4.4 Establishing a relationship between competence and barriers

4.4.1 Barriers

4.4.1.1 Function

The term 'barrier' was one of Haddon's ten strategies of safety countermeasures, which he defined as a separation by insertion of a material barrier. Progressively, 'barriers represent the diverse physical and organisational measures that are taken to prevent a target from being affected by a potential hazard' (Johnson, 2003, p. 26-27; Basnyat et al., 2007, p. 546).

The notion of barrier function denotes the purpose of a barrier for controlling a particular hazard. According to Markert et al. (2013) a barrier function is 'a function planned to prevent, control, or mitigate the propagation of a condition or event into an undesired condition or event. Furthermore, a safety barrier is a series of elements that implement a barrier function, each element consisting of a technical system or a human action' (p.284).

Barriers are usually classified by functions in so-called Bowties. The Bowtie model originates from Haddon's Hazard-Barrier-Target (HBT) model and represents the generic strategies for control of potentially harmful energy flows (Haddon, 1973). This model is a causal model for building accident scenarios, with the application of both the fault and the event tree (Nielsen, 1971, 1974; Ale et al., 2006; Hollnagel, 2008; Markowski et al., 2009; de Ruiter and Guldenmund, 2016). An accident scenario is represented by a cause-effect trajectory through the Bowtie describing the sequence of an accident or incident (Nielsen 1974). In the Bowtie, an accident scenario is a 'description of a typical situation that covers a set of possible events or situations' (Khan and Abbasi, 2002, p. 468).

In Bowties barriers are added to prevent, control or mitigate both the critical event and its consequences. On the left hand side of the Bowtie, the barriers are to prevent the critical event from taking place. According to the logic of the Bowtie model, 'this can be done by hindering preconditions or initiating factors from having an effect that changes the critical event from a possibility to a reality' (Hollnagel, 2008, p. 223). On the right hand side, the barriers are 'to protect against the consequences of the critical event if or when it happens, all the precautions notwithstanding' (Hollnagel, 2008, p. 223). However, some barriers are both preventive and protective to some extent. For instance, monitoring is a preventive barrier, that is, an activity, before a building might catch fire, but could be useful also after a fire has occurred, although then it is considered a protective barrier. Defining barrier functions is one way to describe a barrier and its functions can change with different applications.

4.4.1.2 Phases

Barrier phases represent the sequences in activating a barrier. For instance, Duijm (2009) uses the 'Detect–Diagnose–Act' sequence, taken from the I-RISK, ARAMIS and WORM projects, to classify individual barriers. Similarly, in the Bowtie-XP analysis tool , most barriers have a similar activation sequence of 'Detect–Decide–Act'. A barrier could be in place to detect some threat, could decide which action to take given the threat, and then could act, i.e. become fully functional. However, not all barriers need to complete this full sequence to be functional as a barrier. For example, during a flood a dam functions passively as a barrier. Obviously, it then only works in the 'Act' phase. In general, however, barriers carry out their function through this sequence.

4.4.1.3 Types

Defining a barrier typology means dividing a large amount of different barriers into a small set of separate groups. Table 4.1 shows an overview of barrier classifications. Some typologies relate to definitions of barriers, some are based on barrier functions and others are classified following the application of the barrier as presented by Sklet (2006).

Table 4.1 – Overview of barrier classifications

Author(s)	Based on	Classification
Hollnagel (2008)	Barrier system and barrier functions	1. Physical 2. Functional 3. Symbolic 4. Incorporeal
(Bellamy et al., 2007)	Full operation of a barrier to fulfil a safety function: detection, diagnosis, and action	1. Passive hardware barriers 2. Active hardware barriers 3. Behavioural barriers or elements that involve some kind of human intervention (or humans refraining from interfering with hardware barriers)
(Betten, 2004; Duijm, 2009; Guldenmund et al., 2006)	Distinction between hardware, software and behavioural (i.e. human involvement) barriers and Rasmussen's skill, rule and knowledge typology (Rasmussen, 1983)	1. Permanent passive control (hardware) 2. Permanent passive barrier (hardware) 3. Temporary passive (Temporary) 4. Permanent active (hardware) 5. Activated/on demand (hardware) 6. Activated-automated (hardware) 7. Activated-manual (behaviour: rule or skill-based)) 8. Activated-warned (temporary) 9. Activated-assisted (behaviour: rule or skill-based) 10. Activated-procedural (behaviour: rule or skill-based) 11. Activated-emergency (behaviour: knowledge-based)
(de Dianous & Fiévez, 2006)	ARAMIS-project	1. Passive barriers 2. Activated barriers 3. Human actions 4. Symbolic barriers
IEC 61508/11	Definition	1. Prevent 2. Control 3. Mitigation

In order to understand how a barrier operates effectively with the appropriate operators' competence, we classify barriers using five different types (see Table 4.2). (1) A behavioural type of barrier requires human involvement during its full sequence; (2 and 3) a socio-technical barrier involves man-machine control and focusses on the interaction between the operator and the barrier; furthermore, a hardware type of barrier can operate automatically or logically, the (4) active hardware type has a full barrier sequence without human involvement whereas the (5) continuous and passive hardware type normally only are active during the act phase of the barrier sequence (e.g. a wall or levee). This typology is based on barrier types presented by Bellamy et al. (2014) and on the ARAMIS-project.

After classifying barriers, we need to analyse how competence affects different types of barriers and how important safety competence is for them. Competence of people is a management issue referring to human involvement with barriers; behavioural and social-technical types of barrier all require direct human behaviour to be effective, hardware barriers only have indirect human involvement during all hardware life-cycle phases, i.e. purchase, installation, use, monitor, maintenance, inspection, improvement. Both a behavioural and a hardware barrier need input from the competence delivery system.

Table 4.2 – Barrier types based on barrier phases

Barrier type	Barrier type in ARAMIS-project	Examples	Detect	Decide	Act

1. Behavioural	10, 11	First aid and assess extent of injury, consider diversion/emergency procedure, follow start up/shutdown procedure	Human	Human	Human
2. Social-Technical (a)	7, 8, 9	Calling fire brigade on alarm, refraining from smoking, manual shutdown in response to instrument reading or alarm, advise ATC of your current situation and provide regular updates	Hardware	Human	Human
3. Social-Technical (b)	3, 7, 11	Fire watch activates fire fighting system, using helmet/gloves/goggles	Human	Human	Hardware
4. Active hardware	5, 6	Sprinkler system, pressure relief valve, shutdown system	Hardware	Software/logic	Hardware
5. Continuous/passive hardware	4	Active corrosion protection, heating/cooling system, ventilation			Hardware
	1,2	Dike, pipe/hose wall, anti-corrosion paint			Hardware

4.4.2 Barrier failure resulting from improper competence delivery

The mean failure percentage of all barriers resulting from improper competence delivery is around 12% (Aneziris et al., 2008; Bellamy et al., 2008). In Figure 4.3, 36 hazardous occupational situations are presented and the contribution of competence therein, based on an analysis of 12,000 occupational accident records in the Netherlands (Aneziris et al., 2008). The graph shows that lack of competence as a management factor contributes differently to different kinds of accidents. Insufficient competence of people is one of the main management deficits in controlling occupational hazards. Furthermore, the specific failure modes are various and competence is involved in different proportions for different scenarios. For instance, the scenario 'Contact with extreme hot or cold surface' is not affected by competence, but 27% of the accidents in the scenario 'Contact with hazardous substance without Loss of Containment' result from insufficient competence. However, more detailed aspects of the competence delivery system cannot be derived from Figure 4.3 and the possible relationship with barrier performance is also not revealed by sole accident data.

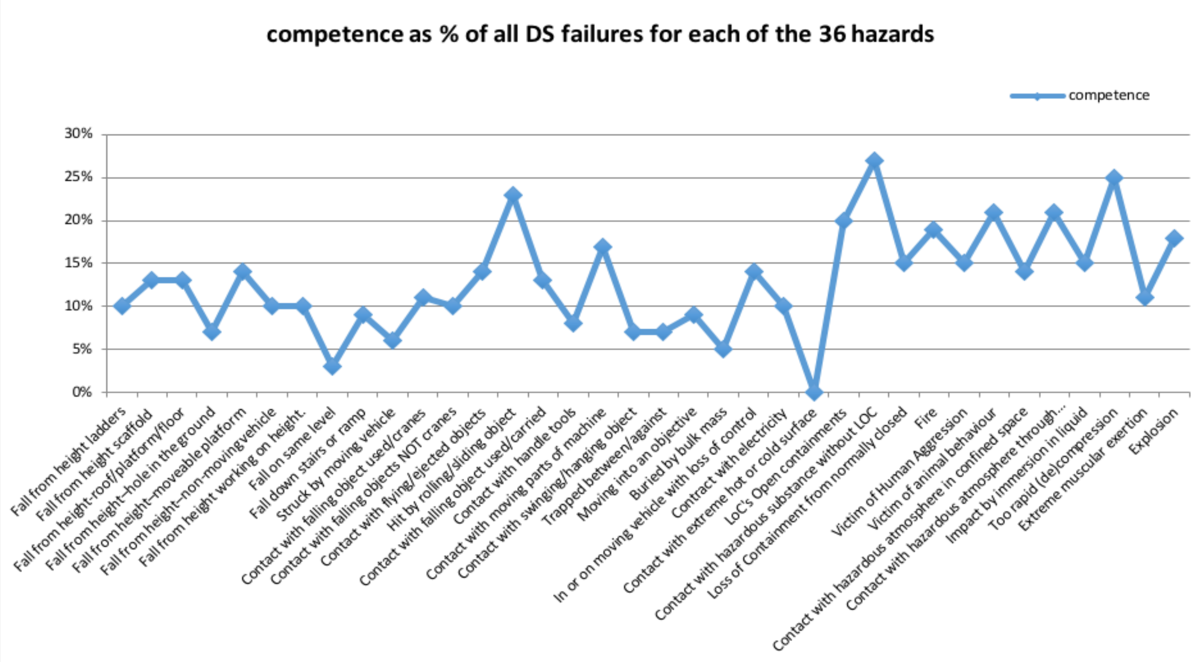

Figure 4.3 – Statistics of improper competence causes incidents and accidents[1]

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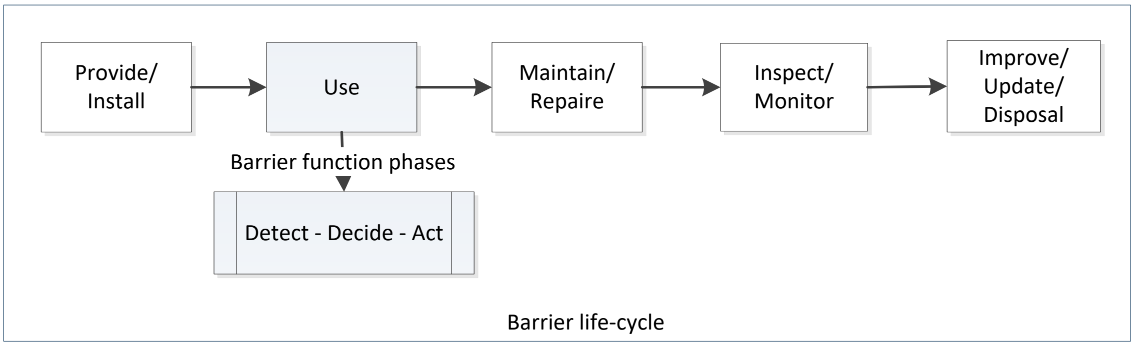
[1] Data from the National Institute for Public Health and the Environment, Ministry of Health, Welfare and Sport, the Netherlands.

4.4.3 Management tasks for barriers

4.4.3.1 Framework of tasks for behavioural and hardware barriers

Management tasks for barriers' performance are collections of necessary activities and responsibilities for various jobs related to proper barrier functioning. The software program Storybuilder (Bellamy et al., 2007) and the HSE-report from Lisbona and Wardman (2010) put forward four general management tasks for proper barrier functioning: provide, use, maintain, and monitor (see Figure 4.4). In the WORM-project, failure of management tasks is calculated separately using Dutch accidents data. In a similar way, in the ARAMIS-project barrier life cycle tasks were defined, which had an impact on barrier effectiveness. These tasks are design, install, use, maintain and improve (Betten, 2004). At the sharp end tasks are people's actions to complete a behavioural and/or hardware barrier successfully. Actions related to behavioural barriers encompass three phases: detect, decide and act, with different tasks or activities in different phases.

Tasks related to hardware barriers are different from those related to behavioural barriers as these carry out the barrier function actively or passively. Except of the automatic 'use stage' of barrier functioning, the management of hardware barriers is connected to almost the whole life-cycle of barriers, and it is also critical for hardware failures. For example, a safety valve is a hardware barrier for a pressure boiler, it functions actively without manual work, but the maintenance and replacement of this valve have a strong safety management influence even though it is not a behavioural barrier per se. Thus the management of the life-cycle of hardware barriers is composed of indirect management tasks. In some equipment maintenance or inspection could be an independent barrier in controlling a hazard and it may be classified as a behaviour or social-technical barrier. Social-technical barriers combine both human behaviour and hardware, and they have to some extent human intervention in both their behavioural phase tasks and hardware life-cycle tasks (See Appendix B). Most of the time, tasks for these barriers focus on man-machine interaction, for instance, reading safety indicators from a control panel, or use of a manual tool for safety work.



Delivery systems manage barriers

Figure 4.4 – Tasks for managing barriers

4.4.3.2 Management tasks for five types of barriers

Appendix B outlines general tasks for the five types of barriers presented in Table 4.2, at operational and managerial levels. These tasks are executed by operators, who work in different positions of an organisation and are responsible for safety tasks. For example, in order to accomplish a behavioural barrier, frontline workers or engineers may identify a hazard and carry out the preventive or protective activities following a prescribed procedure; if operators cannot stop the development of an accident scenario, they will report it immediately and communicate with the people who can solve the threat. Managerial actors could be professional HSEQ managers, who can check and audit barriers. However, other managers – e.g. HR, technical – or other senior-managers, may either be coordinators, supervisors or decision-makers in the lifecycle of a barrier, and at the same time actors in those phases.

The appendix illustrates that these actors play pivotal roles with barriers requiring human intervention or maintenance. On the one hand, competence is extremely important for behavioural- barriers (included in Type 1, 2 and 3) because the quality of this kind of barriers directly relies on the activities of personnel. Furthermore, the process of competence (see Figure 4.2) shows that it firstly develops the tasks of barriers and then defines the required competence needs for them. On the other hand, hardware- (software-) barriers (included in Type 2, 3, 4 and 5) are provided, installed, maintained, repaired, monitored, even updated fully or partly by humans. Therefore, the appendix suggests the role of human involved tasks for five types of barriers, which can be further analysed for specific barriers.

As a part of the safety management system, the competence delivery system process is also mapped onto the barrier tasks (see Appendix B). It also turns out that safety management factors are important in the management of specific barriers. The competence delivery system delivers qualified competence to perform barrier tasks explicitly. Although Appendix B mainly displays the content of the competence delivery system, other delivery systems could be mapped onto the barrier tasks as well. For instance, following a procedure task need 'procedure, rule goals delivery system' as well; following instruction also needs communication, coordination delivery system. Actually, these barrier management tasks are completed by the synthesis of all delivery systems.

4.4.4 Competence indicators

4.4.4.1 Development of a competence indicator

The competence delivery system is one of the behaviour-related delivery systems in the safety management framework depicted in Figure 4.1 (see also Guldenmund et al., 2006). It generates competence of people for barriers, through which organisations control hazards and risks. According to the definition of safety competence above, KSEA (knowledge, skill, experience and attitude) are identified as first level indicators. There are also contributors specific to the safety professional, which are regarded as second level indicators. General competence indicators are those which are not only for competence for safety barriers but also for other purposes, while specific (safety) competence indicators are identified by considering all barrier life-cycle phases. Indicators at a second level could be assessed by specific parameters using nominal, ordinal, or ratio level measurement. Utilising these indicators, the relationship between competence and barrier performance could be assessed.

Rasmussen (1997) has proposed a socio-technical framework that has a six level safety management hierarchy illustrating that 'many levels of politicians, managers, safety officers, and work planners are involved in the control of safety' (p. 184). For barrier control, companies usually consider only people below the so-called management level because higher authorities or policy makers do not belong to the company level. Regarding inspection of safety competence using a competence management system (CMS) guideline, people in an organisation are split into top-tier and lower-tier. In this chapter we focus on the people who are involved in barrier tasks, that is, barrier providers, including organisational managers and operators; barrier users, including operators and safety supervisors; barrier reviewers, including safety managers, safety supervisors, and internal or external auditors. In Table 4.3 and Appendix B, two general levels are considered: operators and managers, whose specific titles may vary in different industries.

Operators could be defined broadly as the employees who complete the operational tasks, including frontline workers, engineers, inspectors etc.; managers refer to all managerial personnel like mid- or senior- managers, who complete the managerial tasks. As their responsibilities regarding (the functioning of) a barrier are different, some indicators of competence are designed only for managers, such as general management system knowledge, organisation knowledge, and particular management skills and experience. Other indicators only apply to operators, like the skills of using some specific tool or equipment. Managers' competence is not entirely different from operators', but they could have different requirements even with the same indicator when the tasks related to a barrier are carried out (Table 4.3).

Table 4.3 – The indicators of competence

Indicator (first level)	General/ (Safety) Professional	Indicator (second level)	Examples	Operators	Managers	Measure
Knowledge (K)	GK	General SMS	ISO standard, company SMS		✔	Yes/No
	GK	Organisation knowledge	Staff, department, organisational function		✔	Degree
	PK	Hazard scenario	(Fire, explosion) threats and consequences	✔	✔	Percentage
	PK	Barriers	Regular inspection, firefighting system	✔	✔	Percentage
	PK	Tasks procedure	Emergency procedure	✔	✔	Degree
	PK	Regulation/rule for specific tasks	Disposal of hazardous materials; confined space	✔		Degree
Skill (S)	GS	Communication skill	Verbal, written communication for inspection	✔	✔	Degree
	GS	Reading/writing skill	Local language	✔	✔	Degree
	GS	Management skills	Encourage employees, safety competition		✔	Degree
	PS	Identification of hazard/threat	Using a hazard detection tool or method	✔		Degree
	PS	Hardware using skills	Fire extinguisher	✔	✔	Degree
	PS	Behaviour barrier skill	First aid, confined space protection	✔	✔	Degree
	PS	Reporting method	Using online information system	✔	✔	Degree
Experience (E)	GE	Education level	Diploma	✔	✔	Degree
	GE	Working time	Years	✔	✔	Time
	GE	Frontline (engineer) experience	Specific skill diploma, job training time	✔	✔	Times/number
	GE	Management experience	Management certificate, years of management job		✔	Degree
	GE	Accident (Hazard) experience	Accident/injury experience, accident/hazard analysis involvement	✔	✔	Times
	PE	Using barrier tools (just using tool maybe not for safety work)	Using extinguisher, PPE, cleaning tools, etc.	✔	✔	Degree
	PE	Experience specific barrier	Firefighting, housekeeping	✔	✔	Times
	PE	Safety training	Certified safety training	✔	✔	Times/Degree
Attitude (A)	GA	Safety awareness	Strong/weak	✔	✔	Degree
	GA	Attitude towards accident	Panic/calm	✔	✔	Degree
	PA	Attitude towards barrier cost	Costly/beneficial	✔	✔	Degree
	PA	Habit of mind for barrier	Fixed/growth	✔	✔	Degree
	PA	Attitude towards barrier tasks/procedure	Willingness/unwillingness	✔	✔	Degree
	PA	Attitude towards barrier result	Positive/negative	✔	✔	Degree

	PA	Attitude towards specific rules/regulations	Disobey/comply	✔	✔	Degree

G – General, P – (Safety) Professional

4.4.4.2 Knowledge, Skills, Experience and Attitude (KSEA) and their relationships

Competence for management of barriers is typified by four main indicators. Knowledge for barrier's management not only includes the information of the general and specific regulations and the procedures of tasks, but also pertains to 'heuristic know-how' at the workplace (Rasmussen, 1997). The ability of accomplishing or fulfilling a barrier is determined knowledge of the barrier itself, its handling or operation (skill-based knowledge), and some basic knowledge or common sense. Skills of operators for barrier tasks consist of identifying hazards and choosing suitable barriers. Skills of managers are focused on management skills, including skills of arranging manpower, equipment and other resources that ensure barriers can be applied effectively. Some skills, like communication and reporting, are required for both operators and managers. Experience is also an important indicator: experience with accidents or injuries provides good lessons for an organisation; training courses or competition experience could enhance safety knowledge and skills; even experience of handling a barrier improves professional safety skills. Finally, the attitude towards barriers is the last of the competence indicators and it precedes the intention to act and therefore affects competence of barrier tasks. Attitudes of people are influenced by mindset, safety awareness, balancing costs and benefits, etc. Table 4.3 shows these main competence indicators illustrated with more specific indicators.

In addition, KSEA-indicators also affect each other. Experience improves one's level of knowledge and skill. Knowledge and skill usually go together. Attitude is influenced by one's knowledge, skill and experience. Therefore, the four indicators are not expected to be independent and possible correlations between these need further exploration.

4.4.5 Relationship between competence and barriers

4.4.5.1 A systematic approach to safety management

Figure 4.5 shows the overall framework for our research. It elaborates the relationship between a delivery system, competence, and a barrier. Because a barrier is complicated and plays a crucial role between the SMS and an accident or incident scenario, the type of barrier (behavioural, socio-technical, etc.) is embedded in this logic. In addition, the competence delivery system delivers competence to manage specific barriers by executing or implementing management tasks. Although the approach is developed only at a theoretical level, the arrows in Figure 4.5 do not simply mean linear connections. These connections can be also complex. One reason is that there are multiple specific barriers and barrier tasks; another reason is that not all indicators are easy to identify and quantify.

As we want to explain this logic in a systematic way, firstly, individual barrier types are classified using the five types discussed earlier, making management of barriers more transparent and efficient. Secondly, general tasks for the five types of barriers are developed. When an organisation adds a barrier, tasks are subsequently implemented for this barrier. Thirdly, when competence indicators have been identified, they will have a different impact on different kinds of barriers. The weights of competence indicators for barriers are important because industries expect to know the critical indicators to improve competence for barriers and further improve safety performance. Fourthly, those indicators represent the output of a competence delivery system. If the relationship between barrier performance and competence indicators is known, a performance assessment of this delivery system can be carried out. As this delivery system is a part of a safety management system, the whole SMS performance can be assessed also. As a result, these indicators facilitate safety audits and a KPI (Key Performance Indicator) system in any organisation.

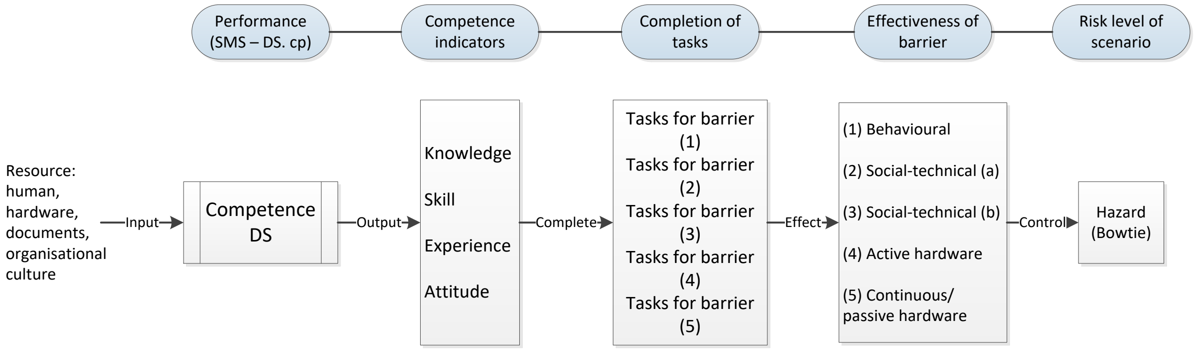


Figure 4.5 – The structure of the research approach

4.4.5.2 A simple case of 'Use behavioural barrier'

The output of the competence delivery system, with indicators KSEA, affect the five types of barriers through the five management tasks for barriers (Figure 4.5). As an illustration, a straightforward case of the modelling of a behavioural barrier is presented. Competence of personnel plays a critical role in all (behavioural) barrier function phases, which include a detect, decide and an act phase. As can be seen from Table 4.2, there are people involved in all stages of a behavioural barrier. To illustrate how the competence of personnel influences barriers, we describe the use of a behavioural barrier applying the modelling method SADT (Structured Analysis & Design Technique, also called IDEF0). With SADT any activity can be modelled in a systematic way using only the input, the actual process and the output of the system as well as the controls for that system to keep its process within its boundaries and the resources (mechanism) for the system that are applied in the process to produce its output. This system could again be decomposed into similar sub-systems, sub- sub- systems, and so on. In this way, we will find what kind of competence is needed to run a behavioural barrier, and how. Thus the logic between competence of personnel and barrier can be clarified clearly.

Figure 4.6 & 4.7 show a generic model of the use of a behavioural barrier, which can be decomposed to model specific operational activities. The inputs (I), controls (C), mechanism (M) refer to the deliveries in a SMS model, i.e. the resources of an organisation. For example, mechanism M1 in this model is labeled competence of personnel, which is the output of the competence delivery system. The output O1 denotes the barrier performance which should lead to safe performance ultimately. If barrier performance is acceptable we will achieve safety; however, if it is unacceptable, a threat remains and the barrier will need to be activated again. Inputs, outputs, controls, and mechanisms at a lower level (Figure 4.7) should appear also at the top-level diagram (Figure 4.6). We could elaborate detect, decide and act phases further in detail by using the tasks in Appendix B. Thus, the model shows the link between delivery systems and specific management tasks, and also the connection between the management tasks and a barrier.

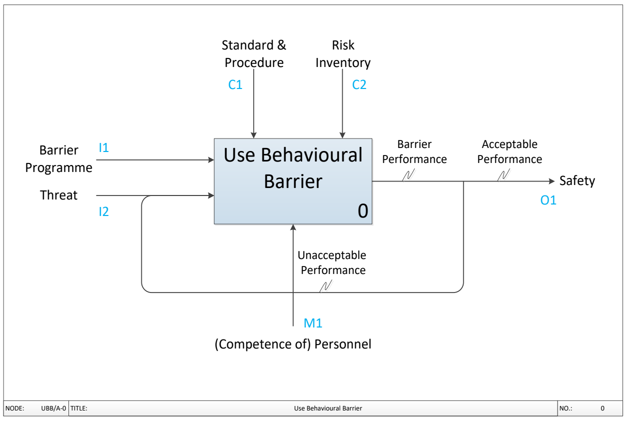


Figure 4.6 – The top-level diagram of model 'Use behavioural barrier'

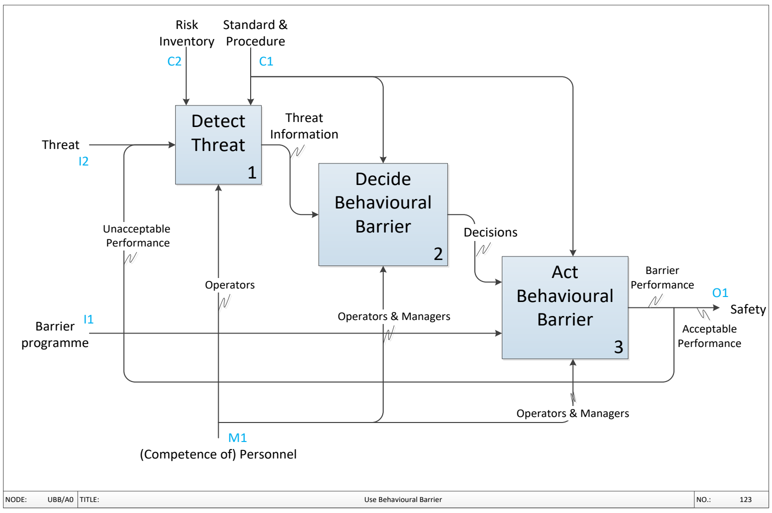


Figure 4.7 – Decomposition of the model 'Use behavioural barrier'

4.5 Discussion of a potentially quantitative approach

Based on the model of the relationship between the competence of personnel and the performance of barriers, a quantitative approach to safety management can be proposed. Assuming that barriers are all provided for a particular hazard or accident scenario, currently there are two ways to evaluate the performance of barriers (BP_j is defined in Table 4.4). One method is by monitoring the performance of a particular barrier, if its performance can be monitored and evaluated. Most of these barriers are hardware barriers and their indicators are probabilities, such as reliability rate, failure rate, etc. However, there are a large number of barriers having behavioural or social-technical elements which are much more difficult to observe or monitor continuously. A way to monitor their functioning is through auditing, using pertinent questions about the barrier. For instance, what is the frequency of inspections? Although carrying out 'barrier-audits' might solve some data issues, but certainly not all. Firstly, audit questions refer to different aspects of barriers (frequency, effectiveness, efficiency, availability, etc.) and some these cannot be expressed in numbers. Therefore, it will require a uniform indicator to describe the performance of any barrier. Secondly, a criterion is needed to evaluate the answer. Not all barriers have regulations or common rules to comply to. This chapter provides a systematic way to observe, monitor, or audit any barrier.

Since barrier performance is an outcome of safety management and is modelled with barrier tasks, the extent to which management tasks are fulfilled determines the performance of a barrier. Appendix B provides a framework of tasks that will facilitate the evaluation of barrier quality. It shows that modelling management tasks and even more specific activities for barriers is a feasible and reasonable method to get data on barrier performance, which are otherwise hardly ever obtained as such. Table 4.5 summarises the performance of five types of barriers that can be evaluated by using a scale from 0 to 10.

Table 4.4 – Definition of the parameters

Parameter	Description	
i	$i \in I$	$I = \{K, S, E, A\}$ (Indicators)
j	$j \in J$	$J = \{1, 2, 3, 4, 5\}$ (Types of barriers)
BP_j	The performance of barrier type j	
CA_j	The competence required for barrier type j	
C_i	The aspect i of competence (first level indicators presented in Table 4.3)	
W_{ij}	The weight of competence C_i for barrier performance BP_j	

Table 4.5 – Barrier performance (BP)

Type (group) of barrier	Barriers	Fulfilment of barrier tasks (score)	Barrier performance (BP) for each type of barrier
(1) Behavioural	Behavioural barrier 1, 2, 3, 4, …	(0-10)	BP_1 (0-10)
(2) Social-technical (a)	Social-technical (a) barrier 1, 2, 3, 4, …	(0-10)	BP_2 (0-10)
(3) Social-technical (b)	Social-technical (b) barrier 1, 2, 3, 4, …	(0-10)	BP_3 (0-10)
(4) Active hardware	Active hardware barrier 1, 2, 3, 4, …	(0-10)	BP_4 (0-10)
(5) Continuous/passive hardware	Continuous/passive hardware barrier 1, 2, 3, 4, …	(0-10)	BP_5 (0-10)

The primary aim of this quantitative approach is to find the weight of competence indicators for different types of barriers (W_{ij}). It also means that different aspects of competence might contribute to different types of barriers differently. Furthermore, by using this approach we can address some safety management issues, such as which aspect of competence is critical and how much is needed for a particular behavioural (type of) barrier, a social-technical (type of) barrier, an active hardware (type of) barrier, etc. Hence, these weights can also be used as criteria for safety management and safety audit systems.

Quantification of competence pinpoints the appropriate competence for a certain (type of) barrier. It enhances not only the effectiveness of barriers but also the efficiency of appointing the right person or hardware to carry out the correct barrier tasks. As for auditors and managers, quantitative methods or numeric results are also more accessible and clear-cut.

Assuming that knowledge, skills, experience and attitude (KSEA) are independent, the upper part of Figure 4.8 shows a simple linear relationship of parameters and the way to find the weight. Here, assuming that BP_j (to some extent) is determined by CA_j, the competence C_i can be calculated by the indicator system (Table 4.3). To find the quantification of each indicator C_i, experts will be approached. Then, through the equation $BP_j \sim CA_j = \sum C_i W_{ij}$, the unknown weight W_{ij} can be calculated. If this assumption could be proved, appropriate knowledge, skills, experience and attitude contribute to the performance of barriers.

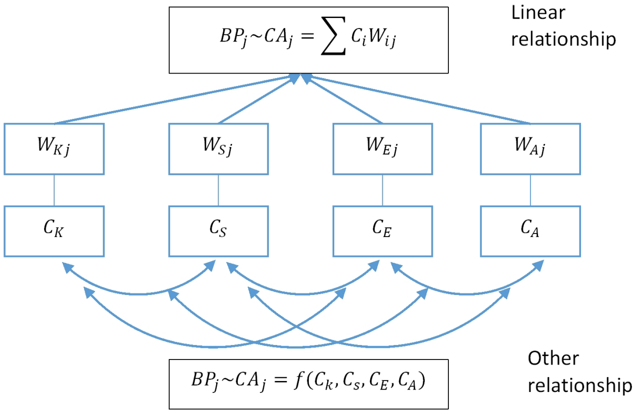


Figure 4.8 – A quantitative approach for the relationship between competence and barrier

However, the competence indicators K, S, E, and A might not be presumed independent. Based on competence indicator data and using for instance, structural equation modelling (Alteren and Hovden 1997; Tomás, Meliá et al. 1999) or Bayesian network (Lin, 2013), we can derive these relationships among indicators, and the relationship between competence and barriers. The bottom of Figure 4.6

also shows the structure of complicated relationship that is denoted by the equation $BP_j \sim CA_j = f(C_k, C_s, C_E, C_A)$. Here, the function or relationship required more data to be defined.

The next step of this research is to develop an algorithm of the quantitative approach for the safety management delivery system 'competence' and the link between appropriate competence and the accomplishment of barriers. Figure 4.8 gives an overview of our approach.

4.6 Conclusion

This chapter has discussed the link between barriers and delivery systems from a systems view perspective. The barriers are the countermeasures that could prevent unwanted events happening or protect organisations from unexpected consequences. In previous research (e.g. in Tripod Delta, ARAMIS, etc.) on barriers, the bowtie model has been used to illustrate hazard scenarios and explain the role of barriers in these scenarios. In this chapter, other aspects of barriers such as its function, its phases and types are clarified in more detail. As a result, five types of barriers have been identified based on their particular use.

Delivery systems were originally established as the (management) processes that deliver outputs of safety management accurately. These management processes deliver competence, commitment and availability of personnel, all aspects of safety communication, procedures and hardware (including interfaces) to control the barriers, in order to meet safety standards. In this study, delivery systems are used to model safety management processes especially for the management of barriers with the following characteristics: (1) delivery systems are the management systems that constitute a SMS; (2) delivery systems can be modelled and decomposed into specific safety management processes; (3) delivery systems support barrier functions; (4) critical factors in delivery systems contribute to barrier and, hence, safety performance; (5) delivery systems provide a systematic approach to quantifying how management factors influence barriers.

The competence delivery system has been used as an example because insufficient competence is a main cause of accidents based on Dutch occupational accidents data. This study has explored competence for safety using four main indicators: knowledge, skills, experience and attitude (KSEA). Every barrier task requires qualified operators and managers to apply their particular competence. Thus, competence is not only one of the delivery systems, but also an organisational factor that contributes to barrier performance.

The competence of personnel supports the whole life cycle of barriers especially their use stage (which also happens to be one of the barrier functions). To analyse the logic between delivered management and barriers, we model the use stage of a behavioural barrier (Figures 4.6 & 4.7). This model not only shows the top-level with detect – decide – act phases, but also standardises operational barrier tasks, because every phase box could be modelled as child and grand-child diagrams in this way. The use of barrier models illustrates that the delivery systems play a pivotal role, providing barrier functions with controls (constraints) or resources (mechanisms) (see Figures 4.6 and 4.7).

The generic barrier tasks are identified, since they are the link between delivery systems and barriers. The tasks include detection, decision and action activities that personnel could take as countermeasures in terms of the behaviour involved in barriers. If there is active, passive, or continuous hardware in barriers, they will function automatically. However, hardware and even software also require personnel to install, maintain, and update them. Consequently, barrier tasks include all the activities of a full life-cycle of a barrier (as presented shown in Appendix B).

Based on delivery systems, this chapter also presents a generic quantitative approach for safety management modelling. A potential quantitative method is proposed, aiming at identification of the relationship between contributors of competence and barrier performance. By using data and applying this method, a concrete competence delivery system and the quantitative relationship between barriers will be obtained. In addition, the other delivery systems could be quantified in a similar fashion. Furthermore, after the quantification of all delivery systems, risk control monitoring and auditing should be carried out. Currently, however, the lack of performance data is not sufficient to provide a quantitative result. More quantitative work on this systematic approach will be carried out.

In conclusion, this chapter has shown how safety management integrated into a SMS, provides a structural way to safety management modelling. Risks are usually analysed by probabilistic methods using accident scenarios, in which barriers could mitigate the risks by preventive or protective functions. Delivery systems have been proposed to manage these barriers. The challenge of this study is to find a precise relationship between different types of barriers and various delivery systems.

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5 MANAGING THE DELIVERY OF COMPETENCE TO SAFETY BARRIERS FOR LIFTING RISK

Abstract

In the last chapter, delivery systems were developed and the competence delivery was decomposed systematically. However, it was theoretical as it was not used in an industrial case. Therefore, this generic approach is discussed further in this chapter, which describes how safety management factors affect risks by influencing the functioning of barriers in such a case – specifically, in regards to a lifting risk.

Lifting risk is one of the most common occupational safety risks, and therefore we will use it to develop the scenario of this study. Firstly, we identify six major scenarios based on actual crane accident data. Secondly, safety barriers are defined to control lifting risk by using the bow-tie method. The process of safety barrier functioning consists of three phases – detect, decide and act – all of which need hardware or active human involvement. The competence of people plays a vital role in these phases, since it affects the operational and managerial tasks associated with safety barriers. In this chapter, managing competence is provided by the overall SMS. We model this relationship using SADT (Structured Analysis and Design Technique). Furthermore, we establish competency indicators for knowledge, skills, experience and attitude as related to lifting. The details of these indicators and how they work on the barrier tasks are clarified systematically. This chapter provides the method with which we will collect concrete evidence for the case study of the quantitative analysis of delivered management.

5.1 Introduction

The competence of personnel pertains to the ability to accomplish work tasks, including safety interventions. Competence also influences the performance of safety management itself. In safety management systems, competence is regarded as a delivered management factor for good functioning of technical/procedural barriers and controls (Hale, 2005). Safety barriers are defined as defences against unwanted events. By implementing these, risk can be controlled or mitigated. Thus, the performance of barriers is critical for safety management and managing competence supports this performance.

Incompetence in operation could be a cause of failure in work processes; furthermore, incompetence regarding a safety barrier could be a cause of an accident. According to the analysis of occupational accident records in the Netherlands, the mean failure percentage of all safety barriers resulting from improper competence delivery is around 12% (see section 4.4.2). It implies that insufficient competence for a safety barrier could lead to failed safety performance and, subsequently, to an incident or accident happening. In this chapter, the relationship between managing competence and safety barriers is developed in the context of lifting risk.

5.2 Lifting risk scenarios

5.2.1 Lifting hazards

A lifting operation is concerned with using lifting devices in the lifting or lowering of a heavy load. Lifting devices are widely used at construction sites, factories, harbours, ports, and other industrial places. These devices could be cranes, forklift trucks, derricks, excavators and so on. Lifting devices are used for different purposes in different sectors. Take the common crane as an example: telescopic cranes, mobile cranes, truck-mounted cranes, tower cranes, etc. are used at construction sites; overhead or bridge cranes are found in many factories like a machine manufacturing plant. At harbours or ports, container handling gantry cranes are used, as well as mobile cranes and floating cranes; derricks are commonly found aboard ships and oil wells.

Although there are obvious differences between all these cranes, those used for lifting (hoisting) share some common characteristics regarding lifting risk. Considering man-machine-environment system (MMES) safety, a crane work system consists of equipment, lifting tackle, load procedures, people and an environment. Failures can happen in interactions between human and machine, especially in the operations of lifting, hoisting, handling and loading. These failures of operations result in high risks, which could cause both injuries and property damages. This section will focus mainly on lifting related (crane) hazards and scenarios.

As for the lack of a standard risk inventory, the hazards are classified based on a review of accident data (Table 5.1). In the 1990s, Häkkinen (1993) identified some significant situations related to serious crane accidents, such as ‘falling of loads, fastening or unfastening of loads in danger areas, lifting of persons, dismantling of cranes, overturning of mobile cranes and contacts with overhead power lines’ (p. 269). He also found that accidents always occurr at the beginning of the lifting stage, so the identification of hazards before starting a lifting operation is very important. Moreover, only 20% of the injuries happened with operators, the rest are slingers, signalmen, and other workers assisting at the work site. Therefore, lifting safety is an issue concerning all frontline personnel.

Lifting related accidents have been analysed from different viewpoints. Abdelhamid (2000) summarised the root causes of construction accidents and developed an accident root causes tracing model, which emphasises unsafe conditions and the response of workers to the unsafe conditions. Based on over 500 crane fatality data from US narratives spanning the years 1985-1995, Shepherd (2000) classified crane fatality types in terms of the kinds of damaging energy involved. Neitzel (2001) reviewed crane safety in the construction industry and discussed injury and fatality types according to US crane data (from OHSA). Similarly, by using the data of crane-related fatalities between 1997 and

2003, Beavers (2006) identified more specific accident types in the construction industry, which considered proximal cause and contributing factors. The proximal causes are the critical events in crane accidents such as struck by a load, electrocution, etc., and the contributing factors are the threats to these critical events. Most of these are identified as equipment, component and work process failures. However, underlying causes of (crane) accidents have not been analysed systematically in the literature.

In general, OHSA identifies four main hazards in the construction industry, namely electrocution, struck-by, caught-in or -between, and falls. In lifting operation and crane accidents, these four hazards are also the main causes of injury and death. Moreover, crane collapse and overturn lead to serious consequences like fatalities, so they are also proximal causes of crane accidents at the construction site. However, being crushed during assembly and disassembly and hence, not during a lifting operation, is excluded in this chapter. Based on the data in Table 5.1 and the four types of common hazards at construction sites, six main critical events of lifting hazards can be identified:

1. Object (load, counterweight, boom, jib, etc.) drops: any object drops from the crane to down below;
2. Contact with power lines: workers come into contact with an overhanging power wire;
3. Caught-in or -between: people are caught between either the crane or its load and another object;
4. People fall: either operators or lifted people could fall down;
5. Crane collapse: the crane collapses due to improper lifting or any other cause;
6. Crane upsets or tips over: strong wind or overload could cause a tip-over.

Table 5.1 – Accident modes according to crane data from literature

Accident types	Record period	Cases (fatalities)	Contact with power line / electric current	Caught in or compressed by equipment or objects	Falls	Struck by crane booms/jibs	Struck by crane loads	Struck by cranes/ counter weight	Crane collapse /tip over	Crush (during assembly/disassembly)	Others	Reference
Crane fatalities	1985-1995	525	41%	6%	17%	28%			7%		1%	(Shepherd et al., 2000)
Crane-related fatalities	1997-2003	125	27%		2%	12%	32%	3%	11% (tip-over)	12%		(Beavers et al., 2006)
Crane-related fatalities	1992-2006	323	32%	7%		18%	7%	6%	21%		10%	(McCann, Gittleman, & Watters)
Crane-related deaths in construction	1992-2006	632	25%	5%	9%	12%	21%	7%	14%		7%	(Cho, Boafo, et al., 2016)
Crane Fatalities Causes	2002 -2012	662	10.9%	7.3%	26.4%	34.1%				17.1%	4.2%	(Cho et al., 2016)
Crane Injuries Causes	2002-2012	466	5.6%	14.2%	26.8%	33.9%				10.9%	8.6%	(Cho et al., 2016)
Crane-related fatalities	2000-2008	22	22.7%	0.0%	9.1 %	13.6%	45.5%	4.5%	4.5% (tip over)			(Gharaie, Lingard, & Cooke, 2015)
Crane accidents	2005	not clear	10%	30%	8%	34%			5%		13%	(Wang, 2010)
Crane accidents	2006-2011	370	1.6%	3.8%		24.3%			11%		59.3 %	(Wang, 2013)

5.2.2 Bowtie-based scenarios

5.2.2.1 Bowtie model

The Bowtie model follows from Haddon's Hazard-Barrier-Target (HBT) model and is one of the generic strategies for the control of potentially harmful energy flows (Haddon, 1973). This model is a causal model for building accident scenarios, with the application of both the fault and the event tree (Ale et al., 2006; de Ruijter & Guldenmund, 2016; Hollnagel, 2008). An accident scenario in the Bowtie model is represented by a cause-effect diagram which describes the sequence of an accident/incident. The model describes a typical situation that covers a set of possible events which lead to critical unwanted events and consequences.

5.2.2.2 Risk controlled by barriers

Barriers are inserted into the Bowtie model to prevent the occurrence of an accident, from causes to negative consequences. The Bowtie model properly 'allows chains of cause-effect diagrams to be built with specification of the barriers' (Hale et al., 2004, p. 612). The barriers are functioning to prevent, control and mitigate both the critical event and the consequences. With the barriers, the risks that are represented in the Bowtie model can be controlled.

The risk is commonly defined in a scenario, which combines the severity of negative consequences and the likelihood of the accident pathway through (series of) unwanted events. As we will elaborate the lifting risk by using the Bowtie model, to prevent unwanted events and consequences from occurring, safety barriers in the scenario should be functional. Safety barriers can mitigate risks by both decreasing the likelihood of the unwanted event and the severity of the loss. In this way, the management of safety barriers becomes essential for risk control.

5.2.2.3 Lifting risk scenarios: 'object drop' case

Object drop is one of the most common critical events in lifting risk and it has a number of causes and consequences, which we will elaborate through a Bowtie model (Appendix C). On the left side of the Bowtie, the starting events of an accident are called threats. Threats have been described as: 'unacceptable structural property reductions; digressions beyond limit loads; spurious and/or unreported damage' (Backman, 2010, p. 33). The threats of the object drop are structural failure, overload, strong winds and so on; while the consequences are injuries, damages, or losses. These are elaborated on the right side of the critical event object drop. There are as many barriers inserted between threats and consequences to control the risks sufficiently. Except for the threats, the failures of these barriers, however, can cause object drop leading to particular consequences, so the management of these barriers is important for safety performance. Appendix C develops examples of lifting hazard scenarios with barriers, the other five critical events also can be modelled and analysed by using Bowties.

5.2.3 The failure of barriers

Since barriers are paramount for risk control, the failure of barriers could cause targets being exposed to risks. Although the occurrence of scenarios may vary in different contexts like different countries, the safety barriers are the same or comparable. For example, in the US and China, 'power in contact' is a major hazard during the lifting operation, whereas in the Netherlands and Belgium it is not a common hazard. It probably because the overhead power line is differently installed and the height of buildings also vary greatly. But most other incidents and accidents just happen worldwide, like crane collapses, tipping overs, object drops, etc. Besides, safety measures and requirements are universally applied, like using nationally certified cranes or certified crane drivers. Even the barriers in these hazards are failing in similar ways, like not performing a pre-lift check, not using camera/CCTV for blind angles, etc. (see Appendix C). In crane accidents, the failure of barriers actually is an important causal factor. In the following, these failures are analysed in the context of two countries.

5.2.3.1 In the context of the Netherlands

In the Netherlands, a Bowtie-based tool called Storybuilder was used by RIVM (National Institute for Public Health and the Environment) for occupational accidents analysis (Bellamy et al., 2007). 36 (or 64 in more detail) Bowties have been developed through analysing 9142 reported accidents, and ‘contact with falling objects cranes’ is one of the main accident types. Coupled with a survey from a pertinent population, the degree of exposure to the occupational accident hazard, which is an important indicator for the occupational risks including lifting related risks, was determined (Bellamy et al., 2015). Actually, lifting risk is not only associated with the hazard of ‘contact with falling objects cranes’, but also relates to some other occupational hazards outlined by Storybuilder. For instance, ‘fall from height’ could include crane operators falling; ‘contact with swinging/hanging objects’ could be crane parts caught-in or -between. Overall, Dutch crane risks within the occupational accident risk inventory have been thoroughly analysed by means of the Bowtie model.

Within the Storybuilder data[2] (contact with falling object cranes), incident factors, regulation violations, safety barrier failures, human error, etc. are all defined and identified. Taking ‘contact with falling objects cranes’ as an example, these incident factors are similar to the threats in our Bowtie model (Appendix C). The barrier failures and human errors (in Table 5.2) also correspond to the barriers in our model. However, considering Storybuilder data, it is difficult to distinguish the incident factors from the barrier failures. For example, crane operation failure can be either a deviation from normal operation (incident factor) or a failure of a safety barrier activity (Table 5.2). Since the identified human error could cause the failure of behavioural barriers, like violations and mistakes, the barrier failure modes and human errors are there all considered for the purpose of risk control.

Table 5.2 – Barrier failure modes and human error based on Dutch cases.

Barrier Failure Mode (BFM)	Human Error
○ Integrity of load/attachment (strength) failure	○ (Situational, exceptional, routine) violation
○ Rigging failure	○ (Knowledge-, rule- based) mistakes
○ Crane operation failure	○ Attentional slip
○ Crane/hoisting equipment failure	○ Memory lapse
○ Crane assembling failure	
○ Lifting a load in excess of the safety capacity envelope of the crane	

In the Dutch cases, the underlying causes for the failures of barriers can be traced back to the safety management system in place and other influencing factors. These management systems consist of various ‘delivery systems’ (see Chapter 4). The relationship between barriers and managerial delivery systems has been explained, and the competence of personnel is one of the deliveries. According to Storybuilder data, the contributions of competence (of personnel) to lifting related occupational hazards are shown separately in Table 5.3. Although the contribution of competence to barrier failures has not been derived yet, the connection between competence and hazards is the management of safety barriers.

Table 5.3 – The competence contributes to occupational hazards which relate to lifting operation

Code	Scenario (hazard)	Competence
03.1	Contact with falling object used/cranes	11%
04.	Contact with flying/ejected objects	14%
08.1	Contact with moving parts of machine	17%
08.2	Contact with swinging/hanging object	7%
12	Contact with electricity	10%

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[2] The occupational accidents data (in NL) can be downloaded from the website http://www.storybuilder.eu/catalog.htm.

5.2.3.2 In the context of China

In China, the crane (also called hoisting machinery) is one of eight special (high-risk) equipment types, and their safety is overseen by the General Administration of Quality Supervision, Inspection and Quarantine. The accident ratio in every 10,000 cranes is one of the most important indicators for assessing the safety performance of cranes. Although there are a large number of lifting accident cases, without an accident investigation model involved, most academic papers describe independent causes. However, the main types of accidents are still the six critical events that we already encountered before in this chapter. These causes are not only design problems, technical problems, failure of structures, materials and any part of the equipment, but also the failure of management. Most management failures are the failures of delivered management to safety barriers. From the perspective of managing competence, the failure mode of barriers can be summarised as follows.

a. Non-certified crane (certified installation)
b. Non-certified operator
c. Violation of regulation
d. The absence of a procedure
e. Insufficient competence (knowledge, skill, experience, attitude) to take proper safety barrier actions
f. Hardware barrier failure (because of insufficient inspection)
g. A “blame” culture

Table 5.4 – Review and analysis of Chinese cases in papers

Causes / Cases	a	b	c	d	e	f	g	Reference
10 major accidents in 2008-2012	√	√	√	√	√	√		(W. Chen, 2014)
More than 1000 casualties in 2013	√	√	√	√	√	√		(Z. Chen, 2014)
655 accidents of construction cranes	√	√	√				√	(Guo & Peng, 2013)
370 crane accidents in 2006-2011	√	√	√	√	√	√		(F. Wang, 2013)
Not clear			√		√	√	√	(J. Wang, 2010)
60 accidents of construction cranes	√	√	√		√	√	√	(Guo, 2007)

Using certified cranes or operators seems very simple for any organisation, and it is a preliminary safety barrier for lifting risk (see Appendix C). Even though it hardly proves that using uncertified cranes or recruiting uncertified operators increases the lifting risk directly, the uncertified cranes or operators appeared to be a serious problem according to Chinese accident data in papers. The underlying causes of these barrier failures in China are also managerial factors, which support the safety activities, like the check, inspection and audit. Most safety activities still need the competence of personnel.

According to the failures of safety barriers in Chinese cases, even organisations are blamed because of incompetence. In a “blame” culture, the fear of punishment is a reason for not registering or not reporting hazards, like using non-certified operators. This is also a violation of the regulation, therefore, some people suggest that punishment is a recommended action for crane safety management (Hu, 2014). The culture is not a direct cause but an obvious factor contributing to the failure of safety barriers.

Some literature indicated that the execution of regulations and rules was not strict and not adequate so that incidents occurred. For example, at the construction site, the workers have low educational background without any certificate, thus “they must be removed from the work site” (Guo, 2007, p. 19). Uncertified operators are prohibited from operation when complying with the regulations; however, some workers use forged certificates in order to have a job (Guo, 2007; Guo & Peng, 2013). This involves another hazard and may increase risk, since spotting these forgeries is difficult. A “blame” culture also exists in other countries and in different forms. The fear of punishment or embarrassment influences the safety behaviour.

5.3 Competence for lifting risk

5.3.1 Competence required according to regulations

Regulations are used for developing safe operating instructions. They provide requirements for various aspects including the competence of different roles in an operation. Some of them are mandatory like required crane licenses and operator licenses in the Netherlands or China. Others are suggestions or rules provided by crane-using organisations or maintenance institutes.

The UK regulation highlights competence assurance, which requires duty holders to follow the competence management system (CMS) as a guideline for the Control of Major Accident Hazards (COMAH). CMS commonly incorporates 'recruitment requirements, site induction materials, training courses, risk assessment tools, human error analyses and training needs analyses' (Lovell & Hill, 2013, p. 1). In line with CMS, the managing competence for lifting risk is not only the ability to use lifting devices but the capacity of using all the safety barriers during the lifting operation.

The requirements of the performance of these barriers are shown in specific regulations. For instance, Table 5.5 summarises the safety requirements of OHSA regulations on crane operation. For each item, specific competences are required based on the safety activities or barriers. Operators, riggers, spotters, and other employees should take their responsibilities to complete their tasks safely. They can be qualified through training courses according to the regulations. In general, during the lifting operation, regulations always expect competent personnel to work in a right way.

Table 5.5 – A summary of competence required based on regulations (adapted from Cho et al., 2016)

Item	Competence required according to OHSA crane regulation
Ground Condition	emphasizes the suitability of the ground
	A/D director or the operator assess ground condition
Assembly/Disassembly	requires employer to comply with manufacture's procedure and prohibition
	requires a qualified person to develop company procedures
Power Line Safety	calls for a dedicated spotter to assist the operator
	emphasizes employer provides training for each operator and crew member
Inspection	requires the equipment to be inspected by a qualified person
	a competent person must carry out a visual inspection of the equipment prior to each shift
Wire Rope, Crane	requires inspection of the wire rope before each shift by a competent person
Signaling & Safety Devices	the employer must train each signal person in the proper use of signals applicable to the use of the equipment
Operation and Signal Person Qualification	the operator has the authority to stop and refuse to handle loads until a qualified person has determined that safety has been assured
	prior to operating any equipment the operator is qualified or certified to operate the equipment (based on local rule)
Training	the employer must provide training as follows: workers near overhead power line; each operator; each assigned signal person
	each competent person, each qualified person, each operator and employee authorized to start/energize equipment
Personnel Platform	when using equipment to hoist employees, they must be on a dedicated personnel platform that meets the requirements of 1926.1431(b)
	it is required to conduct a trial lift with the unoccupied personnel platform

5.3.2 Competence for safety barriers

According to regulations, the safety requirements for lifting operations seem easy, but the violation of them is still one of the causes of barrier failure. Besides, safety regulations do not automatically assure the safe performance of a lifting operation. Figure 5.1 shows that the competence for safety barriers is an integrated part of the competence of personnel. In a business process, like a construction project, the input of raw materials is transferred to a designed construction which is the business output.

Let's take a small case – lifting operation – as an example. During the lifting process, the risk control is necessary to assure the performance and providing a safety criterion; the demanding delivered competence is an important resource (mechanism) to this process. That is, competence of personnel, competence supports the lifting operation. In addition, risk control is provided by safety barriers; it is the output of these barriers' processes. These barriers also need competent people to complete installation, implementation, maintenance and monitoring stages, although a barrier can be hardware, behaviour or social-technical. As a result, providing sufficient competence for barriers sustains the risk control.

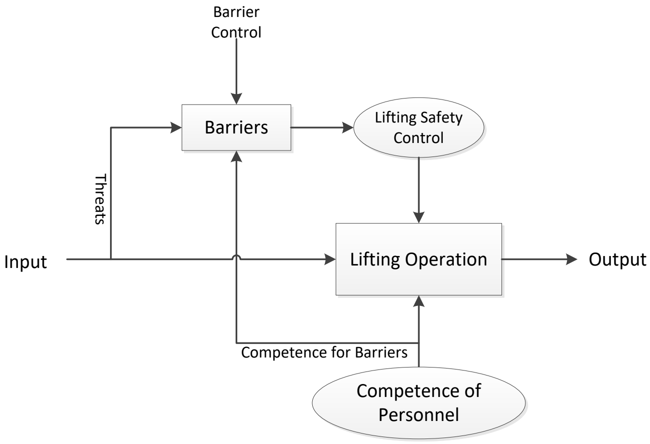

Figure 5.1 – The competence for barriers in a lifting operation (adapted from Figure 2.4)

Without threats or hazards, when every employee has sufficient job competence and the job responsibility is well allocated, during the lifting operation, nothing could go wrong. In practice, however, a lot of threats and failures are present during lifting operations, and some of the threats are directly prevented using competent personnel. Except for the required competence in regulations, the content of safety competence to barriers for lifting risk was not explicit. The general competence of personnel has various dimensions, which were defined from different perspectives (Kauertz, Neumann, & Haertig, 2012). As delivered competence has been modelled with knowledge, skills, experience, and attitude (KSEA) in Chapter 4, the indicators of competence to the barriers for lifting risk are developed based on this model.

Regarding the risk control of the lifting operation, the KESA indicators are described in Table 5.6. In order to quantify these indicators, the measurements of specific indicators are designed as well, although the quantitative analysis is not discussed in this chapter. As the operational safety activities are so different from higher level safety management activities, the competence of operators is different from required managers' competences. Carrying out most safety barriers requires both operational and managerial competence cooperatively.

Table 5.6 – The indicators of managing competence for lifting risk (based on Table 4.3)

Indicator (first level)	General/ (Safety) Profession al	Indicator (second level)	Examples of indicators	Operators	Managers	Measure
Knowledge (K)	GK	General SMS	ISO standard, company SMS		✔	Yes/No
	GK	Organisation knowledge	Organisation function		✔	Degree
	PK	Hazard (threat) scenario	Object drop, etc. (six scenarios)	✔	✔	Percentage
	PK	Barriers	Regular inspection, brake system, etc. (see Appendix C)	✔	✔	Percentage
	PK	Tasks procedure	Emergency procedure, audit procedure, etc.	✔	✔	Degree
	PK	Regulation/rule for specific tasks	Crane safe load regulation; lifting operation regulation; general safety regulation; etc.	✔		Degree
Skill (S)	GS	Communication skill	Verbal, written communication for inspection	✔	✔	Degree

	GS	Reading/writing skill	Local language (reading, writing, speaking)	✔	✔	Degree
	GS	Management skills	Planning, organising, supervising, checking, etc.		✔	Degree
	PS	Identification of hazard/threat	Means; frequency	✔		Content; degree
	PS	Hardware using skills	Skills of using PPE, boom stop system, etc.	✔	✔	Degree
	PS	Behaviour barrier skill	Pre-lift crane check, pre-lift risk awareness talk, etc.	✔	✔	Degree
	PS	Reporting method/skill	Oral/written formally/causally	✔	✔	Degree
Experience (E)	GE	Education level	Diploma	✔	✔	Degree
	GE	Working time	Working years	✔	✔	Time
	GE	Frontline (engineer) experience	Specific skill diploma, job training times	✔		Content; Times
	GE	Management experience	Management training; years of management job		✔	Degree
	GE	Accident (Hazard) experience	Accident/injury experience; accident/hazard analysis involvement	✔	✔	Times; degree
	PE	Using barrier tools (just using tool maybe not for safety work)	Frequency of using or familiar of PPE, , boom stop system, etc.	✔		Degree
	PE	Experience specific barrier	Involvement in both hardware/behavioural barriers	✔	✔	Degree
	PE	Safety training	Certified safety training	✔	✔	Times /Degree
Attitude (A)	GA	Safety awareness	Strong/weak	✔	✔	Degree
	GA	Attitude towards accident	Panic/calm	✔	✔	Degree
	PA	Attitude towards barrier cost	Costly/beneficial		✔	Degree
	PA	Habit of mind for barrier	Fixed/growth	✔	✔	Degree
	PA	Attitude towards barrier tasks/procedure	Willingness/unwillingness	✔	✔	Degree
	PA	Attitude towards barrier result	Positive/negative	✔	✔	Degree
	PA	Attitude towards specific rules/regulations	Disobey/comply	✔	✔	Degree

5.4 Managing competence to support barriers

5.4.1 Barrier features

5.4.1.1 Life-cycle of a barrier and its function phases

Safety management of a lifting device, its operation and its barriers have a life-cycle incorporated with various management tasks involved. Management tasks for barriers involve necessary activities and responsibilities for various jobs, which relate to proper barrier functioning. Five management tasks are distinguished in Chapter 4. Here, we focus on how people's competence work on this life-cycle (Figure 5.2). The competence for barriers pertains to the life-cycle of barriers, which means the ability to carry out the barrier tasks especially for assuring the barriers' safety functions. The safety barriers are functioning actively or passively only in the 'use' stage; however, the failure of a safety barrier can relate to a dysfunction of any task. Therefore people's competence for safety barriers supports the whole life-cycle.

Barrier function phases represent the sequence in activating a barrier. As mentioned in Chapter 4, most barriers share a similar activation sequence of ‘Detect–Decide–Act’. A barrier for lifting risk is in place to detect some threat (e.g. overweight); then, decide which action to take given this threat (e.g. overload protection); and, finally, an act (activate, perform, etc.) this barrier. This sequence shows the ‘use’ of a barrier. However, not all barriers (e.g. continuous/passive hardware) need to complete the full sequence to be functional as they belong to different types.

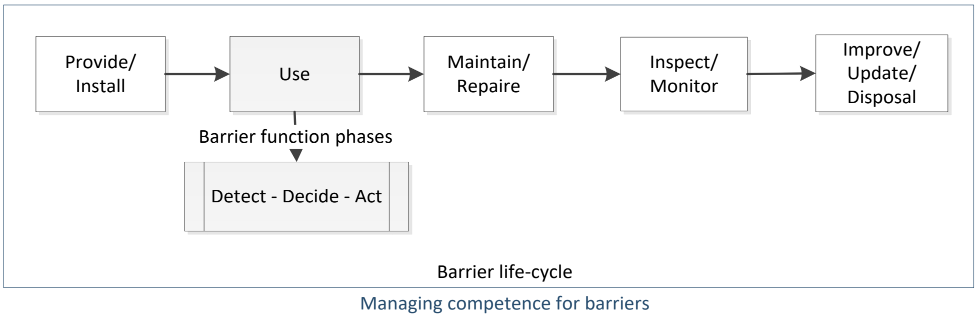

Figure 5.2 – Competence for the life-cycle of a barrier (adapted from Figure 4.4)

5.4.1.3 Barrier function phases

5.4.1.2 Barrier types

In order to understand how a barrier operates effectively with appropriate operators’ and managers’ competence, we classify the barriers using five different types, which are distinguished in Chapter 4. (1) A behavioural type of barrier requires human involvement during its full sequence; (2 and 3) a socio-technical barrier involves man-machine control and focusses on the interaction between the operator and the barrier; furthermore, a hardware type of barrier can operate automatically or logically, the (4) active hardware type has a full barrier sequence without human involvement whereas the (5) continuous and passive hardware types normally only are active during the act phase of the barrier sequence.

Table 5.7 shows the barriers applied in ‘object drop’ scenarios contain all five types and most of them involve behaviour in the use stage. It also reflects the importance of people and their competence for the functioning of safety barriers. Even there is no human involvement during the use stage of the hardware (e.g. automatic trolley brakes or electronic monitor); however, human involvement does occur during the other tasks of these hardware barriers. This indicates the importance of personnel and their competence.

Table 5.7 – The classification of barriers in ‘Object Drop’ scenarios (based on Table 4.2)

Barrier Types	Case: Barriers for ‘Object Drop’	Detect	Decide	Act
1. Behavioural	Pre-lift load calculations; Pre-lift risk awareness talk; Supervisor intervention; Limited lift stability check; Certified cranes; Check inspection status of the crane; Include weather forecast in planning; Use lifting plan; …	Human	Human	Human
2. Social-Technical (a)	Use camera/CCTV for blind angles; Monitor and adhere to weather criteria and stop lift if limits are exceeded;…	Hardware	Human	Human
3. Social-Technical (b)	Check safe work load manifest; Pre-lift rigging double check; Use slewing/rotating brake; Personal protective equipment;…	Human	Human	Hardware
4. Active hardware	Overload protection; Boom stop system; Automatic trolley brakes;…	Hardware	Software /logic	Hardware
5. Continuous/passive hardware	Monitor; Anti-freeze protection; Falling objects protective structure;…			Hardware

5.4.2 Model a barrier by SADT

5.4.2.1 Method – SADT

The managing competence for safety barriers is critical for the functions; however, the relationship between specific competence and barrier tasks is still not clear. The specific activities carried out by operational and managerial roles need to be modelled. In order to control lifting risk, all of the barriers in Table 5.7 are expected to be functional. Thus, taking one of the behavioural barriers as an example, the functional use stage means that the employees carry out the designed safety actions, based on sufficient competence (for knowledge, skills, experience and attitude aspects).

SADT is a method that could model a system with input, process, output, control and mechanism. By using SADT – structured analysis and design technique – a generic 'use behavioural barrier' can be modelled systematically and competent employees are the mechanism of the barrier function (see Figures 4.6 & 4.7).

5.4.2.2 Example: pre-lift crane check

In Appendix C, a number of behavioural barriers are established to control lifting risk. The 'pre-lift crane check' is one of them. It is commonly used for different kinds of crane management, so we apply SADT to model this barrier (Figure 5.3 & 5.4). The inputs for 'pre-lift crane check' are: barrier programme, lifting condition and the threat *structural failure of the crane*. The controls are: related regulations, procedures, risk inventory and criteria. The support people are operators and supervisors because this is a front-line operation. The output are various documents and records, which means a 'pre-lift crane check' has been performed; in other words, the structural failure is avoided.

During the implementation of 'pre-lift crane check': first, a checklist should be developed based on the provided information of crane and worksite (e.g. construction site) condition; second, the check activities are mainly conducted by the frontline supervisors and operators; third, to meet safety requirements, the to be checked items should be assessed to determine if there are any hazards or risks; then, if there are unaccepted risks, the operator should take safety actions in time; meanwhile, a record of the checklist and possible safety countermeasures should be done; and the managers can review these documents as part of their safety management tasks or for an audit. To describe specific activities and the systematic logic of this barrier, the 'pre-lift crane check' is modelled as shown in Figure 5.4.

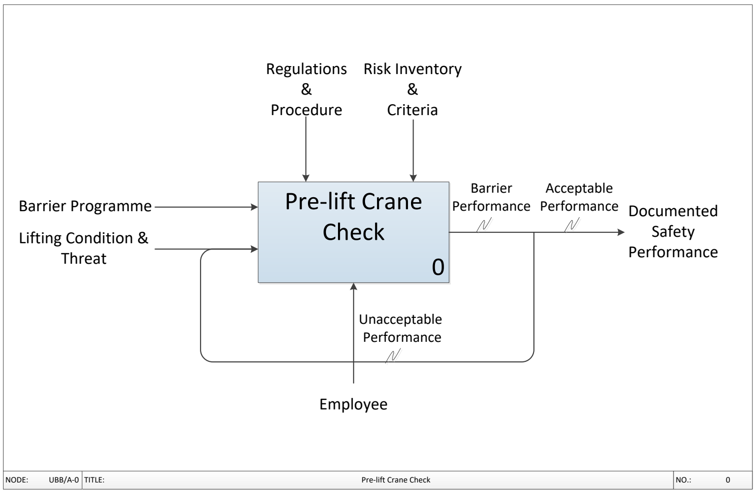

Figure 5.3 – The top-level diagram of model 'pre-lift crane check'

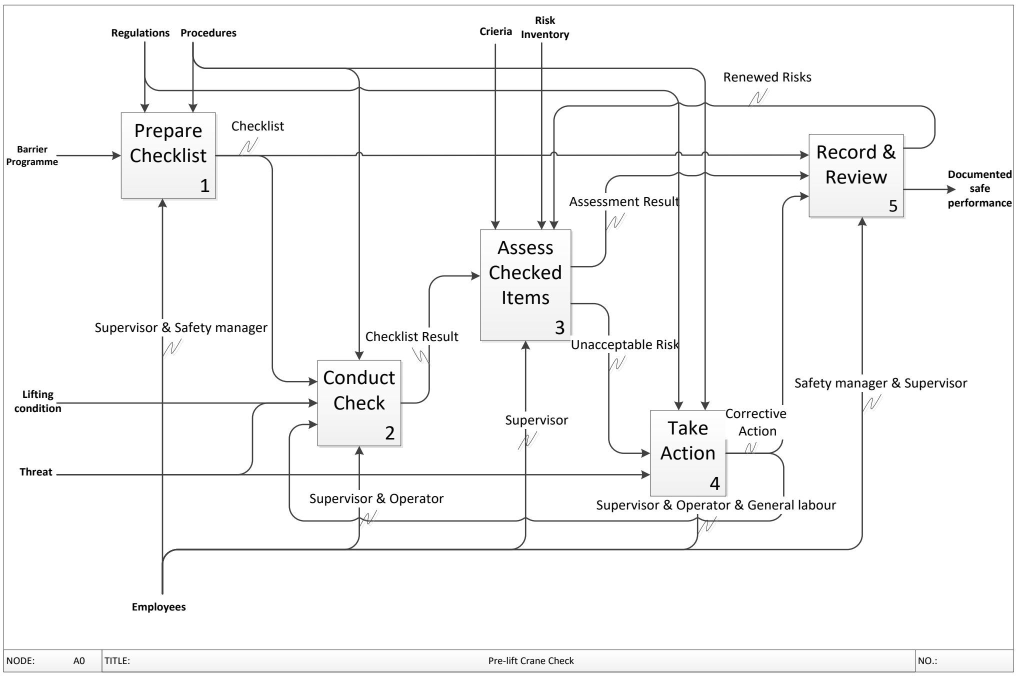

Figure 5.4 – Decomposition of the model 'pre-lift crane check'

5.4.2.3 Managing competence for 'pre-lift crane check'

The employees are involved in the implementation of 'pre-lift crane check', and they play different roles in various activities. Regarding the input, activities, output, controls and human resource, the managing competence to complete this barrier is clear. The delivery, *competence of personnel*, for each activity is given in Table 5.8. In this way, the indicators of competence denote the specific mechanism of the human resource during the 'pre-lift crane check' process. The competence for using barriers should be specified. If any failure of barriers is caused by improper or insufficient competence, this table is handy to check which activity of the barrier has failed and which corresponding competence is absent.

Table 5.8 – Deliver KSEA to 'Pre-lift crane check' barrier

Activity **Competence**	Prepare Checklist	Conduct Check	Assess Risk	Take Safety Actions	Record & Review
Knowledge	Tasks procedure; Regulation/rule for specific tasks;	Tasks procedure;	Hazard (threat) scenario;	Barriers; Tasks procedure;	General SMS; Regulation/rule for specific tasks;
Skill	Communication skill; Reading/writing skill;	Reading/writing skill; Management skills;	Reading/writing skill; Identification of hazard/threat;	Hardware using/ behaviour barrier skill;	Management skills; Reporting method/skill;
Experience	Experience items could contribute to every activity				
Attitude	Habit of mind for barrier; Attitude towards barrier tasks/procedure;	Attitude towards barrier tasks/procedure; Attitude towards specific rules/regulations;	Safety awareness; Attitude towards accident; Attitude towards barrier result;	Attitude towards barrier cost; Attitude towards barrier result; Attitude towards specific rules/regulations;	Attitude towards barrier tasks/procedure; Attitude towards specific rules/regulations;

5.5 Conclusion

In this chapter, the common risks of a lifting operation were identified mainly based on crane accidents data. Although these data come from different countries and the occurrences of events are also different, the six common hazards are almost the same. By using a Bowtie model, the scenarios of these hazards and the inserted safety barriers are developed. These safety barriers mitigate the lifting risk by preventing unwanted events. However, after analysing causes of accidents, there are a number of underlying reasons rather than threats, like the barrier failures. It indicates that the performance of these barriers determines the risk control, and influence the safety management.

We found that, regardless of the safety barrier types, such as hardware, social-technical or behavioural barriers, the competence of personnel is one of the decisive management factors for the life-cycle of safety barriers. The life-cycle includes installation, use, maintain, monitor and disposal stages. Among them, the use stage is the stage with the functions of safety, since only at the use stage the barriers could mitigate the risk. In this stage, we analysed the characteristics of activities and proposed five types of barriers. Personnel play different roles during using phases, including detect, decide and act. Thus, to complete a barrier function, the competence of personnel becomes critical. Also the Storybuilder data show that insufficient competence contributes to the failure of barriers and accidents.

Even though our hypothesis that managing competence supports barriers is not analysed statistically in this chapter, the relationship between safety barriers and competence is elaborated. We modelled a behavioural barrier ‘pre-lift crane check’ with the SADT method and analysed the supporting competence for the detailed activities. Furthermore, we would like to focus on the quantification of these competence indicators and barrier activities to find out their statistical relationships. It will not only reveal which knowledge, skills, experience and attitude are important for barrier performance but also find out how the operational and managerial competence influence safety barriers.

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6 A QUANTITATIVE APPROACH TO SAFETY MANAGEMENT DELIVERY: CASE STUDY OF COMPETENCE

Abstract

Previously, delivery systems modelled the safety management processes and control safety barriers. Although the models elaborate the management activities systematically, how much of each management should be delivered to keep barriers functioning is still uncertain. An organisation expects to optimise its management and resources precisely. Therefore, the quantifying safety management deliveries are meaningful. Managing competence is one of the seven deliveries. This chapter, under the circumstance of lifting risk, quantifies in detail the delivery of competence and models the quantitative relationship between delivery systems and safety barriers.

Safety barriers to lifting risk are frequently used in its scenarios. In the context of a lifting risk scenario, with as its central event "object drop", data of safety barriers and delivered competence are obtained through a survey in seven crane-using companies. Using principal component analysis, we found the general factors of managing competence for safety. Furthermore, a regression model predicts that the product of managerial and operational competence significantly affects the performance of barriers. This relationship can be illustrated in an isoquant plot, which visually shows the quantification of competence and barrier performance. Using the principles of quantifying competence delivery, other delivery systems can be quantified as well benefiting the full management of safety.

6.1 Introduction

Safety management systems are used in a range of industrial applications. Models of these systems usually emphasize three aspects: a sequence of causal events leading to an accident and loss, preventive or protective safety barriers, and the management of those barriers. Numerous approaches have been applied to model these three parts. They aim to illustrate the process of safety management delivery from accident analysis to risk control, and from the identification and implementation of controls to assessing safety performance. Both quantitative and qualitative methods are used in the process of safety management (Øien, 2001). Although quantitative methods rely on a qualitative analysis of accident and risk, the quantitative result will, ultimately, improve the efficiency of safety management and, therefore, the quality of a safety management system. Before we embark on the issue of management quantification, we first briefly review how the management of safety has been quantified and for what purpose.

6.1.1 The quantification of risk and safety

A safety risk is commonly defined as a scenario with an adverse outcome and the likelihood of its pathway through a series of unwanted events. Probabilistic techniques are the main (quantitative) methods used for risk analysis, which also make them a sensible basis for risk-based safety management. Probabilistic risk analysis methods have appeared since the 1970s (Oostendorp et al., 2016), along with the development of system safety techniques, like, for instance, fault tree analysis. During the same time, safety management systems came into vogue, which applied these techniques. It is nowadays common that quantitative safety risk analysis assists the management of safety in industries.

Paté-Cornell (1994) proposed numerical safety goals regarding quantitative targets for risk management. The legal philosophy of risk regulation gradually changed from a zero-risk philosophy to a best acceptable or best practicable technology, e.g. the ALARP rule. To reach such a risk agreement, an assessment of risks in the form of a probabilistic risk analysis (PRA) was required. According to Paté-Cornell a PRA-result supports safety improvement on three aspects: optimising the safety budget, achieving the safety target level and improving safety performance of facilities. For Apostolakis (2004), the traditional safety methods and quantitative risk assessment (QRA) complement each other. He proposes that the methods used for QRA should include both probabilistic risk assessment and performance assessment. He concludes that safety-related decision-making is risk-informed, not risk-based as the QRA-result is not the sole basis.

Both the standards of *risk assessment techniques* (IEC, 2009) and *reliability modelling and calculation of safety systems* (ISO, 2013) apply the classic techniques used for risk assessment, reliability and safety systems. These techniques include hazard analysis methods, risk analysis methods, scenario analysis, safety control assessment and statistical methods for probabilistic calculation. Based on these techniques, many quantitative risk models have been developed (Aven, Renn, & Rosa, 2011; Wu et al., 2010). Most of these models aim to evaluate risk and control unacceptable risk and their output is used to optimize managerial decision-making. However, how the output of risk analyses precisely improves safety is still unclear.

Another standard titled *functional safety of electrical/electronic/programmable electronic safety-related systems* (IEC, 2005) puts forward four safety integrity levels (SILs) with fixed ranges of probability of ‘failure on demand’. The SIL-level depends on a target likelihood of failures of a safety function, e.g. safety machinery. According to the standard, these quantitative safety targets are applied mostly in hardware systems. Furthermore, a methodology for the assignment of SILs was developed by the Health and Safety Executive in the UK. It connects risk to a certain safety level. This methodology does not only contain the process of risk management, including hazard identification, risk estimation and reduction, but also specifies ‘the amount of risk reduction that a particular safety function needs to provide in terms of assignment of a SIL’ (Charlwood, Turner, & Worsell, 2004, p. 6).

The essence of this methodology is a safety functional system that can obtain a level of safety by reducing a particular amount of risk. The use of SILs offers a more sophisticated approach towards the quantification risk, although it still much focussed on the technical aspects of safety (Beugin, Renaux, & Cauffriez, 2007).

The measurement of safety actually is a controversial topic, since the success of safety is measured by lower levels of system failure (Cooper & Phillips, 2004). Quantification of system failure or activities that ascertain system success are both important because they reflect the performance of a safety management system. A functional safety management system requires a proper scientific estimation of its performance but these estimates are still limited. According to Hale's framework (2005) all accidents, or system failures, as well as risk control and safety management activities should be regarded as system performance information. Therefore, safety management, the activities that should ensure system success, is in need to be quantified properly also.

6.1.2 Risk quantification for safety management

6.1.2.1 Causal events model for risk quantification

Causal event models and metaphors describe the mechanisms of accidents (Swuste, van Gulijk, & Zwaard, 2010, 2011). These accident models aim to develop an accident/hazard scenario with a sequence of logic events. The events can be connected through quantitative methods, such as a fault tree, an event tree, a bowtie-model, a Bayesian network, amongst others. The philosophy of cause and consequence is commonly assumed in these scenarios. The failure rate of these events or the likelihood of failure is calculated by probabilistic methods and combined with a risk model, and the risk of a scenario system can be calculated (de Ruijter & Guldenmund, 2016; Khakzad, Khan, & Amyotte, 2013; Papazoglou, 1998). A quantitative causal events model can illustrate how the system can fail and with what risk (Apostolakis, 2004).

In most cases mentioned above, quantifications only involve hardware failure or simple event failure. Some attempts have been undertaken to quantify the behavioural failure of people. For example, in a nuclear risk analysis study, human errors were classified and the probabilities of these errors can be calculated (Vaurio, 2007). In aviation, the fatigue of pilots is one of the causes for flight error; it was quantified in a Bayesian belief network to explore the influence of human performance on flight risk (Ale, Bellamy, Cooke, Duyvis, & Kurowicka, 2009; Groth, Wang, & Mosleh, 2010). These are two examples of the quantification of independent 'soft' factors in an accident scenario, that still rely on probabilistic methods and a risk model.

Within the structure of a causal events model, the probabilistic result normally shows how failures of events affect the failure of a system. When the result is highly uncertain, however, the quantitative result does not mean much. The uncertainty is caused by insufficient events being modelled, a fuzzy probability of the event and the ambiguity of events logic. Adding uncertainty to the probabilities of events is also one of the difficulties in quantifying organisational factors and behavioural factors.

6.1.2.2 Risk calculation after barriers are inserted

Barriers are inserted into the causal events chain, e.g. in a bowtie model, to prevent the occurrence of an accident, from causes to negative consequences. Barriers can be hardware, behavioural or social-behavioural safety activities (Duijm & Markert, 2009; Guldenmund et al., 2006). The analysis of risk in a scenario involving safety barriers is also important for safety management. From a quantitative perspective, barriers are applied to decrease the risk by means of lowering the likelihood of causal events and mitigating the severity of consequences.

The assessment of risk after barriers are inserted depends on the quantification of both causal events and barriers. This progress of safety risk quantification was shown in a series of bowtie-model-based projects, such as WORM[3]. In this project, the risk scenarios and the controlling barriers developed were collected from a large number of accident reports. By using the co-occurrence of accidents and causal events, the risk rate of a single accident or hazard was obtained (Papazoglou et al., 2015). Then, a probabilistic approach to the risk was designed that involved specific barriers. This risk rate is a conditional probability which relates to the states of barriers. Papazoglou (2017) provides an occupational risk example ('Falling from a fixed scaffold') and the probability of the risk is determined by the states of barriers involved, such as present or absent *falling object protection*, proper or improper *scaffold strength*, adequate or inadequate *user ability to stay on a scaffold*, etc. In this way, a barrier's contribution to the risk is modelled and, hence, the risk of a scenario including barriers can be quantified.

Overall, safety barriers are the link between primary risk and risk after safety barriers have been implemented. The safety barriers are both safety activities and hardware for risk control and their implementation requires safety management throughout the whole organisation. An extensive, quantitative study on safety barriers will therefore contribute to a better underpinning of safety management. But it still unclear, how much of the delivered safety management will contribute to a particular state of a safety barrier. To answer this question (delivered) management factors should be quantified as well.

6.1.3 Safety performance measurement

6.1.3.1 A vast range of indicators

The most popular organisational management performance tool is Key Performance Indicators (KPIs). Key safety performance indicators are used in many fields, like the oil and gas industry. This tool can contain all the aspects and items of safety risk, barriers and of safety management. Hale (2009) states three purposes for using it: 1) monitoring the level of safety in a system; 2) deciding where and how to act if action is needed; 3) motivating those in position to take the necessary action. To achieve these purposes, a clear-cut framework of numerical indicators is required. The concepts of leading and lagging indicators for safety management prevailed over the last ten years.

Generally, leading and lagging indicators are the performance information obtained from the accident causal process and the safety management process. Swuste (2016) concludes that lagging indicators are the result indicators and leading indicators relate to organizational and management activities. Sheehan (2016) defines that lagging indicators are the safety performance related to injuries and accidents, whereas leading indicators are associated with organisational active and passive barriers. He also reasons that safety leadership plays the moderating role between leading and lagging indicators. More specifically, Sinelnikov (2015) states that all the information that enables organisations to identify and correct deficiencies before injury or damage, like early warning signs, are leading indicators. He also argues that effective leading indicators should process and describe safety management delivery systems, which are defined as modifiable factors in his research. However, the two groups of indicators are not distinguished clearly as various researchers and practitioners operationalize them differently.

The relationship between leading and lagging indicators is not distinct. Some indicators could be both leading and lagging indicators, as leading and lagging are relative terms applied in a specific scenario or event. For example, near-miss incidents can be both leading and lagging (Sinelnikov, Inouye, & Kerper, 2015). Lag- or lead- sometimes just means a relative time of an event. It is also not proven yet

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[3] WORM has been part of a series of European or Dutch projects aimed at risk control and safety management. The other projects are I-RISK: Development of an Integrated Technical and Management Risk Control and Risk Monitoring Methodology for the Quantification and Management of On-site and Off-site Risk; and ARAMIS: Accidental Risk Assessment Methodology for Industries. WORM: Workgroup Occupational Risk Model.

that to distinguish them, offers a better safety management. Many organisations only can define and collect the safety key performance indicators. Regardless of lag- and lead-, organisations care for the indicators determined by safety performance rather than these groups.

As long as these leading indicators, lagging indicators and safety key performance indicators are useful and practical, they could be 'in the spotlight' for safety management (Swuste et al., 2016). Good indicators of safety can always provide straightforward information to take suitable actions (Hale, 2009).

6.1.3.2 The quantification of the indicators

Safety performance indicators have been developed by researchers and practitioners. As mentioned before, safety performance indicators sit within a complete safety management system rather than only in quantitative risk analysis. The quantification of safety indicators will make a safety management system more functionally efficient. However, to quantify all of them is not an easy task.

Some scholars developed a framework for safety performance indicators and provided a generic quantitative approach. Øien (2001) proposed a framework for the quantitative path of organizational factors affecting either safety or risk. In this framework, the risk model and actual safety performance are shown as two independent paths, because 'safety' is a positive result of safe performance, while 'risk' is the opposite. Based on the philosophy of defence-in-depth, he defined four levels or areas of performance, namely: 1) safety management, 2) control of the operation, 3) safety functions and 4) physical barriers (Øien, Utne, & Herrera, 2011). However, it is difficult to validate that these indicators really relate to safety. Other frameworks of safety indicators have similar problems. For example, Reiman & Pietikäinen (2012) developed a framework of drive indicators, monitor indicators and outcome indicators. They describe extensive measures of these three groups but they do not explain how these specific indicators affect safety. Mohaghegh & Mosleh (2009) proposed a multi-dimensional measurement method for organizational safety causal modelling. More specifically, they are: 1) indirect measurements of causal factors; 2) predictions based on indirect measurements; 3) predictions based on extrapolating direct statistical data and; 4) Bayesian combination of direct and indirect measurement. This framework seems promising as it reflects current safety information and predicts future safety (risks). However, without concrete evidence, this theoretical framework is still too generic.

Others directly define and quantify the safety indicators in an industrial case study. For example, technical factors in process safety are always quantified. The safety or risk level can be defined by several indexes, like the unit inherent hazard index, so the technical factors influencing risk or safety can be analysed quantitatively (Tugnoli, Landucci, & Cozzani, 2009). In a control room in the process industry, safety performance was assessed by a survey of the operators, and statistical methods were used to study how human factors elements affect safety performance (Omidi et al., 2018). However, methods used to quantify specific indicators in a random case are difficult to generalise. Therefore, they are rarely used in other fields or for a complete SMS.

Although big data methods have already been proposed for safety performance (Tan, Ortiz-Gallardo, & Perrons, 2016), to develop a systematic and quantitative approach to safety management using such data is still problematic. The quantitative approach should be more than a probabilistic method used in a risk model. If safety management factors can be quantified, they should be within an SMS framework. The framework of safety performance should be top-down, from the general safety management system to explicit barrier tasks; the quantification of these factors should, however, be bottom-up, from specific safety activities to generic safety delivery factors. This approach is able to provide reasonable and useful information for safety decision making.

6.2 A systematic and quantitative approach

6.2.1 Framework

The quantification of an SMS consists of the quantification of causal events to calculate the initial risk, the risk analysis after implementation of barriers and the indicators of safety performance for the quality of the SMS. Figure 2.3 shows the main issues of a complete safety management system and the corresponding quantifications. These issues and the fundamental models were reviewed Section 2.4. Here, we specially introduce how to take advantage of the links between accident scenarios, barriers and safety management.

6.2.1.1 Bowtie-based failure calculation

An accident scenario is a sequence of events, which can be connected to each other with a certain type of logic like Boolean logic. This is the basis for risk analysis. A bowtie model describes a typical situation that covers a set of possible events which lead to critical unwanted events and their consequences; i.e. a bowtie model describes several accident scenarios. This model also connects fault tree analysis and event tree analysis through the critical (top) event (de Ruijter & Guldenmund, 2016). These two methods provide the mathematical calculation of risk as they can combine the probabilities of events and the consequent severity of these events. Ultimately, the initial risk can be modelled and estimated by the bowtie-model.

Thereupon, safety barriers are inserted in the bowtie-model to mitigate the risk by preventing the occurrence of a subsequent event. As safety barriers can be events, behaviours or hardware equipment, methods to quantify barriers also vary. The reliability of a safety hardware barrier is concerned with the barrier function under a stated condition for a specific time. However, an unwanted event or a failing behavioural barrier can be regarded as a causal event, with a particular failure rate. Viewed this way, the risk including barriers can be calculated as well.

Barrier influencing factors are the most difficult aspects to quantify. Because of inadequate safety management efforts, safety barriers might not function as specified. These management aspects have been analysed in the WORM project, mentioned previously. Management contributions to the failure of barriers were grouped into eight key safety management factors. The percentage of these factors, leading to 9187 Dutch occupational accidents, were calculated (Aneziris et al., 2008). These safety management factors form the empirical foundation of the so-called safety management delivery systems (DSs) (Li, Guldenmund, & Aneziris, 2017).

For the quantitative part of a bowtie-based scenario, specific events and barriers must be modelled; they are quantified based on actual data. The failure rate of both causal events and safety barriers is used to calculate risk. With the events logic embedded, the risk calculation is straightforward. Failure data are commonly obtained from the records of accidents, incidents and near-misses, so the bowtie-based failure calculation is also empirically based. This calculation is mainly used to know the risk, which is, however, affected by the barrier influencing management factors. Their calculation will reveal the control of risk.

6.2.1.2 The development of delivery systems

Based on the theory of latent failure in defences, the failure of safety barriers results from inadequate management decisions and organizational processes (Reason, 1995). This management directly and indirectly influences safety barriers to control risk. In previous studies, safety management for barriers was modelled as safety delivery systems (Chapter 4). It contains seven generic managerial systems: competence, commitment, communication, procedures, hardware, interface, and availability. Hale (2005)'s generic SMS model shows the role of delivery systems in the process of safety management. DSs provide all requirements for the functioning of technical and procedural barriers and controls. These safety management delivery systems have been modelled by the SADT-method (Structured

Analysis and Design Technique). This method systematically models a process with an input-process-output structure. The total output of these delivery systems is the full management of barriers.

How the delivery systems affect basic event parameters, which are also called technical parameters, have been analysed quantitatively in the I-RISK project (Papazoglou et al., 2003). Specific management delivery processes were developed and confirmed in a subsequent project, named ARAMIS. In this project, their audited quality was used to adjust safety barrier performance, as well as SILs (Safety Integrity Levels) (Duijm & Goossens, 2006; Guldenmund et al., 2006). In the WORM-project, these seven generic management factors figured explicitly in the causes of failures of barriers and events. The CATS-project also used the seven DSs to study managing factors influencing air transport risk (Lin, 2011). These series of studies on delivery systems form the background of the current study.

6.2.1.3 DSs - based barrier control

Previous projects or other quantitative safety research focuses on the quantification of risk and the barriers affecting risk. Delivery systems were developed to control safety barriers, but how and to what extent these can be quantified is still unclear. In a business process, the safety delivery systems could both control barriers and provide resources to safety barriers. In other words, the safety delivery systems manage the provision, implementation, maintenance and decommissioning of safety barriers.

The competence delivery system and how to manage competence delivery and fulfil the function of barriers has been explicitly discussed elsewhere (see Chapter 4). Organisations hire competent employees, but they also provide safety and professional training to have them meet these requirements. The output of the competence delivery system is managed competence, which we could specify further as four groups of indicators: knowledge, skill, experience and attitude (KSEA). Safety tasks for barriers require input from both management and operations. They apply their personal ability and safety professional expertise to safety barrier functioning, thus controlling the risk. Based on this reasoning, we are going to study the influence of competence delivery on safety barrier functioning. The next sections describe how we carried out this study.

6.2.2 An industrial case: lifting operation

6.2.2.1 Lifting risk scenario

A lifting operation is concerned with using lifting devices in the lifting or lowering of a (heavy) load. Lifting devices are used extensively at construction sites, factories, harbours, ports, and so on. These devices can be cranes, forklift trucks, derricks, excavators, etc. Lifting devices are used for different purposes in different sectors. However, the risk of a lifting operation has common scenarios. The six most frequent critical events in these scenarios have been identified in Chapter 5:

1. Object (load, counterweight, boom, jib, etc.) drops: any object drops from the crane to down below;
2. Contact with power lines: workers come into contact with an overhanging power wire;
3. Caught-in or -between: people are caught between either the crane or its load and another object;
4. People fall: either operators or lifted people could fall down;
5. Crane collapse: the crane collapses due to improper lifting or any other cause;
6. Crane upsets or tips over: strong wind or overload could cause a tip-over.

6.2.2.2 Safety barriers for ‘Object drop’

‘Object drop’ is one of the most common critical events in lifting risk and it has a number of causes and consequences, which can be described with a bowtie-model (Appendix C). Safety barriers can be inserted to mitigate the risk of an object drop. Companies implement such barriers to control the lifting risk.

Table 6.1 lists the safety barriers commonly used in the 'Object drop'-scenarios and classifies them roughly into three types according to the 'nature' of the barrier. Behavioural barriers rely on people's activities; hardware barriers are safety machines, equipment or tools; social-technical barriers involve both behaviour and hardware. People play an important role in using these barriers. Even though some barriers are 'passive hardware' (they do not need human intervention to be 'activated', e.g. a gate or a levee), human involvement does occur during the other stages of these hardware barriers, like the maintenance stage.

Table 6.1 – The safety barriers for lifting risk 'Object drop'

Code	Barrier name	Types of barriers
1	Always do pre-lift load calculations correctly	BB
2	Always give pre-lift risk awareness talk	BB
3	If there are any hazards, the supervisor always intervenes	BB
4	Always carry out lift stability check well	STB
5	Strict use of certified cranes	BB
6	Strictly check inspection status of the crane	STB
7	Strictly restrict access to lifting area	BB
8	Strict use of lifting plan	BB
9	Always use camera/CCTV for blind angles correctly	STB
10	Stop lifting if limits are exceeded	STB
11	Check safe work load manifest strictly	STB
12	Always do pre-lift rigging check strictly	STB
13	Correct use of slewing/rotating brake	STB
14	Always correct use of personal protective equipment	STB
15	Overload protection always functions well	HB
16	Crane (boom, trolley, etc.) emergency brakes always function well	HB
17	Electronic monitor always functions well	HB
18	Falling objects protective structure always functions well	HB

Note: BB – Behavioural Barrier, STB – Socio-Technical Barrier, HB – Hardware Barrier.

6.2.2.3 The delivered competence for barriers

According to occupational accident data in the Netherlands, 11% of the failure of barriers for 'Object drop' is caused by inadequate competence of personnel[4]. The victims of lifting risks are not only crane operators but also people around the lifting operation. Assuming that these victims have safety knowledge, awareness, and the skills to protect themselves, and the crane operators have already communicated safety risks, or secured their surroundings, or applied any other safety barriers, unwanted consequences probably can be avoided. To supplement the crane operator's competence, the managers need to prepare a proper safety plan and supply appropriate safety barriers. Therefore, managers and operators work together to fulfil and support all safety barriers.

Managing competence can be subdivided into four groups of indicators, namely knowledge, skill, experience, and attitude (KSEA). Employees need safety-related knowledge to complete their assigned work processes and also to protect themselves from any harm. Knowledge of the general safety management system, of lifting accidents and any specific controlling tasks are all considered for managing barriers. For the mitigation of risk, there is no indication that any particular knowledge is more critical than others.

The skills to handle safety barriers are management skills, behavioural skills and skills to use particular hardware. Apart from professional safety skills, generic skills like communication and coordination are critical as well, because some safety barriers, i.e. behavioural barriers, involve actions and the quality of these actions depends on these skills. For example, if labourers cannot communicate in a common language, critical information may not be delivered correctly to colleagues and supervisors, even if front-line workers identify problems.

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[4] Available at http://www.storybuilder.eu/catalog.htm, with hazard scenario code 03.1.

Safety-related experience normally enhances knowledge and skills. For example, through managing or using barriers, knowledge and skills are obtained. As a result, the safety competence of personnel is improved. Regarding safety issues, the experience of having or witnessing an incident or accident will have a strong impression on people and might affect their attitude towards barriers.

Attitudes affect individual behaviours and, therefore, also influence the implementation of safety barriers. According to the theory of planned behaviour, an attitude is the determining factor of individuals' behavioural intentions and behaviours (Armitage, 2001). Similarly, the attitude towards (the use of) safety barriers affects the performance of these barriers. If the attitude of personnel towards carrying out work in the safest possible way is positive, compliant and complete, a safety barrier will, theoretically, work according to specification. As a result, any known risk will be controlled (more) effectively and efficiently.

Based on the KSEA-division, both operational and managerial competence for safety barriers to control lifting risk are specified in Appendix D. The specific indicators have been identified to find out which aspects of the personnel's competence are critical for safety performance and how the delivered competence affects the performance of barriers. Using the outcome, a company can improve their safety performance by focussing on those aspects of management that have significant impact empirically. For example, the HR-department can recruit suitable personnel much better, or auditors can focus directly on critical indicators. To be able to identify these competence indicators in the scenarios of 'Object drop', an extensive survey has been designed.

To summarise, management delivers competence to its personnel. With this competence, personnel can carry out their tasks regarding barriers and ensure their proper functioning. Competence can be specified further. We can distinguish two types of roles related to barrier tasks, i.e. managerial and operational roles (see Figure 6.1). In the next section we describe the development of a survey to explore how competence delivery might impact safety barriers.

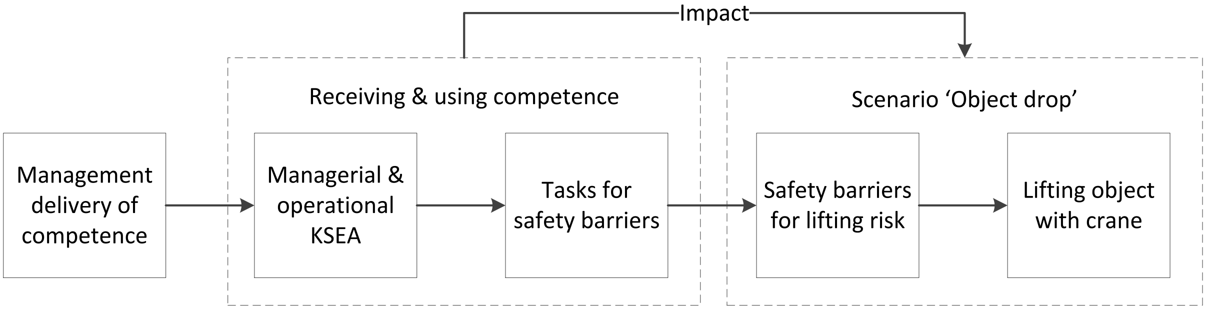

Figure 6.1 – Competence delivery to safety barriers for lifting risk

6.2.3 Survey design

Safety management can be envisioned as a pathway from general safety policies and strategies to specific risk controls and barriers. In the context of risks related to lifting objects, the survey is designed to explore the relationship between the competence of personnel (in terms of KSEA) and safety barriers. In an organisation, both managerial and operational roles provide different KSEA to deliver their competence to safety barriers, so we developed separate questionnaires for these two groups. Furthermore, as safety professionals and auditors are both specialised in safety, they can provide expert information about the performance of safety barriers.

6.2.3.1 Checklist for barrier performance

The checklist is for the people who are familiar with the performance of safety barriers of lifting, such as safety inspectors or auditors. The checklist is meant for the actual performance of barriers. As the aim of this study is to investigate how safety barriers are affected by delivered competence, actual barrier performance should also be obtained. This checklist is administered only when (audit) performance data of safety barriers are not available.

6.2.3.2 Questionnaire for managerial roles

This questionnaire is for the people who have management responsibilities and are not directly involved in front-line work, like middle managers, senior managers but also staff members of a company. It aims to get actual information about the KSEA of managerial roles used for (lifting) safety barriers (Appendix D. Table D.2). Management of barriers is in the planning, organizing, implementing, checking, and supervision stages of lifting operations and equipment. Also, staff members play the role of provider, assessor, and supervisor of barriers. All these aspects affect strategies regarding safety management and barriers.

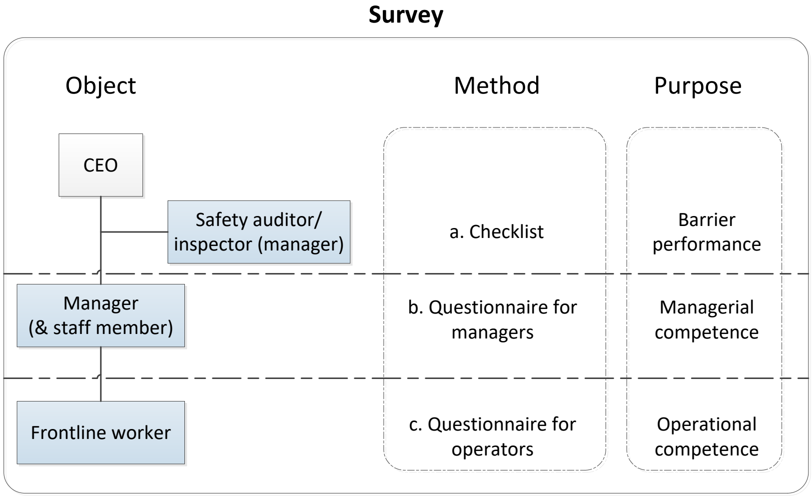

Figure 6.2 – The structure of the survey on safety competence

6.2.3.3 Questionnaire for operational roles

This questionnaire is for the people who are exposed to the lifting risk, such as front-line workers at a construction site or a manufacturing plant. It aims to get actual information about the knowledge-skills-experience-attitude (KSEA) of operational workers involved in safety barriers (Appendix D. Table D.1). The tasks regarding safety barriers are very practical safety activities, so front-line workers' competence potentially affects the performance of these activities. In order to improve the safety performance at a worksite, companies should know what ability these operators should have to work safely.

6.2.3.4 Informal interviews

To be able to understand the lifting scenario, the risks involved and the safety barriers that have been developed for these risks, multiple informal interviews have been carried out with safety professionals and managers at work sites. The content of the checklist and questionnaires is the result of these interviews. After we designed the checklist and questionnaires, the safety managers and professionals reviewed these for us and checked if they were complete and exhaustive.

6.3 Data and analysis

6.3.1 Data description

6.3.1.1 Sample

We carried out the survey in China in seven crane using companies in the manufacture and construction industries, performing lifting operations on a daily basis. In the survey, the lifting operation particularly focused on the use of an overhead or bridge crane. Besides, the companies have a few other types of crane and even other lifting devices. However, the lifting risk 'Object drop' and all the barriers identified for this risk scenario, as modelled in a bowtie-model (Appendix C), are the same. Therefore, in this survey, these companies are considered comparable lifting condition units.

Initially, we expected that barrier performance data were directly available from safety audit results. However, we could not obtain this information directly from most companies. Instead, the checklist of 18 commonly used barriers was scored by 101 experts. They are the professionals who are familiar with the assessment of safety barriers for lifting risk. Data on delivered safety competence has been obtained for the two distinct roles, operational and managerial. In total, 509 questionnaires were completed, 320 from operational workers, and 189 respondents having a managerial or staff role. However, as different managers and staff members have disparate responsibilities, they are subdivided into distinctive groups. We used factor analysis to explore and group the managing of competence.

6.3.1.2 General information

Regarding personal data, we asked respondents about their age, gender and job as these data reveal some characteristics of the sample. However, we also assumed that any personal information of the experts would not affect their estimates of barrier performance, so they completed the checklist anonymously.

6.3.1.2.1 Age

We selected respondents randomly in the seven companies for both operational and managerial levels. The histogram charts show the age of operators and managers as well as their approximated normal distributions (Figure 6.3). The age range for operational roles is between 18 and 55, and for managerial roles is between 18 and 60. The mode age is 30 years for both managers and operators; the mean age of managers (36) is higher than the age of operators (34), but this difference is not significant.

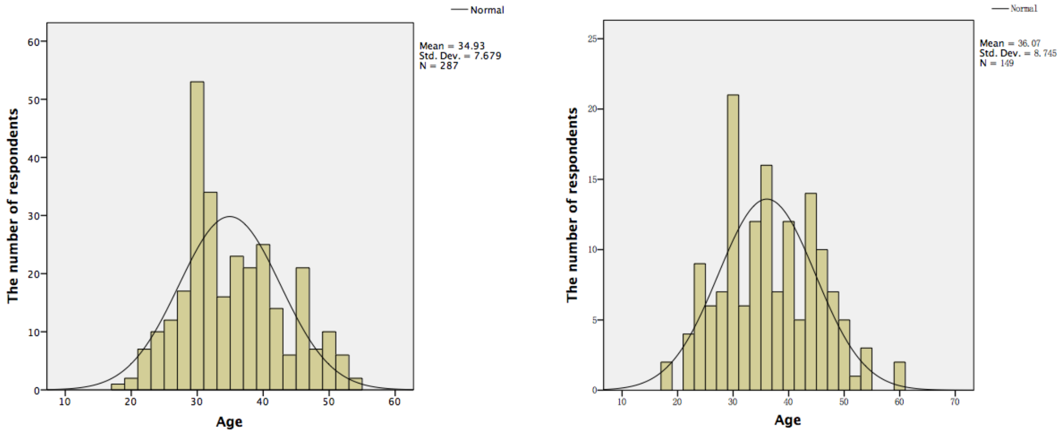

Figure 6.3 – The distribution of ages of operational roles (left) and managerial roles (right)

6.3.1.2.2 Gender

The sample of this survey did not show a bias regarding gender (according to an independent sample T-test, p-value is 0.79), although the male/female ratio is unequal, which is not really surprising, given the type of work involved. For operational roles, the number of males is 4 times greater than that of females; for managerial roles, the ratio is even a little higher (4.5). The gender difference is not part of this study, but it would be interesting to check if there is any competence difference between females and males and whether this difference affects barrier performance. As we use random samples, the gender difference is acceptable for the purpose of this study.

6.3.1.2.3 Professional background of operators

Workers are working in different roles on different tasks, work sites or departments (Figure 6.4). The plants or projects in this study all employ lifting operations. Figure 6.4 shows the activities and places of work of the operators. Most of them are technical labourers and use lifting devices for their daily work. If the operators have the ability to do the lifting operation safely, it means the safety barriers for the lifting operation function well. The diversity of work does not affect the common management of safety barriers but shows the different working skills that these operators have.

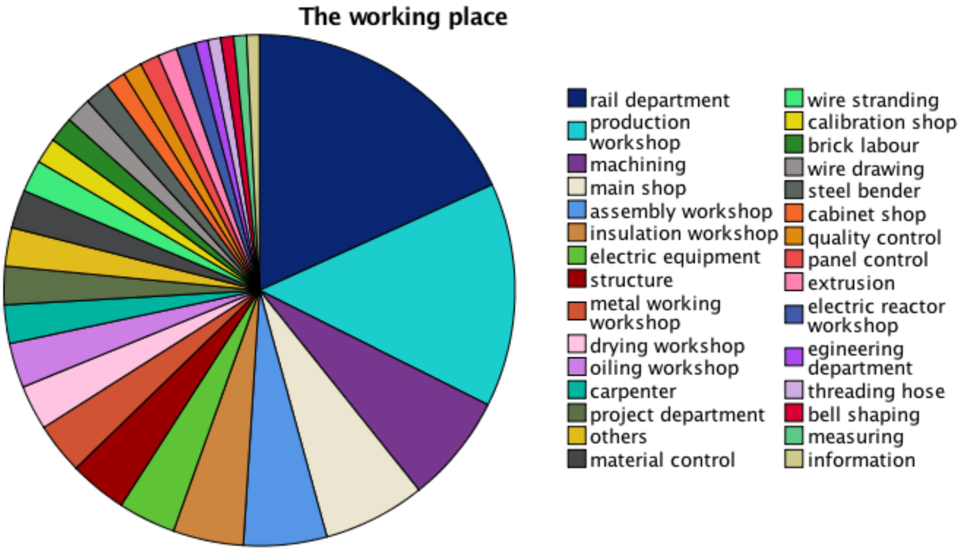

Figure 6.4 – Professional background of all the workers (247 operational roles answered working place)

6.3.2 Barrier performance

6.3.2.1 General performance of barriers

We assessed barrier performance (BP) on a scale from 0 to 10. The score 0 means the barrier has never been implemented or is absent. Going from 0 through 10 the scores represent: not implemented, extremely bad, very poor, poor, fairly poor, medium, above medium, fairly good, good, very good and perfect. The number 10 is the highest score and means this barrier is always used correctly and functions as specified. When experts are not familiar with the barrier, they can choose 'barrier unknown'. In this section, we only roughly analyse the performance of 18 barriers in seven companies.

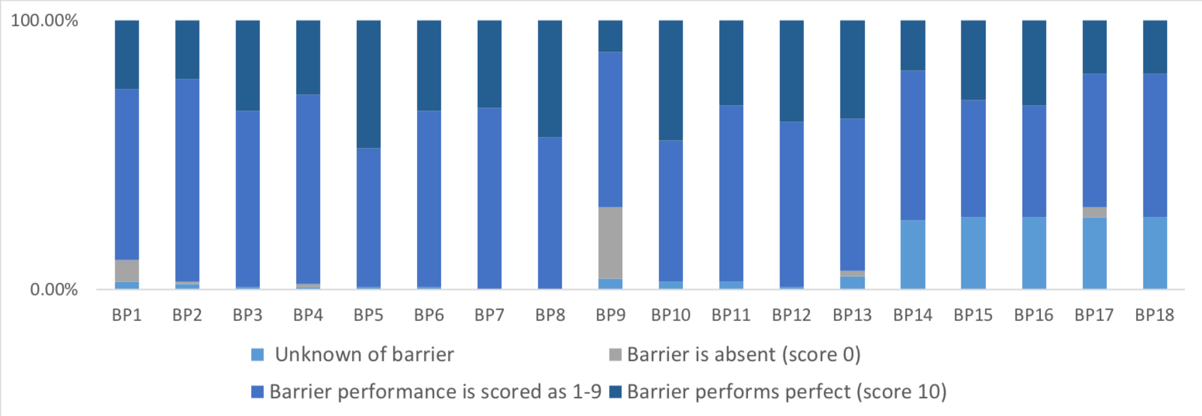

Figure 6.5 – The general performance of 18 barriers

6.3.2.1.1 Barrier has good performance (BP=10)

Barrier 5 and 8 are the two best performing barriers. They are used at every worksite and are compulsory. Moreover, experts believe that their companies implemented them very well. 'Checking the certificate of a crane' and 'Following lifting procedure' are indeed easy to carry out. Barrier 10, 'Stop lifting if limits are exceeded', is also well-implemented. This barrier is also compulsory in most crane-using environments. However, still 3% of the experts indicate that they do not know this barrier's performance. Consequently, some accidents have happened because of the failure of this barrier. This barrier prevents the threat of overload and needs professional competence, knowing the limit and the ability to stop the lifting. Overall, well-performed barriers are usually easy to carry out, and most of them are mandatory as well.

6.3.2.1.2 Barrier is absent (BP=0)

Safety barrier 9 seems largely absent, it stands for 'Always use camera/CCTV for blind angles correctly'. This finding was also confirmed by informal interviews with safety managers, since it is not a mandatory requirement. Barrier 1 'Always do pre-lift load calculations correctly' is also sometimes absent. This barrier requires an engineer's or crane operator's knowledge and skill. If this barrier is absent the operator only can guess or try the weight threshold of a load when a lifting operation is in progress. Overall, barriers that are found to be absent are also not very easy to carry out, because they are costly or they require particular skills.

6.3.2.1.3 Barrier is not known by some local experts

Some experts (25%–27%) are not familiar with barriers 14, 15, 16, 17 and 18. There are two reasons for this finding: some companies maybe never use them or some experts just ignore them at workplaces. These barriers are mostly passive protective barriers. The fact that these barriers are relatively unknown, indicates that people are less concerned with passive hardware protective barriers. But if critical events or incidents happen, these barriers are able to mitigate the negative consequences, so maintaining them to function well is nevertheless important.

6.3.2.2 The level of barrier performance in companies

The data of barrier performance is not collected for its own sake but for studying the relationship between barrier performance and managing competence. These 18 barriers are regarded as representative of all the safety barriers used in this particular risk scenario because they are implemented and commonly used in the industry (based on data from industry and confirmed by safety experts in lifting). To be able to use their quantification for every unit, the mean value of performance for all barriers is calculated (Formula 1). These numbers represent the assessment value of all barriers.

$$\text{BPs} = MEAN\ (BP_1, BP_2, BP_3 \ldots BP_i) \quad (1)$$

Where BP_i means the barrier performance of barrier i; BPs means the general barrier performance of all barriers in a particular scenario.

The seven companies in this study are regarded as seven units although the number of experts in each unit are not the same as the companies are not similar in size. The comparison of the seven companies' expert opinions on the barriers therefore can be meaningful. Does the difference of BPs between the companies have any relationship with the difference of the delivered competence between these companies? This question will be answered in section 6.4 after the analysis of both BPs and competence.

The graph of the cumulative proportion (Figure 6.6) reflects the difference of safety barrier performance between the seven companies. The dot in the figure is the value of BP according to the score given by experts from the different companies. By connecting the dots of the experts' data from the same company we get seven lines that represent the BP value of the companies. These lines are described by the formula:

$$F_{BPs}(x) = P(BPs \leq x) \quad (2)$$

Where the right-hand side means the probability that the variable BP takes on a value less than or equal to x. The range of BP values here is from 2 to 10, which means the mean value of the scored performance of the 18 barriers lies between 2 to 10.

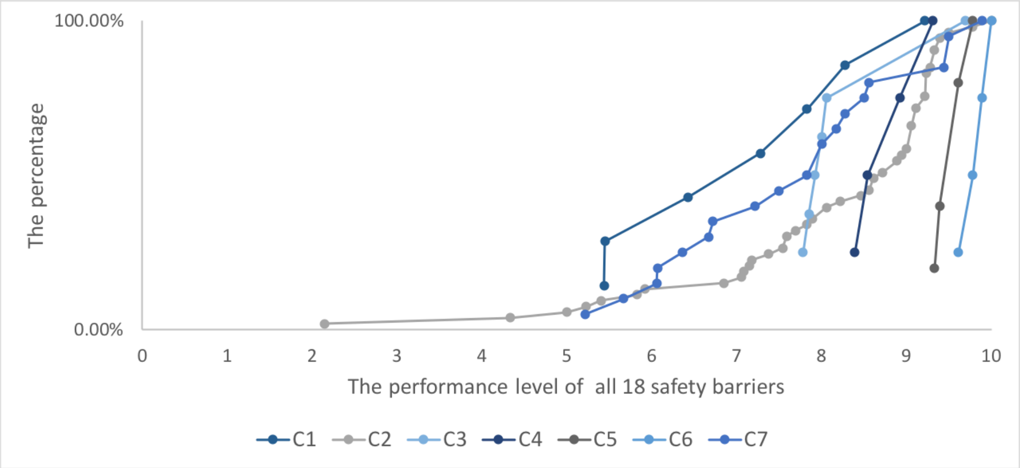

Figure 6.6 – The barrier performance (BPs) cumulative probability distribution in seven companies (C1 to C7)

It can be seen that the BP values of some companies are higher than others. In general, the line towards the right is higher, towards the left is lower. For example, companies C6 and C3 all have good performing barriers, while their BP values are all over 9; however, C1, C2, and C7 all have lower BP values as experts in these companies estimate that their safety barriers are generally not that well performed. This simple comparison shows the performance of safety barriers is useful as input for a safety audit at different companies. If auditors (experts) are the same for the different units, the result of the comparison would even be more reliable and valid.

6.3.3 The analysis of operational competence

According to the informal interviews with safety managers and professionals, operational roles regarding lifting operations differ as well as the associated safety activities. In some plants, crane operators are also called general labourers, and they account for 83% of the respondents; they accomplish the main tasks of lifting operations. The remaining workers are riggers, technicians, engineers, inspectors and so on. All of them work in tandem to complete the safety tasks at the frontline.

There are 147 specific indicators (called third level variables here) for operational competence used in the survey (Appendix D. Table D.1). As explained before, these indicators are designed specifically in the context of lifting risk scenarios. They include both general indicators of competence and specific indicators of KSEA required to control the risk at the frontline. Most of these variables are quantitative, including ordinal and interval level variables, but some are categorical variables providing nominal information. To identify the key factors of managing competence, a two-phase analysis was carried out.

6.3.3.1 Variable reduction phase 1 – the mean of specific variables or indicators

In the first step of the analysis we aim to reduce the number of 147 indicators drastically. As explained above, the indicators pertain to the knowledge, skill, experience and attitude required for properly applying safety barriers in a lifting scenario. Respondents involved in the operation of these barriers scored the KSEA required for these barriers. The various questions regarding KSEA of course differed, and hence, their answering scale. Sometimes the answer was a simple ‘Yes’ or ‘No’ (‘Are you involved in any of the following processes?’), more often a more elaborate 7-point scale was used (‘How familiar are you with the following activities?’, or ‘How difficult is it for you to identify the following threats?’). As most questions involved different aspects of the same issue (e.g. familiarity with various activities, identification of multiple threats) we explored to what extent the ratings of these indicators could be collapsed into a single score.

Firstly, we plotted the various aspects of the same question into one plot to explore their mutual relationships (Figure 6.7). These plots generally indicated that these issues had similar frequency distributions. Thereupon, the correlation was calculated between the ratings of the indicators. As these correlations were often high, they supported our notion that these indicator ratings are comparable. Finally, to make sure the ratings of these indicators could be collapsed into one rating, i.e. the mean value of these ratings, we carried out a reliability analysis.

Consider, for example, the question 'knowledge of barriers'. The respondents from operations rated their knowledge on more than one aspect or indicator, such as (a) using a certified crane; (b) restricting access to lifting area; (c) do a safety intervention and; (d) use personal protective equipment. As these variables are at an ordinal level of measurement, we calculated their Spearman (rank-order) correlations. The correlation coefficients are all over 0.8, which means the indicators have a close relationship with each other. Table 6.2 and Figure 6.7 show that indeed the ratings of these four indicators are highly correlated and have a similar frequency distribution.

Table 6.2 – The Spearman's rho correlation of variables in the Knowledge barriers group

		K_barrier_a	K_barrier_b	K_barrier_c	K_barrier_d
K_barrier_a	Correlation Coefficient	1.000	.901**	.840**	.801**
	Sig. (2-tailed)	.	.000	.000	.000
K_barrier_b	Correlation Coefficient	.901**	1.000	.805**	.770**
	Sig. (2-tailed)	.000	.	.000	.000
K_barrier_c	Correlation Coefficient	.840**	.805**	1.000	.895**
	Sig. (2-tailed)	.000	.000	.	.000
K_barrier_d	Correlation Coefficient	.801**	.770**	.895**	1.000
	Sig. (2-tailed)	.000	.000	.000	.

**. Correlation is significant at the 0.01 level (2-tailed).

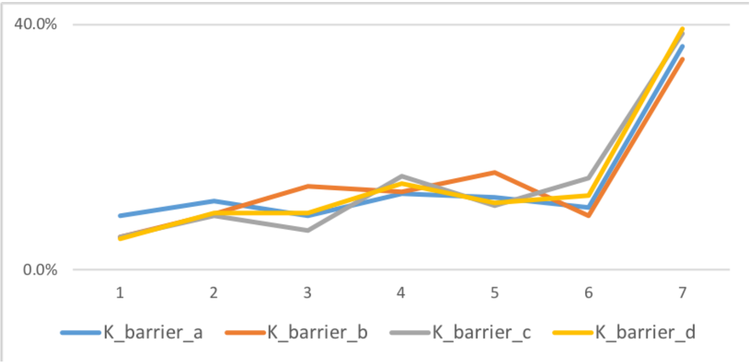

Figure 6.7 – The frequency distribution of knowledge of barriers

To test whether the collapsing of indicators is indeed justified, we carried out Cronbach's Alpha (α) reliability analyses to test whether the indicators within a particular question together form a reliable whole. This indeed turned out to be the case; all α-coefficients were higher than .9. Thereupon, we combined the ratings (or indicators) of the barriers by calculating their mean:

$$\text{Indicator} = MEAN\ (Indicator_{item\_a}, Indicator_{item\_b}, Indicator_{item\_c} \dots .) \quad (3)$$

where Indicator is a second level variable, and $\text{Indicator}_{\text{a,b,c, etc.}}$ pertains to third level variables (see Table D.1). For example:

$$\text{K\_barriers0} \;=\; \text{MEAN}\ (\text{K\_barrier\_a}, \text{K\_barrier\_b}, \text{K\_barrier\_c}, \text{K\_barrier\_d}) \quad (4)$$

After aggregating all the indicators, we ended up with 34 generic indicators at the second level. These variables correspond to the indicators that we initially developed for the assessment of safety competence. Appendix D (Table D.1) specifies the details of the KSEA-model and the indicators used in the survey for operational competence.

Table 6.3 – Quantitative operational indicators (also second level variables, see Table D.1)

Name of indicator	Explanation
K_standardO	Knowledge of standard used in the organisation
K_liftingO	Knowledge of lifting operation process
K_threatsO	Knowledge of threats (abcdf) that contribute to object drop
K_barriersO	Familiar with barriers (abcde) that contribute to object drop
K_procedureO	Familiar with procedure of barrier tasks (abcde)
K_btasksO	Knowledge of barrier tasks in own work
K_regulationsO	Knowledge of (crane) regulations
S_certificateO	Possession of how many types of certificates (on crane, skill and safety)
S_languageO	Language level (abc)
S_communicationO	Communication skill for safety (abcd)
S_idhazdsO	Skill level for identifying hazards (abcdf)
S_hardbarriersO	Skill level of using hardware barriers (abcde)
S_sotebarriersO	Skill level of using social-technical barriers (abcde)
S_behabarriersO	Skill level of using behavioural barriers (abcd)
E_workyearO	Years of work experience
E_liftexposureO	Frequency of lifting operation exposure
E_educationO	Highest (equal) level of education completed
E_professionO	Professional level of job
E_trainsafetyO	Duration of safety training per year
E_trainskillO	Duration of occupational skills training per year
E_getsupervisionO	Frequency of supervision provided
E_incidentsO	Experience of incidents (abcdef)
E_useppesO	Frequency of using PPE (abcde)
E_btasksO	Involvement in barrier tasks (abcde)
A_trainsO	Attitude towards safety or job related trainings (abcd)
A_awarenessO	Awareness of different safety activities (abcde)
A_threatsO	Concern for threats (abcdf)
A_incidentsO	Concern for incidents (ghijk)
A_leftbarriersO	Attitude of taking preventive barriers (abcdf)
A_rightbarriersO	Attitude of taking protective barriers (ghijk)
A_preventionsO	Belief in incident prevention (abcde)
A_bresultO	Effectiveness of barriers (abcdef)
A_btasksO	Willingness to complete barrier tasks (abcdefgh)
A_useppesO	Willingness to use PPEs (abcde)

6.3.3.2 Variable reduction phase 2 – Principal component analysis

In this second phase of variable reduction we explore whether there are any underlying factors (components) that can explain possible relationships between the indicators for competence for safety barriers in the lifting risk scenario. We therefore carried out a Principal Component Analysis (PCA) on the 34 second level indicators. PCA is an exploratory factor analysis method which is used to extract common components underlying a correlation (or covariance) matrix.

Firstly, we removed the nominal variables E_professionO and K_standardO as they are unfit for a PCA. The remaining variables are based on an ordinal scale, and according to Yong (2013), such variables can be used in a PCA. Thereupon we carried out an initial PCA and inspected the communalities of all the variables, which should be higher than 0.4 or 0.5 (Yong, 2013, p. 83), to ensure that a significant part of the variable can be explained by an underlying component. All remaining variables passed this check. Furthermore, when an extracted component can explain only one variable, this variable should be removed to obtain a better PCA solution. Often, these variables are independent of all the other variables. Variables E_incidentsO and S_idhazardO are removed based on this criterion. These are probably not suitable operational competence variables. Finally, we checked the correlation matrix for variables having overall small correlations with the other variables. There were no such variables. Consequently, we carried out the final PCA on the remaining 30 variables (second level indicators).

We obtained a Kaiser-Meyer-Olkin measure of sampling adequacy of 0.896, and a Bartlett's test with a p-value > 0.001. This means the variables share common factors and a PCA analysis is permitted. Using Kaiser's criterion (1960), we retained all components with an eigenvalue > 1, meaning that the component can explain more than one variable's variance. Table 6.4 shows the factor loadings after an orthogonal Varimax rotation, listing the final six principal components.

Table 6.4 – Rotated component matrix and total variance explained

	Rotated component loadings					
Secondary variables	OCF1	OCF 2	OCF 3	OCF 4	OCF 5	OCF 6
A_rightbarriersO	.812					
A_leftbarriersO	.809					
A_threatsO	.795					
A_incidentsO	.778					
A_btasksO	.729	.411				
S_languageO	.689					
A_bresultO	.668			.492		
A_trainsO	.666			.513		
K_threatsO	.603					
S_sotebarriersO	.401					
K_btasksO		.826				
K_regulationsO		.769				
K_liftingO		.758				
S_communicationO		.752				
K_procedureO	.408	.734				
E_btasksO		.710				
K_barriersO	.464	.695				
S_behabarriersO	.470	.599				
E_liftexposureO		.521	.484			
E_getsupervisionO			.663			
E_useppesO			.599			
S_hardbarriersO			.580			
A_useppesO			.561			
A_preventionO				.737		
A_awarenessO				.638		
E_trainsafetyO					.873	
E_trainskillO					.872	
E_educationO						.832
E_workyearO						-.564
S_certificateO		.496				.548
Eigenvalues	12.623	2.205	1.955	1.762	1.607	1.208
% of variance	21.735	20.024	8.690	7.914	6.453	6.386
Cumulative %	21.735	41.760	50.449	58.364	64.816	71.202

Rotation method: Varimax with Kaiser normalization.

Note: Only component loadings > .40 are shown.

Table 6.4 shows the resulting six principal components as groups of several variables. The components represent operational competence factors and we will denote them accordingly, i.e. OCF1, OCF2, ..., OCF6. These represent different aspects of knowledge, skill, experience and attitude (Figure 6.8). In contrast to our theoretical KSEA-model, the six components have a specific meaning.

Figure 6.8 shows the contents of the six extracted factors and their corresponding loadings. The percentage in front of every OCF means to what extent this component can explain the variance within operational competence. In total, these six factors explain 71.20% of the variance. We define the six factors as the follows.

OCF1: *Attitude towards safety barriers*. This is one of the most significant components and it describes the attitude towards safety barriers, barrier tasks and threats. The specific attitudes for lifting risk control are found here. Next to these attitudes, there are a few other variables present. Knowledge of threats and skills regarding socio-technical barriers are also related to the scenario and barriers. However, language skill is an exception. We do not remove it because language skill is required for social and social-technical barriers. This variable apparently has a similar response profile as various attitudes.

OCF2: *Knowledge of lifting risk scenario and its specifics*. This factor contains both general and specific knowledge within the lifting risk scenario. Operational roles need to know the lifting work procedures, the safety barriers and their work tasks for the safety barriers. The experience of lifting work and barrier tasks are also included; the skills for establishing barriers are in this component as well. These indicators enhance the knowledge of the lifting scenario and its specifics.

OCF3: *Experience of hardware use*. This group of variables is related to safety hardware use, like the experience and attitude of using personal protective equipment and skills for using hardware barriers. The only deviating variable is the experience of getting safety supervision (E_getsupervisionO, 'Frequency of supervision provided'). As the survey was carried out mostly in manufacturing plants, safety supervision may also focus on hardware usage.

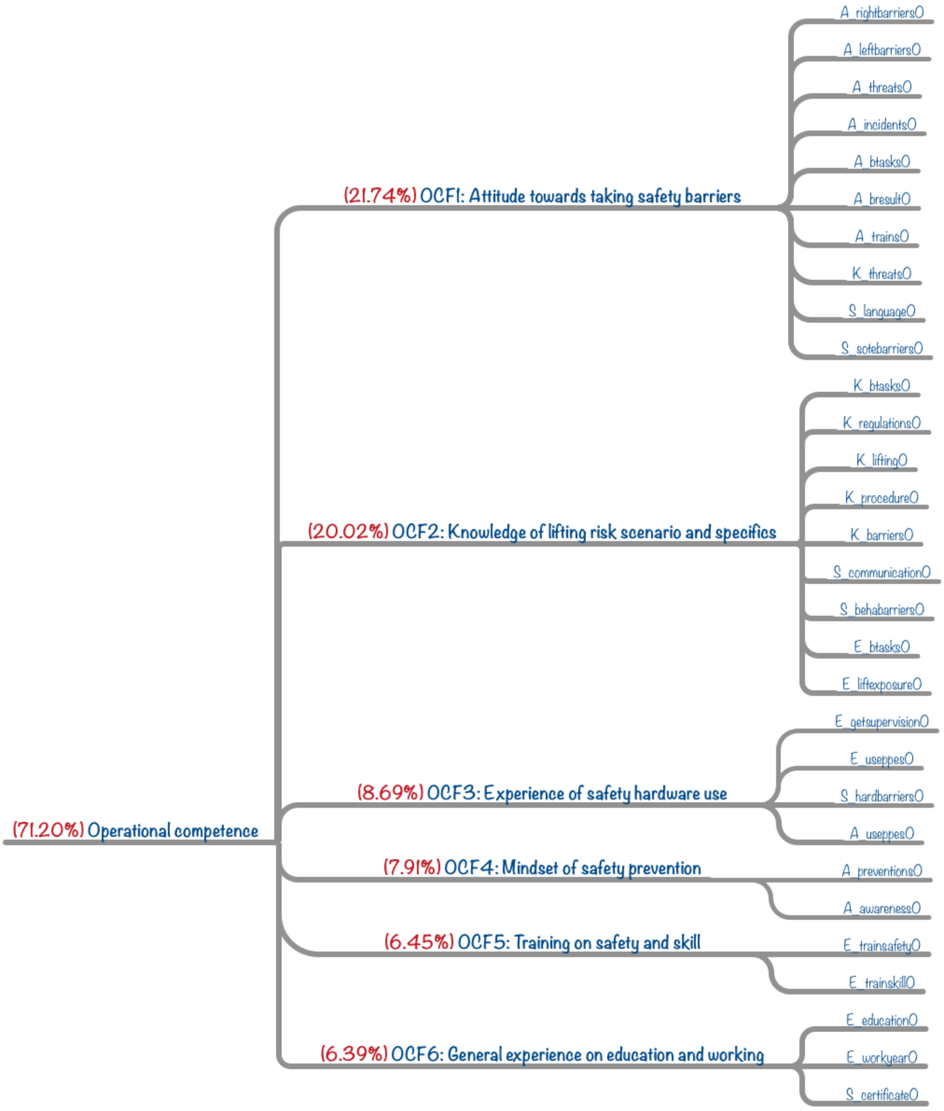

Figure 6.8 – The result of principal component analysis for operational competence

OCF4: *Safety prevention mindset*. There are two indicators here. One is about the belief (of effectiveness) in safety prevention in the plant. This indicator is about a (mental) insistence and persistence to prevent lifting incidents. The other is about the awareness of safety issues including the deployment of both hardware and behavioural interventions. We can easily see that operational roles have either a growth or a fixed safety mindset regarding persistence and awareness.

OCF5: *Training of safety and skill*. Safety training and occupational skills training both affect operational competence. Lifting operation needs specific skills from different roles involved in the operation process. The theory of Safety II tells us that a good safety performance means to do the ordinary work correctly (Hollnagel, 2014). Integrated safety management in everyday work processes may require these two kinds of training.

OCF6: *General experience in education and working*. Education and working experience are the most important inputs for a person's competence. This certified competence also contributes to the competence required for managing safety because this experience determines one's ability regarding many aspects of work.

6.3.4 The analysis of managerial competence

We administered the survey for managerial competence to different managerial roles, and Table 6.5 shows their job titles. According to these titles, we figured out who is involved directly in the management of lifting risk and who carries out some additional safety work in the organisation. But there are some exceptions. For example, an engineer and an assistant engineer answered the questions for the financial managerial staff. The proportion of these cases is very low as most organisations have a distinct responsibility for each employee, and engineers usually do engineering work, not financial work. Titles can show the diversity in background of various managerial roles involved in the management of various safety tasks.

Table 6.5 – The four groups of managerial respondents (based on G_position * G_title crosstabulation)

Groups	Group 1: The positions relate to lifting risk management	Group 2: Financial manager/staff	Group 3: HR manager/staff	Group 4: Plant/project manager
Titles	(General) manager	Assistant economist	Administrative manager	Project manager
	Engineer	Certified accountant	Engineer	Engineer or assistant engineer
	Assistant engineer	Accountant	Assistant engineer	
	Safety technical engineer	Other managerial staff	Economist	Medium senior/ technical worker
	Medium senior/ technical worker	Engineer	Assistant economist	Safety staff (inspector)
	Equipment manager	Assistant engineer	HR-staff	
	Equipment staff			
	Economist			
	Other managerial staff			

We originally defined 126 variables (indicators) for managerial competence regarding lifting risk controls (Appendix D. Table D.2). The first part of the questionnaire is filled with general questions that all respondents can answer because some safety activities do not require professional competence. The next part offers specific questions for each of the four groups of respondents. Group 1 consists of managerial roles that directly participate in lifting risk management. Group 2 only answers financial safety questions. As the safety budget provides the financial slack to implement safety activities and purchase safety equipment, this group needs to complete some questions on the support of safety barriers. Group 3 are the managerial roles which are responsible for recruiting qualified or certified workers and updating training. Group 4 are the senior managers of a particular plant or project. They are the strategy and decision makers in frontline management. All the managerial workers cooperating with front-line workers, impact safety barrier functions.

6.3.4.1 The KSEA of Group 1

According to Table 6.5, first column, engineers, equipment managers and safety engineers and managers are responsible for the implementation of safety barriers. They have the knowledge, experience, skills and attitude to carry out their management tasks, as analysed previously with the SADT method (Chapter 4). Since they are the main group to manage safety barriers – the other groups only answer a few particular professional questions – only this group's competence is analysed to represent the main content of safety managerial competence.

Similar to the exploration of the data of operational competence, dimension reduction is carried out first on the third level indicators. The indicators that have high correlations are collapsed by calculating their mean values (Formula 1). This step resulted in 26 indicators at the second level based on data from Group 1.

Subsequently, following the procedure described for operators above, we carried out a PCA analysis to extract the principal components of managerial competence. After deletion of incompatible variables, the 22 remaining indicators (Table 6.6) were analysed, resulting in five principal components (Figure 6.9). These are the five main components underlying managerial competence.

Table 6.6 – Quantitative managerial indicators (also second level variables, see Appendix D. Table D.2)

Name of indicator	Explanation
K_barriersM	Familiar with barriers for critical events (abcde)
K_tasksM	Involvement in managerial tasks (abcdefghij) for managing safety barriers
S_btasksM	Ability to complete the barrier tasks (abcd)
S_certificateM	Hold how many types of certificates (on safety, management, and crane related)
S_cooperationM	How good at cooperation in safety activities
S_hazardcommuM	The skill level of managing hazards (ab)
S_languageM	The language level (abc)
E_btasksM	Involvement in the tasks (abcd) in fulfilling barriers
E_educationM	Highest (equal) level of education completed
E_liftingM	Involvement in the management process of lifting operation
E_positionyearM	Year of working in current position
E_PPEsM	Involvement in the management processes (abced) of PPE
E_safetyparticipationM	The frequency of participation in safety management (abcd)
E_supervisionM	Frequency of supervising lifting and hoisting operators
E_trainsafetyM	The time for safety training in the last year
E_trainskillM	The time for occupational skill training in the last year
E_workyearM	Years of work experience
A_awarenessM	The awareness of different safety activities (abcde)
A_btasksM	Effectiveness of managerial tasks (abcdefghij) for managing safety barriers
A_mtasksM	Willingness to do managing tasks (abcde) for safety
A_mthreatsM	Consider to manage when threats (abcde) are present
A_regulationsM	Effectiveness of different levels of regulations (abcde)

MCF1: *Managing lifting risk and barrier tasks*. This factor is describing all the aspects of the managerial competence for safety barrier tasks. Attitudes towards these barrier tasks, regulations and threats are important, similar to the operational competence OCF1. However, managerial skills, experience and knowledge of specific management tasks for barriers are also included. The managing of specific competence for lifting risk control and safety barriers is the most significant.

MCF2: *General competence for safety*. The variables that form this component come from the general questions that apply to all groups of managerial roles. Some indicators are generic like language level and certificates obtained. Others are related to safety (not safety professionalism), such as using PPEs, participation in safety activities, safety awareness, and knowing barriers (or not). In an organisation, all managerial roles can participate in safety activities, and so knowledge on countermeasures is necessary when in danger.

MCF3: *Education and supervision experience*. This is the experience to obtain personal competence. Education is academic for managers, while that for supervision is more practical or professional. The combination of these improves a person's managerial knowledge and skills.

MCF4: *Training experience*. Training is similar to education but more professional and on a particular topic. Managerial roles should have management skills to fulfil their managing tasks and they should also know which tasks are required for risk controls. So, both skills training and safety training are included.

MCF5: *Work experience*. Since managerial roles may have varied work experience, both work year and position year explain the worker's working experience. Work year means how familiar they are with their safety tasks. The time staying in the same position means how frequent this person experienced similar safety work and responsibility in this position.

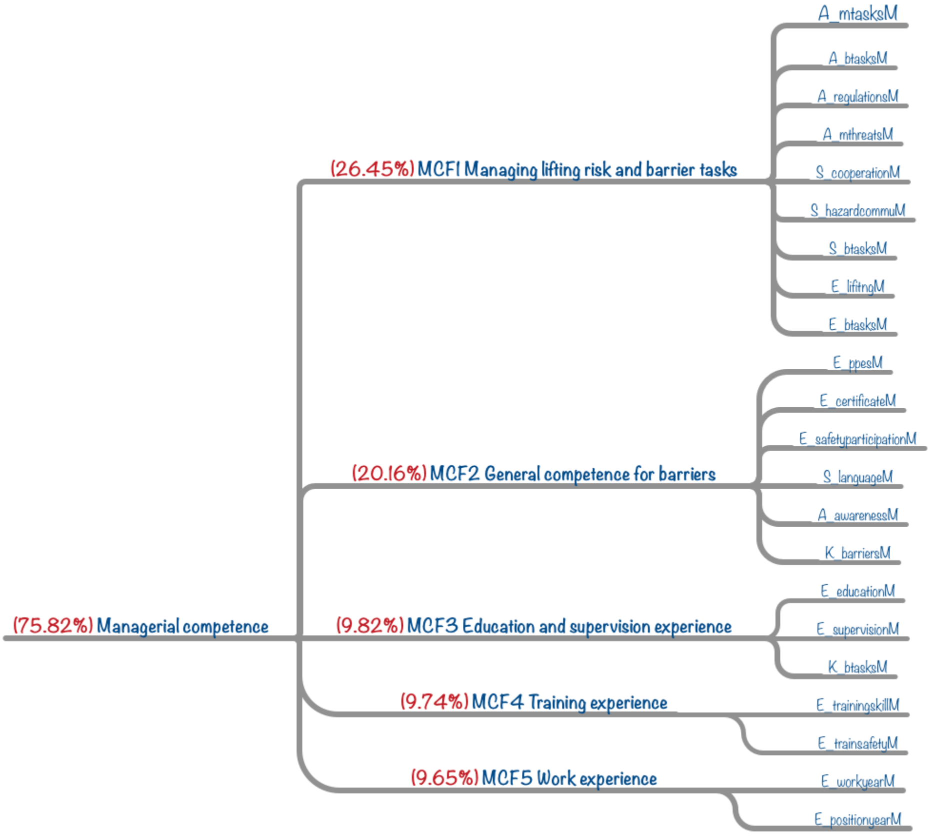

Figure 6.9 – The result of principal component analysis for managerial competence

6.3.4.2 The KSEA information from other groups

6.3.4.2.1 The variables of Group 2

Except for the general questions that apply to all respondents, Group 2 answered two questions about budget and cost. The first question is about the contribution of financial tasks to lifting equipment, safety protective equipment, crane maintenance, safety training and safety audits. We found no conspicuous differences between these five issues, as they have high correlations and similar trends.

However, regarding the budget to cover safety costs and to what degree it covers these costs (second question), the answers are quite different from the first question. Only around 20%-25% of the respondents think that their budgets can fully cover the cost of these five items. It is not beneficial for safety barriers if an organisation does not have enough budget for equipment and safety activities.

These two questions pertain to safety financial competence. They do not only represent the managerial involvement in safety costs, but also the organisation's allocated budget for these safety costs.

6.3.4.2.2 The variables of Group 3

There are around 70% respondents in Group 3 involved in checking required safety professional certificates and checking lifting or hoisting operation certificates. Certificates sometimes are mandatory but who should actually take this action is not prescribed. The data indicate that the HR-department does not fully comply with certificate requirements. Who is responsible for the (mandatory) certificate checking is still debated.

Another question is related to the attitude to training, such as safety training, skills training, new job training and training in the use of new equipment. The attitude towards skills training and training in the use of new equipment is very positive, as over 50% of the respondents rated this issue as very useful; however, the new job training and safety training are considered less useful. Even a few respondents think these are not really necessary.

6.3.4.2.3 The variables of Group 4

In this part, we ask the plant or project managers if they have confidence in preventing lifting accidents. Over 25% of the respondents do not believe that lifting accidents can be prevented. This may affect the performance of the safety barriers because the leader of a plant or project makes safety decisions. However, these data are not analysed further in this chapter.

6.3.5 Discussion of the principal factors of competence

The management of competence for safety barriers is realised by both operational and managerial competence. Principal factors of operational competence and managerial competence have been extracted. At the operational level, we had 320 respondents for the PCA analysis, while at the managerial level, we had only 96 respondents (in Group 1). Together these data describe the delivered competence for managing barriers.

OCFs and MCFs both show that attitude and experience are the main factors. The first component of either operational or managerial competence primarily pertains to attitudes. This attitude is related to the awareness of safety barriers, the willingness to use safety barriers and the belief in the safety function or purpose of barriers. These items affect the use of safety barriers and therefore affect the safety performance.

Experience is equally important as it accounts for around half of the principal factors. The experience of training, education and working are all included in either OCFs or MCFs. With this experience, a person can enhance his (or her) basic knowledge and skills for any activity. Regarding operators, the experience of using hardware barriers is a separate quality underlying the third OCF. It corresponds to the performance of only hardware barriers (Figure 6.5), because especially passive hardware barriers (i.e. barriers that do not need any human intervention to function) do not always receive enough attention, as workers often suppose they are in place and functional. The experience of managers is more about general management abilities, like communication, cooperation, supervision, etc. The difference between these two groups depends on the different roles they play in the barriers' implementation.

Knowledge of the risk scenarios and barriers is important for operators as it is the second OCF. The safety barriers, procedures, and lifting operation are all completed by operators and knowledge about all this is essential competence for them. However, we do not find this in the MCFs because the specific knowledge of barriers and procedures is extensive and not necessary for managerial tasks. The managerial roles need to have the ability to check and make sure all specific knowledge is delivered to every frontline role in the process of controlling lifting risk.

The skills appear neither in the OCFs nor the MCFs. As a matter of fact, most safety barriers are, in effect, quite simple. For example, it is evident that most of the barriers for 'Object drop' do not require any complicated skills. In other words, skills regarding safety barriers do not form a distinct influencing factor. To sum up, companies do not need to focus on their personnel's skills when they want to improve people's competence for safety regarding lifting.

6.4 The relationship between delivered competence and safety barriers

6.4.1 Overall analysis

In order to find the relationship between the management of competence and safety barriers, we need to find aggregated data for these. As we have a multilevel structure in our data, normalisation and aggregation are suitable for this analysis. Below we describe how we obtained these aggregated and normalised data and used these in a regression analysis.

6.4.1.1 Normalisation

As described above, the measurement scales of our variables sometimes vary, so we therefore normalize our data to adjust these to a single, common scale. Given the nature of the data, feature scaling is appropriate for this purpose. It is used to bring the values of all variables into the range [0, 1], using the following formula:

$$x^* = \frac{x - \min(x)}{\max(x) - \min(x)} \qquad (5)$$

where x is the original value, and $x^*$is the rescaled value.

6.4.1.2 Aggregation

In this study, a different questionnaire is used for three groups in different roles in an organization. It is obvious that the answers to checklist A, questionnaire B and questionnaire C are not from the same respondent, so the relationship between individual values of OC, MC and BP cannot be analysed. However, it is more important to find this relationship within an organisation. Considering every company as an organisation, we therefore aggregate all values of OC, MC and BP to the company level.

Table 6.7 – Aggregated data

	The aggregate data of each item			
Company code	BP	OC	MC	OC*MC
C1	0.7134	0.5698	0.5927	0.3378
C2	0.8113	0.6558	0.6236	0.4089
C3	0.9544	0.5662	0.6742	0.3818
C4	0.8790	0.6906	0.7653	0.5285
C5	0.8346	0.4820	0.6584	0.3174
C6	0.9819	0.8260	0.7184	0.5933
C7	0.7658	0.6346	0.6196	0.3932

NB: BP – Barrier Performance; OC – Operational Competence; MC – Managerial Competence

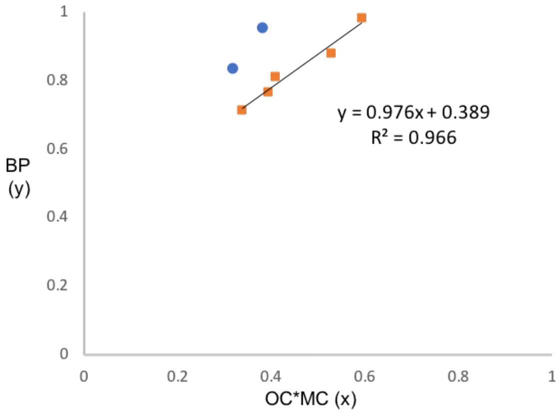

Figure 6.10 – Scatter plot and regression model

6.4.2 Regression model

Using the aggregated data, we find that managerial competence (MC) and operational competence (OC) are correlated, with a coefficient of 0.5. This means that multiple linear regression analysis of delivered (MC and OC) competence on barrier performance is not recommended since operational competence and managerial competence are not independent. However, a simple linear model can express the relationship between barrier performance and delivered competence, because the product of OC and MC is correlated to BP. Based on the data of five companies, a regression model for BP and OC*MC is calculated. Another two companies' data are outliers, which we will discuss later.

The value of R^2 is 0.966 (R is 0.983), which tells us that the combination of operational and managerial competence accounts for 96.6% of the variation in barrier performance. Statistically, if we want to explain why some organisations' barrier performance is better than others, we can look at the variation of the different organisations' barrier performance. Managing competence is an important factor in explaining this variance, although we are not sure what the influence is of any other management deliveries. However, the combination of OC and MC strongly affects BP, or barrier performance.

Table 6.8 – Coefficients of regression model

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	.389	.049		7.978	.004
	OC*MC	.976	.106	.983	9.248	.003

Table 6.8 provides details of the model parameters and the significance of these values, based on a simple regression model:

$$Y_i = (b_0 + b_1 X_i) + \varepsilon_i \quad (6)$$

We can see that the intercept b_0 is 0.389. This means that barrier performance would be about .40 without any operational or managerial competence (OC*MC = 0), even though this extreme situation would not occur in any organization. The value of b_1 is 0.976, which is the slope of the regression line. If the combination of operational competence and managerial competence increases one unit, barrier performance would increase 0.976 extra. Our unit measurements are normalized scales (0 –1), consisting of aggregated variables.

Both parameters' t-test is less than 0.05, which implies that the probability that these results would have been found by chance, is less than 5%. Moreover, b_0 and b_1 are different from 0. We can therefore conclude that the combination of operational and managerial competence OC*MC can predict barrier performance (BP) well.

Based on the regression analysis of the aggregated data between OC, MC and BC, we obtained a significant result on the condition that we exclude the outliers. By testing the 7 companies' data, the regression model is on the condition of:

$$OC_i / MC_i \geq 0.9 \quad (7)$$

Also, as the variables are all normalized, the data range is:

$$\begin{cases} OC_i \in (0,1) \\ MC_i \in (0,1) \qquad (8) \\ BP_i \in (0,1) \end{cases}$$

Therefore, the linear relationship between BP and OC*MC is given by:

$$BP_i = 0.976\,(OC_i \times MC_i) + 0.389 \quad (9)$$

Where the company code C_i = (1, 2, 3, 4, 5, 6, 7).

6.4.3 Isoquant curve

The regression model describes the prediction of barrier performance by multiplying operational competence with managerial competence. We analysed this delivered competence with the SADT method (Chapter 4), and these two levels of competence have both different content and are delivered by different people in an organization. The result of the regression model (Formula 5) shows that together they influence the performance of the safety barriers involved in lifting. While BP has a linear relationship with the product of OC and MC, we can sketch the contours of BP (Figure 6.11).

The isoquant plot in Figure 6.11 represents three dimensions. There is the 2-dimensional plane spanned by OC and MC. The five companies are located somewhere on this plane (shown in Figure 6.12). Figure 6.11 also shows the isoquant curves, which represent different values of BP. Isoquant curves as defined in microeconomics display that various inputs could produce a certain level of output. Here, with OC and MC as inputs, the output is BP. The curves all show a particular level of BP (0.4, 0.5, 0.6 etc.). These curves consist of points, which represent the different OC and MC. Figure 6.11 has the isoquant curves sloping downwards, which means that the same level of BP only occurs when increasing either one value of OC or MC with a lower value of the other. If the value of both OC and MC is increased the BP level will rise. All of these changes are only valid within the boundary set by the regression model.

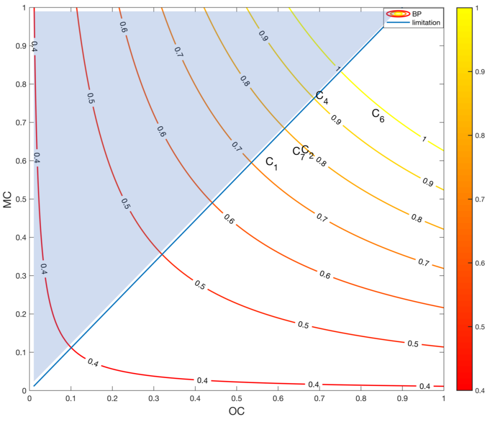

Figure 6.11 – The isoquant plot of BP and OC*MC

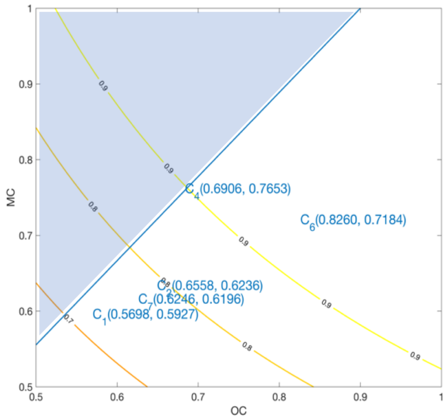

Figure 6.12 – Zoom in the isoquant plot (data map)

The blue line in Figure 6.11 is the boundary condition set by our model. This means the ratio of OC and MC (Formula 7) cannot be less than 0.9, otherwise the company's data are not fit for this regression model. Therefore, only points below the blue line are valid in our study. In Figure 6.12 the C_i points represent the five companies, which are all below the blue boundary line; the two other companies, which we left out of the regression analysis, are not. Using these points, we can locate their corresponding BP level easily. Another restriction is that the three values BP, OC and MC should be in the range from 0 to 1.

The mapping of the isoquant curves illustrates how the performance of barriers is influenced by operational and managerial competence. For an organization, if the performance of safety barriers is not good enough because of its delivery of competence, by using these isoquant curves, it can locate at which level their safety competence is. Then the organisation can look into the details of their competence management and develop ways to improve it. This overall analysis supplies the safety management solution for the competence of managers and operators.

6.5 Discussion

In previous studies a systematic approach has been developed to manage safety barriers, i.e. the notion of management delivery systems (DSs). Considering them as a constituent part of a complete safety management system (SMS), they are similar to other safety management approaches. For example, the International Sustainability Rating System (ISRS), developed to assess SMSs, contains 15 such components, including training and competence, risk control, management assets, etc. (DNV, 2013). These components, especially the management assets, have a similar function as compared to the DSs. In recent years, the idea of delivery of safety management is also integrated into ISRS (DNV, 2016). In general, the safety management system is maturing from the traditional documented procedures to dynamic delivery systems.

Taking a systematic perspective, delivery systems are the management extension of the bowtie scenario model with added safety barriers. From a quantitative perspective, it is also an extension of risk analysis. This study narrows down a broad and generic safety management system to a decomposed specific safety management component and its factors. However, how to quantify the delivered competence for managing safety barriers is not just a mathematical problem. Because so many specific safety barriers are applied to complicated hazards scenarios, how and to what extent these barriers need particular safety competence has not been elaborated before. The problem of quantifying competence indicators and aggregating the overall delivered competence and barrier performance of an organization were broadly solved here. Our study indicates three principles in the quantification of safety management.

Principle one: safety management should be hazard/accident scenarios based

The use of SMSs is common in both practice and research. This study provides insight into the working of an SMS. The essence is to control risk with safety barriers; to execute or install barriers with delivery systems. As has been shown here, delivered management must be based on risk scenarios. Organisations expect all management resources and controls are used for the mitigation of the critical risks, which should be analysed in risk models. Risk is a concept that is only meaningful in scenarios. So, the risk model presented here is based on such hazard or accident scenarios. These scenarios are developed with sequences of events including incidents, accidents, causal events and escalated events. Therefore, the study of safety management should also be based on hazard/accident scenarios.

Principle two: indicators should be shaped/modelled systematically

Management indicators are not something provisional developed for a quantitative study. We suggest a systematic framework of indicators because it is logic and valid. With Hale's SMS model the notion of delivery systems was introduced first. By using the structured analysis and design technique (SADT), we further analysed the process of delivery systems and different types of barriers. The details of delivered competence for barriers can be established further by the analysis of barrier tasks. The operational and managerial competence indicators were framed here in the KSAE framework.

According to this principle, it is important to figure out the hierarchy of safety management factors. This study is like Russian nested dolls: one generic SMS, which contains barrier management or delivery systems, which contain more specific indicators and delivery processes of each system.

Principle three: variables for indicators should be explicit and sufficient

The quantification of safety management does not end with indicators, as many of these are not directly measurable. Variables for each indicator should be explicit and there should be a sufficient amount of these. In other words, a general indicator can be expressed by one or more detectable or measurable variables. In this study, delivery systems are the generic models for these indicators. Each system outputs a group of indicators and the specific variables provide the data for these, in an established scenario. We do not suggest to go deeper into the detectable variables, like the mechanism of a failure frequency. We can obtain these safety management variables from existing records, monitoring data, technical parameters or audit data. Some are numeric, some others can be defined to provide categorical or Boolean numbers. The statistics of these variables and indicators can contribute to the quantitative analysis. The variables in this study involve so many specific safety activities – which we obtained from barrier tasks analysis and the required safety competence – because an organisation implements a barrier by a sequence of tasks from different roles.

Following these principles, many numeric variables describe the management of competence for barriers in a lifting risk scenario. After two phases of indicator reduction, especially after the principal component analysis, the key influencing factors of operational competence and managerial competence have been identified. These key factors come with weights (component loadings) and these might helpful for an organisation to select a certain type of safety competence delivery for improvement.

Safety barriers have always been quantified by failure rates in a risk model. However, the performance of a barrier is not always binary, like functional/not functional. Especially for behavioural barriers quantification is difficult when a system view is lacking. A measurement scale to assess behavioural performance is much more fit for this purpose for several reasons. First, the probability or frequency of the failure of most safety barriers is not recorded; second, it is not easy to judge a failed or successful barrier if the criteria are not fixed; third, whether the barrier performs good or bad or is even absent may affect risk differently. In this study, while the barrier audit data were not available, safety barrier experts gave an assessment of the actual performance on a scale from 0 to 10. This score does not only reflect reality but it is also convenient for statistical analysis.

The contribution of this study is that we connect barrier performance and competence delivery statistically, i.e. through linear regression. We divided the management of competence into two parts: operational and managerial competence. The operational competence directly supports the execution or fulfilment of safety barriers, while the managerial competence is more related to management activities. Together they determine the performance level of safety barriers. More specifically, the product of operational and managerial competence has a linear relationship with the performance of safety barriers. We have shown with contour lines that some level of barrier performance is obtained by a combination of operational and managerial competence. We also constrained the two kinds of competence so that they cannot be out of proportion. They both should reach a certain level of delivery.

Taking the competence delivery as an example of DSs, we presented a quantitative approach to DSs in this study. Based on the structure of DSs, we could decompose all of the generic safety management processes and quantify them in this clear and straightforward way. This raises the question – How do the outputs of other DSs like commitment (of personnel), availability (of people), etc. influence safety barriers? The quantitative analysis as elaborated here, can be applied in a similar way. Then also the relationship between all DSs and safety barriers can be explored. With this insight, companies can efficiently improve the weak(er) aspects of their safety management.

There are some limitations to this study. A set of desirable data is always difficult to obtain. By using a survey, we cannot avoid any answering biases but we can improve the validity by other means, like expanding the number of respondents. A pilot was carried out to test the survey and a large enough number of respondents responded. Another limitation is that the quantitative analysis is somewhat coarse. Most indicators are expressed by specific variables, which probably do not capture all scenarios, although we have checked the reliability of every indicator with Cronbach's alpha. The OCFs and MCFs resulting from the PCA are also rough estimates because they cannot represent the absolute delivered competence. In spite of all this, we used aggregated data for the linear regression, which included all the information. Therefore, the coarse PCA provides a straightforward result and can help with formulating safety strategies. By using a quantitative result, an analysis of safety management systems, safety audit systems, key safety performance systems, and any other management influencing factors can be more efficient and effective.

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7 CONCLUSION

7.1 Conclusion and discussion

This research has provided a solution to the problem of quantifying safety management in the modelling of SMSs. In order to answer the corresponding research question, *How to quantify safety management and to what extent is it possible?,* we carried out a theoretical analysis from full safety management systems to specific safety influencing indicators. We have shown that quantification is possible up to the level of specific safety influencing factors.

Based on Hale's SMS framework, we developed a quantitative approach to safety management delivery. This quantitative approach relies on a logical modelling of the relationship between the issues surrounding safety management, and it demonstrates clearly the importance of obtaining quantitative data at the operational level, i.e. data relating to working tasks, staff and equipment of safety. Although this research views safety management from the perspective of both Safety-I and Safety-II, especially Safety-II thinking supports the quantitative approach. That is, we specifically looked at 'normal' operations and how safety is achieved during the execution and management of that work.

7.1.1 Systems-based modelling is essential

A major conclusion of this research is that the application of systems-based modelling is the most appropriate way to answer our main research question. An SMS, with its constituent elements, is decomposable and hierarchical. It is a socio-technical system rather than a mechanical system. Socio-technical systems are usually not structured in a fixed way, and their functional mechanisms are often not crystal clear. In this dissertation, our broad overview (Chapter 2) has provided much insight into SMSs and their elements. With a better understanding of a full SMS and its functioning elements, we were able to model the details effectively.

Based on the literature, the modelling of safety management systems typically comprises three, closely related parts: events (scenario), safety barriers, and safety management. Safety barriers are incorporated in events models for risk mitigation. Safety management controls these barriers and monitors incident and accident scenarios. An accident (or incident) scenario pertains to a failure of events, dysfunctional barriers or inadequate safety management. This research focuses on the safety management part, which we modelled as delivery systems (DSs).

Both delivery systems and safety barriers can be modelled systematically by the SADT method. SADT is a systems-based method, which provides the safety activities and tasks within process frameworks. Previously, it was used for the modelling of delivery systems in several research projects. This research has further developed the competence delivery system by identifying and quantifying its indicators. Another novelty of the current research is that we modelled safety barriers by SADT as well. We illustrate that both operational and managerial competence are resources that support barrier activities. By using this modelling method, competence indicators and tasks regarding safety barriers are connected at an operational level.

Through systems-based modelling, we show that safety management can be modelled at all levels: the organizational level SMS, the elements of an SMS and safety operational tasks. Systems thinking demonstrates logical connections of (and between) each safety task(s), which are easily mapped onto the specific safety management and risk control systems within the context of a specific industry. With this research we show we can model safety management deliveries and safety barriers in both general and specific ways.

7.1.2 Quantification of safety management is the aim

Modelling the relationship between DSs and safety barriers is the foundation of a quantitative approach to safety management. The traditional quantitative risk analysis approaches (e.g. risk matrix, probabilistic risk assessment) do not include the quantification of management and traditional safety performance analysis (e.g. KPIs, audits) is often too vague. This research aims to develop the principles to solve these issues. To determine the management factors for safety barriers is a crucial step towards their quantification.

We quantify management competence indicators, which are modelled initially as KSEA (Knowledge – Skill – Experience – Attitude), after completing the theoretical analysis of competence delivery. By performing a statistical analysis we achieved an improvement of this indicator framework. Subsequently, we carried out a principal components analysis of the data from seven companies on operational and managerial KSEA and identified the main components of managing competence. This outcome shows that the quantification of DSs actually customises management for the control of *any* risk scenario.

Another interesting result of this quantitative study is that operational and managerial competence together contribute to the performance of safety barriers. It reveals the quantitative relationship between safety barriers and management competence. We propose the isoquant curve to visualise this quantitative result. So, we can predict the overall performance of barriers according to operational and managerial safety competence in an organisation.

This quantitative approach is typically based on a theoretical model; however, to obtain useful data, the variables should be as specific as possible. All the related aspects such as risk, barrier and management, must be specified and customised for specific (industrial) applications. We use statistical methods, which result in aggregated, specific data. In other words, we supply safety management and barriers with empirical data, rather than getting data from a general assessment without any universal criteria of management issues.

Through the case study on managing competence, we show the quantitative approach to safety management in its entirety. Other delivered management (e.g. procedures, communication, maintenance, etc.) we expect we can analyse systematically and quantitatively in a similar way. The factors of other management deliveries contributing to the performance of safety barriers vary, so the data of these management indicators may be obtained in different ways, but the systems-based modelling and quantitative principles are the same.

7.1.3 Consider safety management from both safety-I and safety-II perspectives

In most safety management systems, control of risk is the main task of management. In other words, to decrease risk means the improvement of safety performance, such as widely used risk-based safety management approaches usually do. The focus of our research is therefore on the analysis of risks, hazards, failed events, and the cause-effect logic. This could imply that our perspective is primarily Safety-I. However, hazardous or failed events only account for a rather small proportion of daily work events; risk analysis therefore does not represent safety management in its entirety but provides it with information for safety decision making. Safety management concerns day-to-day safety issues and any inefficiencies pose latent causes of accidents.

Therefore, the view on safety management needs to switch from Safety-I to Safety-II. Safety-II looks for what goes right (Hollnagel, 2014). Different from Hollnagel's (safety) emphasis on daily work processes, we focus on the overarching safety management system, which contains socio-technical work tasks that are part of the daily safety activities.

In this study, we look into how safety management keeps safety barriers and interventions going, thus controlling risk. This logic bridges the gap between Safety-I and Safety-II. Cause-effect logic provides scenarios for safety barriers; management tasks (structured in process or procedure) influence the life-cycle of safety barriers; management systems are broken down into activities and indicators which support barrier tasks. Performance of either safety barriers or management is from the perspective of Safety-II.

Our research question is concerned with the quantification of these performances. After comparison with quantitative approaches used in other projects, such as Phoenix, WORM, and other measurements of risk or safety performance, we suggest using an ordinal scale to assess safety barriers. Bimodality of events, such as the status of barriers (e.g. failure/success), does not fit a complicated system or logic. One barrier's failure or absence is neither sufficient nor necessary for an accident; accident data are just a lagging indicator of safety performance. However, the performance of safety management determines the performance of all safety barriers in real time. So, instead of using the probability of failure/success in tree models, barrier performance using ordinal level measurement can be used instead in the quantification of safety management.

One of the most important principles of quantifying the performance of management is that it must be based on a specific scenario and tasks. As Hollnagel (2014) stated that 'we can only specify the work in detail for situations that we understand completely' (p. 126), our case study focused on a rather simple context of lifting risk and barriers. We elaborated competence with more than two hundred specific variables. It means that safety management performance can only be expressed quantitatively when related issues, such as risk, barriers and management tasks, are elaborated specifically.

Performance improvement relies on management adjustment. As a result of this study, the performance of safety barriers attained a quantitative relationship through a combination of managerial and operational competence for safety. In other words, when we adjust the 'dosage of' management positively, the performance of safety barriers will improve, and risks will decrease. Therefore, safety performance as a whole will improve. Our approach changes the management of safety from post-accident reaction to predictive and proactive performance improvement.

7.2 Difficulties, solutions and limitations

7.2.1 Current bowtie-based tools are insufficient for a holistic analysis and management of barriers

At the beginning of this research, we assumed that data of barriers' performance would already be available. However, such data are not easy to obtain. One of the main problems is the lack of systematic models and a universal type of (performance) data for safety barriers. It urged us to review related models and quantitative methods. The bowtie model and tools are used frequently for barrier analysis. The barrier concept is derived from Haddon's HBT-model, and is now demonstrated in Bowtie-modelled accident scenarios. Tools such as Storybuilder and BowtieXP are created for practical use.

Bowtie-based tools help to develop thousands of practical barriers preventing particular unwanted events, but they do not provide a universal method to manage all barriers efficiently. Moreover, it is difficult to know the general performance of barriers as long as the mechanisms of safety barriers are different. In Chapter 4 we reviewed the categories and features of these barriers and proposed that using task analysis to model each type of barrier by SADT is a potential solution for these difficulties. The management of these tasks has both common and (industry) specific characteristics. Our generic model of managing practical barriers still needs further validation with information from industries.

This leads to another problem. Overall, we lack a universal data type of barrier performance to analyse them quantitatively. According to the literature, a few case studies on the performance of safety barriers described and quantified them individually, such as failure rates of (hardware) barriers. Besides, a practical tool such as BowtieXP assesses barrier performance on two aspects, namely adequacy and reliability. However, narrowing down the performance of behavioural or hardware barriers to these two aspects gives rise to a number of questions. How can companies provide accurate data other than by self- assessment? If a particular behavioural barrier has nothing to do with human reliability per se, how do we then assess its reliability? If passive hardware is always there how do we assess its adequacy? How do we get one numeric value from two different performance aspects? As it is not possible to check the data by using this tool in practice, we doubt whether this solution solves the quantitative problems of barrier performance.

Instead of using failure rates or an assessment result of two fixed aspects of individual barriers, a unified scale of performance will contribute to a full analysis of all barriers. In this research we propose a 0-10 scale to quantify the performance of barriers (Chapter 6). Each barrier is described specifically according to its safety function in the accident scenario. Still, companies cannot provide us with accurate records of descriptions of all barriers, and we do not have enough resources to observe each barrier's performance. The data are still subjective as they stem from the sole judgement of experts. Despite these limitations in data collection, we have developed a unified data type of barrier performance and validated it based on specific cases.

7.2.2 Current quantitative analysis of safety management is still rough

Data collection is often a critical factor in quantifying safety management. Most companies do not record safety competence factors since most SMSs do not specify or include them as detectable or measurable variables. To solve this issue, we have collected all pertinent data through a survey which included a questionnaire, checklist, and (informal) interviews. The survey is based on our theoretical analysis of competence and its generic indicators.

Quantifying these indicators requires detectable and measurable specific variables. The case study elaborates the details of competence and the barriers to lifting risk control. For example, the competence indicator ‘knowledge of barrier’ should be specified with the knowledge (level) required for each barrier involved in the prevention of the event ‘object drop’. Likewise, there are many variables linked to other indicators. This research only uses a limited number (often, less than 10) of variables for each indicator. Admittedly, variables are therefore not covering all the contents of one indicator completely. Obviously, the more incomplete the data for each indicator, the more imprecise the result. Hence, the reliability of these variables belonging to each indicator need to be tested to ensure the validity of the data.

Another issue that increases the uncertainty of results is that variables are mostly measured at the ordinal level. As behavioural performance is rather difficult to quantify, ordinal level measurement is one of the solutions to put numbers on the variables of competence. The PCA-method applied to ordinal level variables is not as accurate as for ratio- or interval-level variables. To solve this problem, we compared the result of using CATPCA (Categorical Principal Components Analysis, a PCA designed specifically for the analysis of nominal- and ordinal-level variables) with the results from a traditional PCA. Despite a slight difference in weightings, the principal components of competence are, in the end, the same.

7.2.3 Are the quantitative results valid in different scenarios or different sectors?

The quantitative study is based on a systematical review of safety management and narrows down to delivery systems, which fit most industries as we aim to develop a generic approach to quantify safety management. As a consequence of the selected approach, safety management should be hazard/accident scenarios based. In this study, we selected lifting risk scenarios as they occur in many industrial sectors. The quantitative analysis has been carried out with scenarios with ‘object drop’ as critical event. Subsequently, safety barriers and management activities were elaborated.

For mostly practical reasons, the case study on quantitative analysis is based on data obtained from seven crane-using companies in China. A pre-test of the survey was conducted in an UK construction industry environment, while the actual quantitative study only uses data obtained from one county (China). Our results show that there is an obvious and distinct relationship between management competence and safety barriers in lifting risk. To be able to apply this result generically, more data from different companies in different places (countries) are needed.

It is difficult to generalise a quantitative result as a principle based on one (particular) study. Still, our approach to quantify safety management can be applied in different scenarios and in different places. It is based on a theoretical foundation of a competence delivery system and safety barriers therein. Even if the risk scenario or application sector changes, we can still develop variables according to competence indicators and identify the practical safety barriers in a new risk scenario. A quantitative analysis of their relationship can be done in the same way.

7.3 Future work

7.3.1 Studies of other delivery systems

This research has successfully demonstrated an approach to quantify competence, which is one of the seven generic management deliveries (according to Hale's SMS-model). The models for the indicators of each delivery system still need to be developed, based on their content and characteristics; for instance, such as the application of the KSEA-model for competence. Further efforts are needed to identify indicators and to develop 'reasonable', (recognisable, valid and applicable) models for other delivery systems, such as availability, commitment, communication, etc. Then we can use a similar approach to explore their contribution to the performance of safety barriers.

Quantifying different delivered management factors requires appropriate methods. In this study, we used a survey to obtain data; however, for some other deliveries, this is not suitable. Other potential methods of data acquisition are field observations and experiments. Nevertheless, we still need to study each delivery system in detail to determine the data collection technique and subsequently perform a quantitative analysis.

7.3.2 Study of the seven DSs

After all principal components of the seven management deliveries are identified, the most significant factors for safety management can be determined. This will help a company to improve its efficiency of safety management. Another topic following from this study is the interaction between the seven DSs and how they affect each other. This will further validate the content of the seven DSs. It will highlight the importance of indicators and will prevent overlaps. To describe safety management quantitatively and generically, DSs should be modelled with a function of key performance indicators (principal components).

$$DSs = \mathrm{F}(Indicator_1, Indicator_2, Indicator_3, \dots)$$

7.3.3 Study of the relationship between general DSs and safety barriers

According to Hale's SMS-model, DSs manage the safety barriers. Apart from theoretical models, the quantitative relationship between them will reveal the critical part of the safety management system. Relevant questions hereby are: how do DSs affect the performance of safety barriers quantitatively? What is required in terms of management to keep safety barriers properly functioning? We expect a quantitative model can be developed that can describe this relationship. By using this model, the performance of safety (showing in safety barriers) will be adjusted by manipulating the seven deliveries. Furthermore, safety performance will be efficiently improved through optimising the delivered management systems.

$$BP = \mathrm{F}(Competence, Commitment, Communication, Procedure, Hardware, Interface, Availability)$$

7.3.4 Develop database and information system for safety management

This research gives an example of managing competence for safety in companies. Obviously, an extensive database covering more aspects of safety management will help companies to improve its overall safety management. A major problem impeding this and future research is lack of management data. There are many databases that record accidents and assessments of risks; however, there is little data available related to organisational risk and safety management. Since these data are often not easy to extract or quantify, one must make use of a designed data type to be able to develop a common database.

Also, it is not always easy to interpret traditional KSPIs (key safety performance indicators) used in many companies, despite that they are likely to contain thousands of indicators. The information system is usually not based on a logical model and its recorded data are not numeric. Developing a quantitative information system for safety management following our research will streamline the organisational safety management information and as such will benefit overall management.

7.4 References

Hollnagel, E. (2014). *Safety-I and Safety-II: the past and future of safety management*. England: Ashgate Publishing Limited.

APPENDICES

Appendix A Elements of SMSs

- Refer to Chapter 3

Table A.1 – The information of elements in SMSs

SMS						**Elements**				
Reference	Name	Industry /field	Document type	Structure for connecting elements	Number of elements (Level1 – Level2)	General element (how many elements for this group) OR element list	The relation of elements	Structure of the element	Element explained	Process OR procedure
(Burk and Smith 1990)	Dupont PSM	Process	Paper	Grouped	12	• Technology (4) • Personnel (4) • Facilities (4)	Independent	Non-structured	No	Procedure
(Carrier 1993)	ADCO's SMS	Oil and gas	Paper	Structured	5-18	• Safety concept (4) • Safety planning (6) • Safety practices & discipline (4) • Safety contingency (2) • Safety performance monitoring (2)	Independent	Non-structured	Yes	Procedure
(Wright, 1996)	The key health and safety issues	General	Guidance (HSE)	Non-structured	11	Commitment; early recognition and assessment; competence; accountabilities and responsibilities; … …	Interact	Non-structured	Yes	Procedure
(HSE, 1997; Salim, 2016)	Health and safety management system	General	Standard/guidance (hsg 2nd ed.)	Structured: PDCA	6	• Auditing • Policy • Organising (4) • Planning and implementing • Measuring performance • Reviewing performance	Interact	Structured: process; input-process-output	Yes	Process & procedure
(IAEA, 1999)	Safety management components	Nuclear power	Standard (INSAG-13)	Structured: structure	4-13	• Definition of safety requirements and organization (2) • Planning, control and support (5) • Implementation (3) • Audit, review and feedback (3)	Interact	Not given	Yes	procedure

(Ho, Ahmed et al., 2000)	Site SM (Audit)	Construction	Implementation paper	Non-structured	14	Safety policy, Project briefing, safety organization, safety committee, safety training and promotion, safety inspection, risk assessment and hazard analysis, accident investigations, … …	Independent	Not given	No	Not given
(Peng and Shiua, 2000)	BOWEC guidelines SM	Construction	Regulations	Non-structured	13	Safety policy, safety working practice, safety training, group meetings, incident investigation and analysis, in-house rules and regulations… …	Independent	Not given	No	Not given
(ILO, 2001)	ILO OSH	General	Standard/ Guidelines	Structured: PDCA; continuous improvement	5-16	• Policy (2) • Organising (4) • Planning and implementation (4) • Evaluation (4) • Action for improvement (2)	Independent	Structured: PDCA	Yes	Procedure & audit
(Gabbar, Chung et al. 2002)	CAPE-SAFE (Function Decomposition)	Oil and gas (plant)	SMS technique paper	Structured: hierarchy; system	5-14-	• Hazard evaluation (3) • Safety training (2) • Safety regulations management (3) • Safety procedures management (2) • Safety data management (4)	Interact	Not given	Yes	Not given
(Santos-Reyes and Santos-Reyes, 2002; Santos-Reyes and Beard 2009)	Systematic SMS model	Oil and gas (fire)	SMS proposed and implementation paper	Not given	7	• Safety policy implementation • Safety co-ordination • Safety audit • Safety functional • Safety confidential reporting • Safety development • Safety policy	Interact	Structured: system	Yes	Not given
(Ivan, J. N., Malenich, J., & Pain, R., 2003)	Integrated SMS (NCHRP report 501)	Highway	Research report	Structured: continuous improvement	8	Organizational structure, leadership, mission & vision, integrated safety management process, … …	Interact	Not given	Yes	Procedure
(Kwan, 2004)	SMS	General	Bachelor dissertation (research project)	Structured: continuous improvement	16-	Safety policy, safety work practices, group meeting, safety training, safety inspection, accident investigation & analysis, … …	Independent	Not Given	Yes	Procedure & process

(Lees, 2005)	CCPS (1989/7)	Chemical Process	Guidelines	Non-structured	12-48	• Accountability: Objectives and Goals (9) • Process knowledge and documentation (7) • Capital project review and design procedures (7) • … …	Independent	Not given	Yes	Procedure (audit)
(Smith 2005, Stolzer 2008, ICAO 2013)	ICAO & FAA SMS	Aviation	Standard/guidelines; paper	Structured: hierarchy, continual improvement	4-12	• Safety policy and objectives (5) • Safety risk management (2) • Safety assurance (3) • Safety promotion (2)	Interact	Structured: system	Yes	Process & procedure
(Su, Tsai et al. 2005)	New VPP items	Occupational health and safety	Research paper	Structured: schematic framework	7	OH&S policy, planning and management program, organization, operational control, emergency response and incidents preventive action, … …	Interact	Not given	No	Not given
(Law, 2006)	FIUSMR's SMS	General	Paper	Structured: group	4-14	Safety policy, safety organization, safety training, in-house safety rules, personal protection programme, … …	Independent	Not given	Yes	Not given
(Bellamy and Geyer, 2007)	SMS factors (in common)	General	Research report (RR543, HSE)	Non-structured	4-9	• Policy (1) • Organising (4) • Planning and implementing (1) • Measuring (3)	Independent	Structured: system, parallel	Yes	Process & procedure
(Charnock, 2007)	Functional SM	Process industry	Paper (based on IEC 61511)	Structured: life-cycle, system	11	Hazard & risk assessment, allocation of safety functions to protection layers, safety requirements specification for the safety instrumented system, … …	Interact	Not given	No	Process & procedure
(Durand and Romei, 2007)	(ALSTOM) SMS	Rail industry	Paper	Not given	9	Safety policy and target; organization and responsibility; skill, competence, training, awareness, … …	Interact	Not given	No	Process & procedure
(Fernández-Muñiz, Montes-Peón et al., 2007)	Scale of SMS	Occupational safety	Research paper	Non-structured	6	Safety policy, incentives for employee participation; training; communication; planning; control, … …	Independent	Non-structured	Yes	Not given
(Sun, Zhao et al., 2007)	SMS blocks	Airport	Research paper	Structured: hierarchy, system	6 (& 8)	Airport SMS objectives; policy, laws, regulations, and rules; organization	Interact	Not given	Yes	Not given

						structure and staff, education and training … …				
(Liou, Yen et al., 2008)	Factors of a SMS	Airlines	Research paper	Structured: group	12	Communication; documentation; equipment; incident investigation and analysis; … …	Interact	Non-structured	No	No given
(Chang and Liang, 2009)	Attributes of SMS	Manufacturing facilities	Research paper	Structured: PDCA, hierarchy	4-20-	PDCA: high level commitment; organization and responsibility; laws and regulations; … …	Independent	Non-structured	No	Not given
(CCPS, 2010)	Risk based process safety (RBPS Pillar)	Process	Guidelines	Structured: hierarchy	4-20	• Commitment to process safety (5) • Understanding hazards and risks (2) • Manage risk (9) • Learn from experience (4)	Interact	Not given	Yes	Procedure
(Hsu, Li et al., 2010)	Component of an SMS	Airline	Comparison paper	Structured: group	6-26	• Organization (6) • Documentation (4) • Risk management (5) • Quality assurance (3) • Safety promotion (5) • Emergency response (3)	Interact	Non-structured	Yes	Not given
(Shimada and Kitajima, 2010)	Elements of OSHA/PSM	Process	Paper	Structured: PDCA, system	14	Employee participation; process safety information; process hazard analysis; operating procedures; … …	Independent	Structured: system	Not given	Process
(Baisheng, Longkang et al., 2011)	Structure of an SMS	Coal plant	Paper	Structured: parallel	6	Safety culture; safety goal; safety product responsibility; emergency management; safety training.	Independent	Structured: process	No	Not given
(Soczek, 2011)	Management of employee and process safety	Chemistry	Report	Not given	12	Management commitment; policy and principles; integrated organizational structure; line management accountability and responsibility; … …	Independent	Not given	Yes	Procedure
(Su, Sun et al., 2011)	Security management mode	Coal mine	Paper	Structured: hierarchy	5-35	Security management system; security implementation; assessment; rewards and penalties; security training.	Independent	Non-structured	No	Not given
(Chen and Chen, 2012)	Factors of a SMS	Airline	Paper	Structured: hierarchy	5-25	• Documentation and commands (7) • Safety promotion and training (7)	Independent	Non-structured	No	Not given

						• Executive management commitment (4) • Emergency preparedness and response plan (4) • Safety management policy (3)			
(Sutton, 2012)	Elements of OSHA's PSM	Offshore	Report (standard)	Not given	14	Employee participation; process safety information; process hazards analysis; operating procedures; training; contractors; … …	Independent	Non-structured	Yes	Procedure
(Saracino, Spadoni et al., 2012)	Methodology for the Implementation and Monitoring of Occupational Safety	Chemistry & Occupational safety	Evaluation system proposed paper	Structured: hierarchy	6-27	• Leadership and coherence with targets • Orientation to risk reduction and people protection, in compliance with the law; • Involvement, learning and development of personal education • Continuous improvement and innovation • Formal and general compliance • Social responsibility	Independent	Non-structured	No	Not given
(Sutton, 2012)	Elements of SEMP/SEMS	Offshore	Report (standard)	Not given	12	Safety and environmental information; hazards analysis; operating procedures; training; pre-startup review; … …	Independent	Non-structured	Yes	Procedure
(Tauseef, Villegas et al., 2012)	A HSE management system	General (oil and gas)	Paper	Structure: continuous improvement	8	Commitment, leadership and accountability; policies and objectives; organization and resources; … …	Interact	Non-structured	Yes	Not given
(HSE, 2013)	Managing for health and safety	General	Standard/guidance (hsg65 3rd ed.)	Structured: PDCA	4-9	PDCA: planning; risk profiling; organising; implementing your plan; measuring performance; … …	Interact	Non-structured/not given	Yes	Procedure
(Rains, 2013)	DuPont process safety management model	Chemistry	Paper	Structure: group, continuous improvement;	15	Process safety information; process hazards analysis; operating procedures and safety practices; … …	Interact	Non-structured	Yes	Procedure

(Kazaras, Kontogiannis et al., 2014)	Viable System Model (VSM)	General	Paper	Structured: hierarchy; system	5-11	• Safety policy implementation (1) • Safety co-ordination (1) • Safety functional (3) • Safety development and adaptation (3) • Safety policy (3)	Interact	Non-structured	Yes	Not given
(Aziz, 2017)	PSM (29 CFR 11910)	Process	Paper, based on standard	Non-structure		Employee participation; process safety information; process hazards analysis; operating procedures; … …	Interact	Non-structured	No	Procedure
(Zhou, 2017)	A Chinese PSM	Process	Paper	Structured: grouped	4-12	• Process safety commitment (1) • Hazard and risk understanding (2) • Risk management (7) • Learning from experience (2)	Interact	Non-structured	No	Procedure
(ISO, 2018)	OHSMS	General	Standard	Structured: PDCA	7(6 if exclude context)	• Context of the organisation • Leadership and worker participation • Planning • Support • Operation • Performance evaluation • Improvement	Interact	Non-structured	Yes	Procedure

Note:

‘Independent’ means you cannot see a clear relationship between the elements.

‘Interact’ means the elements have relationship among each other.

‘Structured’ means these elements are connected with a structured framework.

‘Non-structured’ means these elements are not connected in a framework.

Appendix B Tasks analysis

- Refer to Chapter 4

Table B.1 – Tasks at operational and management level required for barriers

	Tasks at operational level	Actors	Competence DS	Tasks at managerial level	Actors	Competence DS
1 Behavioural barriers	○ Identify threat/hazard	Frontline staff; Engineer; Chief engineer; Assessor;	Box 1	○ Develop general safety policy and required safety commitment	Senior managers, etc.	(Commitment DS)
	○ Provide information of current threat/hazard	Frontline staff; Engineer; Chief engineer; Assessor;	Box 1	○ Listen to/read safety report regularly	Technical manager (Operational manager); HSEQ/safety manager; etc.	Box 8
	○ Judge threat/hazard and (help to) choose barrier	Frontline staff; Engineer; Chief engineer; Assessor; etc.	Box 1	○ (Sometimes) decide which barrier to use	Technical manager (Operational manager); HSEQ/safety manager; etc.	Box 1
	○ Get sufficient training for or related to barrier(s)	Frontline staff; Engineer; Chief engineer; Assessor; Trainer;	Box 6	○ Authorize execution of barrier	HSEQ/safety manager; HR manager; etc.	(Availability, planning of people & hardware DS)
	○ Follow procedures/rules to carry out tasks of a barrier	Frontline staff; Engineer;	(Procedure, rule goals DS)	○ Organise training programmes for or related to barrier(s)	HSEQ/safety manager; HR manager; Training manager;	Box 5
	○ Follow the instructions from director/supervisor	Frontline staff; Engineer; Chief engineer;	(Communication, coordination of groups DS)	○ Coordinate people and tasks for barrier	HR manager; Local supervisor;	(Communication/coordination DS)
	○ Communicate with colleagues in team work (if necessary)	Frontline staff; Engineer; Chief engineer;	(Communication, coordination of groups DS)	○ Check performance of barrier	Technical manager (Operational manager); HSEQ/safety manager; Local supervisor;	Box 8

	○ Monitor/inspect performance of barrier	Engineer; Chief engineer; Assessor;	Box 8	○ Check compliance to regulations related to barriers	Technical manager (Operational manager); HSEQ/safety manager; Local supervisor;	Box 7
	○ Report monitor/inspection result	Engineer; Chief engineer; Assessor;	Box 8	○ Encourage (walk and talk) employees to execute barrier to completion	Local supervisor; etc.	(Communication/coordination DS)
				○ Check audit/review result of barrier	HSEQ/safety manager; senior managers etc.	Box 9
2 Social-Technical (hardware-human)	Hardware/software provide detected information; the use stage of this hardware/software is a part of barrier implementation;					
	○ Get (read, hear, etc.) information of threat/hazard from hardware/software	Frontline staff; Engineer; Chief engineer;	(Interface, ergonomics DS)	○ Listen to/read safety report regularly	Technical manager (Operational manager); HSEQ/safety manager; etc.	Box 8
	○ Provide (convey) information of current threat/hazard (if necessary)	Frontline staff; Engineer; Chief engineer;	Box 1	○ (Sometimes) decide which barrier to use	Technical manager (Operational manager); HSEQ/safety manager; etc.	Box 1
	○ Judge threat/hazard and (help to) choose barrier	Frontline staff; Engineer; Chief engineer; Assessor; etc.	Box 1	○ Authorize execution of barrier	HSEQ/safety manager; HR manager; etc.	(Availability, planning of people & hardware DS)
	○ Follow procedures/rules to carry out tasks of a barrier	Frontline staff; Engineer;	(Procedure, rule goals DS)	○ Organise training programmes for or related to barrier(s)	HSEQ/safety manager; HR manager; Training manager	Box 5
	○ Follow the instructions from director/supervisor	Frontline staff; Engineer; Chief engineer;	(Communication, coordination of groups DS)	○ Coordinate people and tasks for barrier	HR manager; Local supervisor	(Communication/coordination DS)
	○ Communicate with colleagues in team work (if necessary)	Frontline staff; Engineer; Chief engineer;	(Communication, coordination of groups DS)	○ Check performance of barrier	Technical manager (Operational manager); HSEQ/safety manager; Local supervisor;	Box 8

	○ Monitor/inspect performance of barrier	Engineer; Chief engineer; Assessor;	Box 8	○ Check compliance to regulations related to barriers	Technical manager (Operational manager); HSEQ/safety manager; Local supervisor;	Box 7
	○ Report monitor/inspection result	Engineer; Chief engineer; Assessor;	Box 8	○ Encourage (walk and talk) employees to execute barrier to completion	Local supervisor; etc.	(Communication/coordination DS)
				○ Check audit/ inspection result of barrier	HSEQ/safety manager; etc.	Box 9
3 Social-Technical (human-hardware)	○ Identify threat/hazard	Frontline staff; Engineer; Chief engineer; Assessor;	Box 1	○ Listen to/read safety report regularly	Technical manager (Operational manager); HSEQ/safety manager; etc.	Box 8
	○ Provide information of current threat/hazard	Frontline staff; Engineer; Chief engineer; Assessor;	Box 1	○ (Sometimes) decide which barrier to use	Technical manager (Operational manager); HSEQ/safety manager; etc.	Box 1
	○ Judge threat/hazard and (help to) choose barrier	Frontline staff; Engineer; Chief engineer; Assessor; etc.	Box 1	○ Authorize execution of barrier	HSEQ/safety manager; HR manager; etc.	(Availability, planning of people & hardware DS)
	○ Get sufficient training for or relate to barrier(s)	Frontline staff; Engineer; Chief engineer; Assessor; Trainer;	Box 6	○ Organise training programmes for or related to barrier(s)	HSEQ/safety manager; HR manager; Training manager;	Box 5
	○ Follow procedure/rule to carry out a hardware/software barrier	Frontline staff; Engineer;	(Procedure, rule goals DS)	○ Check compliance to regulations related to barriers	Technical manager (Operational manager); HSEQ/safety manager; Local supervisor;	Box 7
	○ Follow the instruction from supervisor or specialist	Frontline staff; Engineer; Chief engineer;	(Communication, coordination of groups DS)	○ Check audit/review result of barrier	HSEQ/safety manager; etc.	Box 9
	○ Monitor/inspect performance of barrier	Engineer; Chief engineer; Assessor;	Box 8			

	Hardware/software performs barrier; the use stage of this hardware/software is a part of barrier implementation;					
4 Active hardware	○ Purchase barrier	Frontline staff; Engineer; etc.	(Availability, planning of people & hardware DS)	○ Authorize purchase of barrier	HSEQ/safety manager; HR manager; financial manager; etc.	(Availability, planning of people & hardware DS)
	○ Install barrier	Frontline staff; Engineer; Chief engineer;	(Availability, planning of people & hardware DS)	○ Authorize installation of barrier	Technical manager (Operational manager); HSEQ/safety manager; etc.	(Availability, planning of people & hardware DS)
	○ Inspect/monitor barrier	Frontline staff; Engineer; Chief engineer;	(Hardware, spares DS)	○ Arrange suitable people to do purchase, installation, inspection, maintenance, repair tasks	Technical manager (Operational manager); HSEQ/safety manager; Local supervisor;	(Availability, planning of people & hardware DS)
	○ Maintain/repair barrier	Frontline staff; Engineer; Chief engineer;	(Hardware, spares DS)	○ Check compliance to regulations related to barriers	Technical manager (Operational manager); HSEQ/safety manager; Local supervisor;	Box 7
	Use/operate stage is automatic; at this stage, the hardware/software carry out barrier function					
	○ Update/change/dispose of barrier	Frontline staff; Engineer; Chief engineer;	(Hardware, spares DS)	○ Check audit/review result of barrier	HSEQ/safety manager; etc.	Box 9
	○ Follow procedures, rules and regulations to do barrier tasks	Frontline staff; Engineer; Chief engineer;	(Procedures, rule, goals DS)			
5 Continuous/passive hardware (human involved tasks) & technical hardware part	○ Purchase barrier	Frontline staff; Engineer; etc.	(Availability, planning of people & hardware DS)	○ Authorize purchase of barrier	HSEQ/safety manager; HR manager; financial manager; etc.	(Availability, planning of people & hardware DS)
	○ Install barrier	Frontline staff; Engineer; Chief engineer;	(Availability, planning of people & hardware DS)	○ Authorize installation of barrier	Technical manager (Operational manager); HSEQ/safety manager; etc.	(Availability, planning of people & hardware DS)
	Use/operate stage is automatic; at this stage, the hardware/software carry out barrier function					

	○ Inspect/monitor barrier	Frontline staff; Engineer; Chief engineer;	(Hardware, spares DS)	○ Arrange suitable people to do purchase, installation, inspection, maintenance, repair tasks	Technical manager (Operational manager); HSEQ/safety manager; Local supervisor;	(Availability, planning of people & hardware DS)
	○ Maintain/repair barrier	Frontline staff; Engineer; Chief engineer;	(Hardware, spares DS)	○ Check compliance to regulations related to barriers	Technical manager (Operational manager); HSEQ/safety manager; Local supervisor;	Box 7
	○ Update/change/dispose of barrier	Frontline staff; Engineer; Chief engineer;	(Hardware, spares DS)	○ Check audit/review result of barrier	HSEQ/safety manager; etc.	Box 9
	○ Follow procedures, rules and regulations to do barrier tasks	Frontline staff; Engineer; Chief engineer;	(Procedures, rule, goals DS)			

Appendix C Bowtie model: scenarios

- ➢ Refer to Chapters 5 & 6

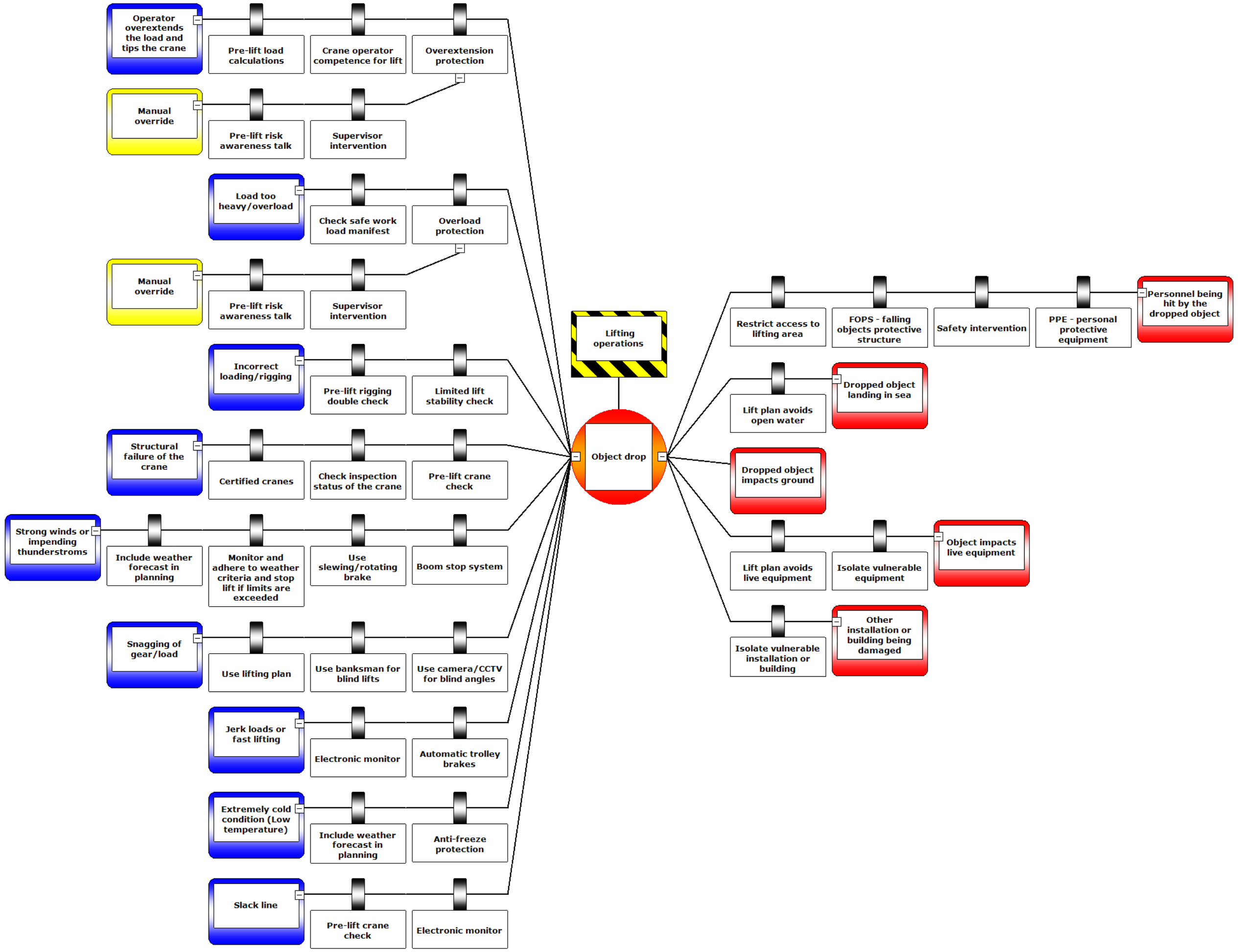

Figure C.1 – Scenario of lifting risk: Object Drop

Appendix D Indicators and variables

- ➢ Refer to Chapter 6

Table D.1 – The KSEA model and survey at operational level

Model			Survey			
KESA model	**General/ (Safety) Professional**	**Indicator**	**Second level variable name**	**Measure**	**Third level variable name**	**Label**
General Information					G_compro	Country-company/indusrial park-unit
					G_ID	Operational participate ID
			G_site	Category	G_site	The working place
			G_genderO	Category	G_gen	Gender
			G_ageO	Numeric	G_age	Age
			G_jobpositionO	Category	G_posit	Current job/position
Knowledge (K)	GK	General SMS	K_standardO	Yes/No	K_std	Safety standard application
			K_stdnameO		K_std_name	SMS name
	GK	Lifting operation	K_liftingO	Degree	K_liftop_a	Involvement in planning lifting operations
					K_liftop_b	Involvement in carrying out lifting operations
					K_liftop_c	Involvement in checking lifting operations
					K_liftop_d	Involvement in supervising lifting operations
	PK	Hazard (threat) scenario	K_hazardsO	NOT MEASURABLE	K_hazard_a	Object drop frequency
					K_hazard_b	Caught -in or -between frequency
					K_hazard_c	Contact with powerline frequency
					K_hazard_d	People falls frequency
					K_hazard_e	Lifting device collapse frequency
			K_threatsO	Degree	K_threat_a	Operator overextends load and tips contributing to object drop
					K_threat_b	Load too heavy (overload) contributing to object drop
					K_threat_c	Incorrect loading/rigging contributing to object drop
					K_threat_d	Structural failure of the crane contributing to object drop
					K_threat_f	Jerk loads or fast lifting contributing to object drop
	PK	Barriers	K_barriersO	Degree	K_barrier_a	Familiar with using certified crane
					K_barrier_b	Familiar with restricting access to lifting area
					K_barrier_c	Familiar with taking safety intervention
					K_barrier_d	Familiar with using personal protective equipment
	PK	Tasks procedure	K_procedureO	Degree	K_proced_a	Familiar with identify lifting operation hazard
					K_proced_b	Familiar with (over) loading check
					K_proced_c	Familiar with pre-lift rigging double check
					K_proced_d	Familiar with pre-lift crane check

					K_proced_e	Familiar with limited lift stability check
	PK	Tasks	K_btasksO	Degree	K_tasks_a	Identify lifting operation hazard relate to work
					K_tasks_b	(Over) loading check relate to work
					K_tasks_c	Pre-lift rigging double check relate to work
					K_tasks_d	Pre-lift crane check relate to work
					K_tasks_e	Limited lift stability check relate to work
	PK	Regulation/rule for specific tasks	K_regulationsO	Degree	K_regula_a	National safety law
					K_regula_b	Crane safety regulation GB6067-2010
					K_regula_c	Crane safety regulation Part5: overhead/gantry crane
					K_regula_d	Company crane safety regulation/requirement
Skill (S)	GS	Hold certificate	S_certificateO	Yes/No	S_cert_crane	Certificate on crane operation
					S_cert_skill	Certificate on professional skills
					S_cert_safety	Certificate on safety
	GS	Language			S_lang_name	Language or dialect name
			S_languageO	Degree	S_language_a	Speaking level of local language
					S_language_b	Reading level of local language
					S_language_c	Listening level of local language
	PS	Communication skill	S_communicationO	Degree	S_commu_a	Participation in pre-lift risk awareness talk
					S_commu_b	Participation in pre-lift crane check communication
					S_commu_c	Participation in supervisor intervention talk
					S_commu_d	Participation in lifting communication
			S_reportwayO		S_reportway	By which method to report hazard
	PS	Identification of hazard/threat	S_idhardfreqO	Degree	S_id_hazard	Frequency of LMRA (hazard)
			S_idhazdsO	Degree	S_idhazd_a	Difficulty in identification of operator overextends load and tips...
					S_idhazd_b	Difficulty in identification of load too heavy
					S_idhazd_c	Difficulty in identification of incorrect loading/rigging
					S_idhazd_d	Difficulty in identification of structural failure of the crane
					S_idhazd_f	Difficulty in identification of jerk loads or fast lifting
	PS	Hardware barrier using	S_hardbarriersO	Degree	S_hardB_a	Difficulty in using overload protection
					S_hardB_b	Difficulty in using slewing/rotating brake
					S_hardB_c	Difficulty in using boom stop system
					S_hardB_d	Difficulty in using automatic trolley brakes
					S_hardB_e	Difficulty in using camera/CCTV for blind angles
	PS	Social-technical barrier using	S_sotebarriersO	Degree	S_SoteB_a	Ability to choose and use safety helmet
					S_SoteB_b	Ability to choose and use high visibility clothing or vest
					S_SoteB_c	Ability to choose and use foot protection
					S_SoteB_d	Ability to choose and use hand protection
					S_SoteB_e	Ability to choose and use safety harness
	PS	Behaviour barrier using	S_behabarriersO	Degree	S_behaB_a	Professional in writing formal safety report
					S_behaB_b	Professional in effective communication with peers
					S_behaB_c	Professional in effective communication with peers

					S_behaB_d	Professional in effective communication with peers
Experience (E)	GE	Education	E_educationO	Degree	E_education	Highest (equal) level of education completed
	GE	Working time	E_workyearO	Years	E_year	Years of work experience
	GE	Occupational skill training	E_trainskillO	Time period	E_ocsktra	Time of occupational skills training per year
	PE	Frontline (engineer) experience	E_liftexposureO	Times (degree)	E_liftexpo	Frequency of lifting operation exposure
			E_professionO	Degree	E_polevel	level of experience at current position
			E_getsupervisionO	Times (degree)	E_getsuperv	Frequency of getting supervision
	PE	Accident (Hazard) experience	E_incidentsO	Times (degree)	E_incident_a	Times of experienced object (load or component) drop
					E_incident_b	Times of experienced caught -in or -between
					E_incident_c	Times of experienced contact with powerline
					E_incident_d	Times of experienced people falls
					E_incident_e	Times of experienced lifting device (crane) collapse
					E_incident_f	Times of experienced lifting device (crane) upset / tip over / overturn
	PE	Using barrier tools (just using tool maybe not for safety work)	E_useppesO	Degree	E_usePPE_a	Frequency of used safety helmet
					E_usePPE_b	Frequency of used high visibility clothing or vest
					E_usePPE_c	Frequency of used foot protection
					E_usePPE_d	Frequency of used hand protection
					E_usePPE_e	Frequency of used safety Harness
	PE	Experience specific barrier	E_btasksO	Degree	E_tasks_a	Involvement in identify lifting operation hazard
					E_tasks_b	Involvement in (over) loading check
					E_tasks_c	Involvement in pre-lift rigging double check
					E_tasks_d	Involvement in pre-lift crane check
					E_tasks_e	Involvement in limited lift stability check
	PE	Safety training	E_trainsafetyO	Time period	E_safetra	Time of safety training per year
Attitude (A)	GA	Attitude towards trainings	A_trainsO	Degree	A_train_a	Usefulness of general safety training
					A_train_b	Usefulness of operational skill training
					A_train_c	Usefulness of new job training
					A_train_d	Usefulness of new equipment use training
	GA	Safety awareness	A_awarenessO	Degree	A_awaren_a	Awareness of the safety signs and alarms
					A_awaren_b	Awareness of using PPE properly
					A_awaren_c	Awareness of all hazards at work site
					A_awaren_d	Know all the safety regulations to the work
					A_awaren_e	Know emergency escape programme
	PA	Attitude towards accident (scenario)	A_threatsO	Degree	A_cricon_a	Concern of operator overextends load and tips…
					A_cricon_b	Concern of load too heavy
					A_cricon_c	Concern of incorrect loading/rigging
					A_cricon_d	Concern of structural failure

				A_cricon_f	Concern of jerk loads or fast lifting
		A_incidentsO	Degree	A_cocon_g	Concern of object (load) drop
				A_cocon_h	Concern of caught -in or -between
				A_cocon_i	Concern of contact with powerline
				A_cocon_j	Concern of people falls
				A_cocon_k	Concern of lifting device collapse
PA	Attitude towards barrier function	A_leftbarriersO	Degree	A_barrier_a	Protect from operator overextends the load and tips...
				A_barrier_b	Protect from load too heavy
				A_barrier_c	Protect from incorrect loading/rigging
				A_barrier_d	Protect from structural failure of the crane
				A_barrier_f	Protect from jerk loads or fast lifting
		A_rightbarriersO	Degree	A_barrier_g	Protect from object (load) drop
				A_barrier_h	Protect from caught -in or -between
				A_barrier_i	Protect from contact with powerline
				A_barrier_j	Protect from people falls
				A_barrier_k	Protect from lifting device (crane) collapse
PA	Habit of mind for safety prevention	A_preventionO	Degree	A_prebel_a	Believe prevention of object (load) drop
				A_prebel_b	Believe prevention of caught -in or -between
				A_prebel_c	Believe prevention of contact with powerline
				A_prebel_d	Believe prevention of people falls
				A_prebel_e	Believe prevention of lifting device (crane) collapse
PA	Attitude towards barrier result	A_bresultO	Degree	A_resultB_a	Effectiveness of pre-lift load calculations
				A_resultB_b	Effectiveness of pre-lift awareness talk
				A_resultB_c	Effectiveness of check safe work manifest
				A_resultB_d	Effectiveness of pre-lift double check
				A_resultB_e	Effectiveness of limited lift stability check
				A_resultB_f	Effectiveness of check inspection status of the crane
PA	Attitude towards barrier tasks/procedure	A_btasksO	Degree	A_task_a	Willingness to identify hazards
				A_task_b	Willingness to report hazards
				A_task_c	Willingness to take safety actions
				A_task_d	Willingness to have safety training
				A_task_e	Willingness to follow safety regulations
				A_task_f	Willingness to follow director's instruction
				A_task_g	Willingness to communicate with colleagues when taking safety countermeasures
				A_task_h	Willingness to check safety barriers
PA	Attitude towards socio-technic barrier	A_useppesO	Degree	A_usePPE_a	Willingness to use safety helmet
				A_usePPE_b	Willingness to use high visibility clothing or vest
				A_usePPE_c	Willingness to use foot protection
				A_usePPE_d	Willingness to use hand protection
				A_usePPE_e	Willingness to use safety Harness

Note: Second level indicator name in blue means that it contains string variables and in black contains numeric variables. Third level variable names in grey mean that they are not used for quantitative analysis.

Table D.2 – The KSEA model and survey at managerial level

Model		Survey				
General/ (Safety) Professional	**Indicator**	**Second level variable name**	**Measure**	**Third level variable name**	**Label**	**The respondents**
General Information				COMCODE	Country-company code	ALL
				ID_M	ID number	
		G_genderM	female/male	G_gen	Gender	
		G_ageM		G_age	Age	
		G_jobpositionM		G_title	The position title	
GE	Working time	E_workyearM		E_workyear	Work year	
GS	(hold certificate)	S_certificateM	Yes/No	S_cer_safetymanage	Certificate on safety management	
				S_cer_manage	Certificate on management	
				S_cer_crane	Certificate relate to crane operation	
GK	General SMS	K_standardM	Yes/No	K_std	Safety standard application	
				K_std_name	SMS name	
GK	Organisation knowledge			K_responsibility	The departments which has the responsibility for safety issues	
GS	Language			S_language_name	Language or dialect name	
		S_languageM	Degree	S_language_b	Speaking level of local language	
				S_language_a	Reading level of local language	
				S_language_c	Listening level of local language	
GE	Management experience	E_safetyparticipationM	Degree	E_safetyact_a	The frequency of participation in safety council	
				E_safetyact_b	The frequency of participation in safety activity	
				E_safetyact_c	The frequency of participation in safety training	
				E_safetyact_d	The frequency of participation in safety audit	
PS	Safety communication skill	S_hazardcommuM	Degree	S_hazard_a	How good at writting formal safety report	
				S_hazard_b	How good at hazard communication	
PS	Behaviour barrier skill	S_cooperationM	Degree	S_cooperation_c	How good at cooperation in safety activities	
PS	Reporting method			S_info_ways	The ways to deliever safety information	
GE	Education level	E_educationM	Degree	E_education	Highest (equal) level of education completed	
GE		E_liftingM	Yes/No	E_optask_a	Involvement in plan of lifting operation	

	Experience of lifting management			E_optask_b	Involvement in implementation of lifting operation	
				E_optask_c	Involvement in inspection of lifting operation	
				E_optask_d	Involvement in monitoring of lifting operation	
GE	Position experience	E_positionyearM	Time period	E_position_year	The year of working in current position	
GE	Occupational skill training	E_trainskillM	Time period	E_trainsk_time	The time for occupational skill traning in the last year	
PE	Safety training	E_trainsafetyM	Time period	E_trainsaf_time	The time for safety traning in the last year	
PE	Accident (Hazard) experience	E_incidentsM	Yes/No	E_incident_a	Heard or encountered object drop	
				E_incident_b	Heard or encountered caught -in or -between	
				E_incident_c	Heard or encountered contact with powerline	
				E_incident_d	Heard or encountered people fall	
				E_incident_e	Heard or encountered lifting devices (crane) collapse	
GA	Safety awareness	A_awarenessM	Degree	A_awareof_a	Awareness of safety signs	
				A_awareof_b	Awareness of using PPEs	
				A_awareof_c	Awareness of safety hazards	
				A_awareof_d	know safety regulations	
				A_awareof_e	know emergency plan	
				G_position	In which position group	
PK	Barriers	K_barriersM	Degree	K_barrier_a	Familiar with barriers for object drop	Group 1 HSEQ/Safety manager; Equipment (Engineering) manager; HSEQ/safety staff; Equipment (Engineering) staff;
				K_barrier_b	Familiar with barriers for caught -in or -between	
				K_barrier_c	Familiar with barriers for contact with powerline	
				K_barrier_d	Familiar with barriers for people fall	
				K_barrier_e	Familiar with barriers for lifting devices (crane) callapse	
PK	Task procedure	K_tasksM	Yes/No	K_taskM_a	Involvement in safety commitment by signature	
				K_taskM_b	Involvement in lifting/hoisting hazard report	
				K_taskM_c	Involvement in decision making which safety barrier to use	
				K_taskM_d	Involvement in authorizing execution of lifting safety barrier	
				K_taskM_e	Involvement in organising safety training programmes	
				K_taskM_f	Involvement in coordinating people and tasks for lifting safety barriers	
				K_taskM_g	Involvement in checking (monitoring) performance of lifting safety barriers	
				K_taskM_h	Involvement in checking compliance with lifting regulations	
				K_taskM_i	Involvement in encouraging employees to execute safety barriers	
				K_taskM_j	Involvement in checking audit/review result of safety barriers	
PK	Regulation	K_regulationsM	Percentage & degree	K_regulation	The name of the regulation that you know	
				K_regu_compliance	The name of the regulation that the company is complied with	
			Yes/No	K_noregulation	Know nothing with the regulation	

PE	Using barrier tools (just using tool maybe not for safety work)	E_PPEsM	Degree	E_PPE_a	Involvement in plan to purchase and allocation of PPE
				E_PPE_b	Involvement in usage of PPE
				E_PPE_c	Involvement in inspection (monitor)of PPE
				E_PPE_d	Involvement in maintenance of PPE
				E_PPE_e	Involvement in disposal of PPE
PE	Communication experience	E_supervisionM	Times	E_supervision	Frequency of supervising lifting and hoisting operators
PE	Experience of accidents (management)	E_incibarrierM	Times	E_incibarrier_a	Times of dealing with incident object drop
				E_incibarrier_b	Times of dealing with people are caught
				E_incibarrier_c	Times of dealing with contact with powerline
				E_incibarrier_d	Times of dealing with people fall
				E_incibarrier_e	Times of dealing with crane collapse
PE	Experience barrier tasks	E_btasksM	Yes/No	E_btask_a	Involvement in operator license/certificate check
				E_btask_b	Involvement in crane certificate check
				E_btask_c	Involvement in (over) loading check
				E_btask_d	Involvement in pre-lift crane check
				E_btask_e	Involvement in lifting safety audit
PS	Skill of barrier tasks	S_btasksM	Degree	S_btask_a	Ability to complete operator license/certificate check
				S_btask_b	Ability to complete crane certificate check
				S_btask_c	Ability to complete (over) loading check
				S_btask_e	Ability to complete pre-lift crane check
				S_btask_d	Ability to complete lifting safety audit
PA	Attitude towards accident (threats)	A_mthreatsM	Yes/No/No responsibility	A_mthreat_a	Consider to manage when load too heavy
				A_mthreat_b	Consider to manage when incorrect loading/rigging
				A_mthreat_c	Consider to manage when structural failure of crane
				A_mthreat_d	Consider to manage when strong winds or impending thunderstorms
				A_mthreat_e	Consider to manage when jerk loads or fast lifting
PA	Habit of mind for barrier management	A_btasksM	Degree	A_btask_a	Effectiveness of declaring safety commitment by signature
				A_btask_b	Effectiveness of listening to/reading lifting/hoisting hazard report
				A_btask_c	Effectiveness of deciding which safety barrier to use
				A_btask_d	Effectiveness of authorizing execution of lifting safety barrier
				A_btask_e	Effectiveness of organising safety training programmes
				A_btask_f	Effectiveness of coordinating people and tasks for lifting safety barriers
				A_btask_g	Effectiveness of checking (monitoring) performance of lifting safety barriers
				A_btask_h	Effectiveness of checking compliance with lifting regulations
				A_btask_i	Effectiveness of encouraging employees to execute safety barriers
				A_btask_j	Effectiveness of checking audit / review result of safety barriers

PA	Attitude towards barrier tasks/procedure	A_mtasksM	Degree	A_mtask_a	Willingness to encouraging employees to have a safe behaviour	
				A_mtask_b	Willingness to supervising employees about safety activities	
				A_mtask_c	Willingness to communicating with employees about hazards and risks	
				A_mtask_d	Willingness to inspecting safety performance of employees	
				A_mtask_e	Willingness to checking machinery performance	
PA	Attitude towards specific rules/regulations	A_regulationsM	Degree	A_regu_a	Effectiveness of international safety standards	
				A_regu_b	Effectiveness of national safety law	
				A_regu_c	Effectiveness of industrial regulations	
				A_regu_d	Effectiveness of lifting & hoisting regulations	
				A_regu_e	Effectiveness of lifting operation and crane usage procedures	
PE	(Safety financial) management experience	E_fiancialsafetyM	Degree	E_fianciasaf_a	Involve the financial work about lifting equipment (crane, excavator, etc.) cost	Group 2 Financial manager; Financial staff;
				E_fianciasaf_b	Involve the financial work about personal protective equipment (PPE) cost	
				E_fianciasaf_c	Involve the financial work about crane maintenance cost	
				E_fianciasaf_e	Involve the financial work about safety training cost	
				E_fianciasaf_f	Involve the financial work about safety audit cost	
PA	Attitude towards barrier cost	E_safetycostM	Degree	E_safcost_a	Budget always cover the lifting equipment (crane, excavator, etc.) cost	
				E_safcost_b	Budget always cover the personal protective equipment (PPE) cost	
				E_safcost_c	Budget always cover the crane maintenance cost	
				E_safcost_d	Budget always cover the training cost	
				E_safcost_e	Budget always cover the audit cost	
PE	(HR) management experience on certificate check	E_checkM	Yes/No	E_checkcer_safe	Involvement in checking required safety professional certificate	Group 3 HR manager; HR staff;
				E_checkcer_crane	Involvement in checking lifting/hoisting operation certificate	
PA	Attitude towards trainings	A_trainsM	Degree	A_train_saf	Attitude towards the general safety training (usefulness)	
				A_train_skill	Attitude towards the operational skill training (usefulness)	
				A_train_new	Attitude towards the new job training (usefulness)	
				A_train_equip	Attitude towards the new equipment use training (usefulness)	
PA	Attitude towards barrier function	A_preventionM	Degree	A_prebel_a	Believe the accident 'object drop' can be prevented	Group 4 Project/Plant manager;
				A_prebel_b	Believe the accident 'people are caught in or between' can be prevented	
				A_prebel_c	Believe the accident 'contact with powerline' can be prevented	
				A_prebel_d	Believe the accident 'people fall' can be prevented	
				A_prebel_e	Believe the accident 'crane collapse ' can be prevented	

Note: Third level variable names in grey mean that they are not used for quantitative analysis; in green means they are not answered by Group 1.

Summary

Safety management systems (SMSs) have gained importance since the 1970s and changed focus from individual management activities to more systematic frameworks. The methods, techniques and tools used in them also became more and more sophisticated. However, from the perspectives of the researcher, company, auditor, government and (safety-specialised) organisation, the modelling of safety management is still in need of improvement.

Modelling of safety management means developing a generic model that can cover all SMSs. This generic model (or system) will look into the common constituent parts of an SMS and details of those parts. Theoretical models have been developed extensively, however, quantifying how safety management controls risk is one of the difficulties in applying these models, especially the quantification of safety management deliveries. Therefore, this research aims to develop a quantitative approach to the modelling of safety management.

Five facets of safety management systems

SMSs are widely used in both industry and academia. However, a common understanding of an SMS has not yet reached consensus, as it still being defined as, for instance, activity, approach, control, process and procedure according to various literatures. This study gains insight into SMSs through a broad overview, leading to a systematical refinement of five facets: definition, evolution, models, purposes and common elements of SMSs. An SMS is a systematic framework that contains all activities, resources and criteria to achieve safety performance. It mainly describes organisational activities and accident events. A practical SMS is for (safety) risk control and regulatory compliance. Risk control and learning processes are the two components of a complete SMS containing functional elements for the two purposes. According to these aspects, a generic SMS can be formed.

The relationship between scenarios, barriers and safety management

This study explores the relationship between scenarios, barriers and safety management because they reveal the essence of an SMS. Through the modelling of events, risk can be analysed within a scenario. To mitigate unacceptable initial risks, safety barriers are developed to prevent unwanted events and to protect from any consequences. Thus, the scenario is controlled, and the risk is reduced. Safety management forms the controls and monitors the deviated events. In the end, all this makes an organisation achieve safe performance. Therefore, Events + Barriers + Management is a typical framework for any safety management system and the basis for this safety research.

Discovering the functions of a generic SMS with elements

This study clarifies the principles of developing elements of an SMS. Elements are related to both general and specific operational levels. Regardless of industrial sector, elements play the roles of: 1) functional components for safety management; 2) key indicators of SMS performance; 3) latent causes of accidents. By using the mapping method to compare various elements of SMSs, the structure and features of elements are determined, e.g. the PDCA-cycle and continuous improvement, processes and procedures. These elements not only constitute a comprehensive SMS but also incorporate the processes and procedures of safety activities. The safety management elements provide the safety influencing factors at the operational level as well. This study reviewed SMS elements to explore the mechanism behind their effectiveness.

Delivery systems: a systematic approach to safety management

Delivery systems, which support the overall management of safety barriers, are the elements of Hale's SMS. We used the SADT method to model (management and operational) processes within delivery systems (DSs), which work on safety barriers. This study takes the competence delivery system as an example and elaborates the features of the safety barriers involved. The functional phases of barriers sometimes involve human behaviour, so people's competences influence the performance of barriers. As a result of the analysis of barrier tasks, operational and managerial competence contributing to these tasks are identified. Through this, we developed indicators for safety management competence, especially those supporting barriers. These are the theoretical foundations for quantifying safety management.

Case study: managing competence for lifting risk

Within DSs, we identify indicators for managing competence and apply them in lifting risk scenarios. These lifting risk scenarios are modelled with the bowtie method, with critical event 'object drop', since this is one of the most common accidents in industry. The barriers inserted in these scenarios to mitigate risk are supported by the management of competence through various, specific tasks. We specifically identified variables that stand for competence indicators. They are used for the quantitative study of managing competence.

Quantitative result: principal factors, and relationship between competence and barriers

We obtained data of management competence and safety barriers from a survey in seven crane-using companies. After statistical analysis, six principal factors for operational competence and five for managerial competence have been determined. They show that attitude and experience are the main factors, while skill is much less important for managing most safety barriers. Furthermore, both operational and managerial competence determine the performance of safety barriers. The relationship between management competence and safety barriers is explored also with a regression model. We use isoquant curves to illustrate how the performance of barriers is influenced by operational and managerial competence.

Three principles in the quantification of safety management

According to this quantitative study, we suggest three principles in the quantification of safety management: 1) safety management should be hazard/accident scenario based; 2) indicators should be shaped/modelled systematically; and 3) variables for indicators should be explicit and sufficient. These three principles not only help us to quantify other safety delivery systems and explore their contribution to safety barriers but might also help other safety management research models in quantifying their organisational safety performance factors.

This research develops a quantitative approach to safety management and elaborates it systematically and quantitatively. The quantitative focus switches from the traditional binary states of events to the current performance of safety functions, or barriers. This study applies Safety-II thinking: our view on safety management looks for what goes right in the functioning of safety barriers. Safety management focuses on the execution of daily work and safety issues therein. We expect the combined perspectives of Safety-I and Safety-II will promote safety research to a more advanced level.

Samenvatting

Veiligheidsmanagementsystemen (SMSs) hebben sinds de jaren 1970 aan belang toegenomen en veranderden de focus van individuele, losstaande managementactiviteiten naar een meer systematisch kader. De gebruikte methoden, technieken en gereedschappen werden meer een meer geavanceerder. Echter, vanuit het perspectief van de onderzoeker, het bedrijf, de auditor, de overheid en bedrijven die hierin gespecialiseerd zijn, is het modelleren van veiligheidsmanagement nog voor verbetering vatbaar.

Modelleren van veiligheidsmanagement betekent het ontwikkelen van een generiek model dat alle specifieke SMSs kan bevatten. Dit generieke model (of systeem) moet de samenstellende, gemeenschappelijke delen van een SMS alsook alle details ervan bestrijken. Theoretische modellen zijn inmiddels uitgebreid ontwikkeld, maar kwantificeren hoe veiligheidsmanagement risico’s controleert, is een van de problemen bij het toepassen van deze modellen, vooral de kwantificatie van de toelevering van veiligheidsmanagement. Dit onderzoek beoogt een kwantitatieve benadering van de modellering van veiligheidsmanagement te ontwikkelen.

Vijf facetten van veiligheidsbeheer systemen

SMSs worden wereldwijd gebruikt in zowel de industrie als in academische instellingen. Echter, tot nu toe is nog geen consensus bereikt over een gemeenschappelijk begrip van een SMS. Het wordt bijvoorbeeld in verschillende publicaties nog steeds gedefinieerd als: activiteit, aanpak, controle, proces en procedure. Met behulp van een breed overzicht, verwerft deze studie inzicht in SMSs met een breed overzicht, leidend tot een systematische verfijning van de vijf facetten: definitie, evolutie, modellen, doeleinden en gemeenschappelijke elementen van SMSs. Een SMS is een systematisch kader dat alle activiteiten, middelen en criteria omvat om veiligheidsprestaties te bereiken. Het beschrijft voornamelijk organisatorische activiteiten en ongevalsgebeurtenissen. Een praktisch SMS is voor beheersing van (veiligheids)risico’s en naleving van de regelgeving. Risicocontrole en leerprocessen zijn de twee hoofdcomponenten van een compleet SMS met functionele elementen voor beide doeleinden (leren en controle). Met behulp van deze componenten kan een generiek SMS worden gevormd.

De relatie tussen de scenario’s, barrières en veiligheidsbeheer

Deze studie onderzoekt de relatie tussen scenario's, barrières en veiligheidsmanagement omdat ze de essentie onthullen van een SMS. Door het modelleren van incidenten, kunnen de risico’s binnen een scenario worden geanalyseerd. Om onaanvaardbare initiële risico's te verminderen, worden veiligheidsbarrières ontwikkeld om ongewenste gebeurtenissen te voorkomen en om ook te beschermen tegen de gevolgen ervan. Met andere woorden, het ongevalsscenario wordt gecontroleerd en het risico gereduceerd. Veiligheidsmanagement vormt de controle en houdt toezicht op afwijkende gebeurtenissen. Uiteindelijk zorgt dit alles ervoor dat een bedrijf veilige prestaties bereikt. Daarom, Gebeurtenissen + Barrières + Management zijn een typisch kader voor een veiligheidsmanagementsysteem en de basis voor dit veiligheidsonderzoek.

Ontdekken van de functies van een generiek SMS met elementen

Deze studie verduidelijkt de principes van het ontwikkelen van elementen van een SMS.

De elementen zijn gerelateerd aan zowel algemene als specifieke operationele niveaus. Ongeacht de industriële sector spelen elementen de rol van: 1) functionele componenten voor veiligheidsmanagement; 2) belangrijke prestatie-indicatoren van SMS-prestatie; 3) latente (verborgen) oorzaken van ongevallen.

Door een projectiemethode te gebruiken om verschillende elementen van SMSs te vergelijken, worden de structuur en kenmerken van de elementen bepaald, aan de hand van de PDCA-cyclus en continue verbeteringen, processen en procedures. Deze elementen vormen niet alleen een uitgebreid SMS maar omvatten ook de processen en procedures van veiligheidsactiviteiten. Ook op operationeel niveau leveren de veiligheidsmanagementelementen veiligheid beïnvloedende factoren op. Deze studie beoordeelt SMS-elementen om het mechanisme achter hun effectiviteit te verkennen.

Toeleveringssystemen: een systematische benadering van veiligheidsbeheer

Toeleveringssystemen (*Delivery Systems*) die het algehele management ondersteunen van veiligheidsbarrières, zijn de elementen van Hale’s SMS. We hebben de SADT-methode gebruikt als model voor processen binnen toeleveringssystemen (DSs), die invloed hebben op veiligheidsbarrières. Deze studie neemt het competentie-toeleveringssysteem als voorbeeld en werkt het kenmerk van veiligheidsbarrières uit. De functionele fasen van barrières omvatten soms menselijk gedrag, wat dus betekent dat de competenties van mensen de uitvoering van barrières beïnvloeden. Als een resultaat van de analyse van barrière-taken, worden de operationele en managementcompetenties die bijdragen aan deze taken geïdentificeerd. Daarom hebben we indicatoren ontwikkeld voor veiligheidsmanagementcompetenties, vooral die barrières ondersteunen. Dit zijn de theoretische grondslagen voor het kwantificeren van veiligheidsmanagement.

Casestudie: competentiegebruik voor het opheffen van risico's

Binnen DSs, identificeren we indicatoren voor het beheer van competenties en passen ze toe bij risicoscenario’s van hijsen. Deze hijsrisico scenario's zijn gemodelleerd met de bowtie-methode, met als centrale gebeurtenis het "vallen van object”, aangezien dit een van de meest voorkomende ongelukken in de industrie is. De barrières die in deze scenario's zijn ingevoegd om risico's te verminderen, worden ondersteund door het beheer van competentie door middel van verschillende specifieke taken. We hebben specifiek variabelen geïdentificeerd die staan voor competentie-indicatoren. Ze worden gebruikt voor de kwantitatieve studie van het managen van competentie.

Kwantitatief resultaat: belangrijkste factoren en relatie tussen competentie en barrières

We hebben gegevens van managementcompetentie en veiligheidsbarrières verkregen via een onderzoek in zeven kraan-gebruikende bedrijven in China. Na statistische analyse, zijn zes hoofdfactoren voor operationele competentie en vijf voor managementcompetentie bepaald. Ze laten zien dat werkhouding en -ervaring de belangrijkste factoren zijn, terwijl vaardigheid (*skill*) veel minder belangrijk is voor het managen van de meeste veiligheidsbarrières. Bovendien, zowel operationele als managementcompetenties bepalen de prestaties van veiligheidsbarrières. De relatie tussen managementcompetentie en veiligheidsbarrières wordt met een regressiemodel verder verkend. We gebruiken isoquant-curves om te illustreren hoe de prestaties van barrières worden beïnvloed door operationele en managementcompetentie.

Drie principes in de kwantificering van veiligheidsbeheer

Volgens deze kwantitatieve studie, stellen we drie principes voor in de kwantificering van veiligheidsmanagement: 1)veiligheidsmanagement moet gebaseerd zijn op een gevaar- of ongevalsscenario; 2)indicatoren moeten systematisch vormgegeven/ gemodelleerd worden; 3) variabelen voor indicatoren moeten expliciet en voldoende (toereikend) zijn.

Deze drie principes helpen ons niet alleen andere veiligheidssystemen te kwantificeren en hun bijdrage aan veiligheidsbarrières te onderzoeken, maar kan ook andere modellen voor veiligheidsbeheeronderzoek helpen bij het kwantificeren van hun prestatiesfactoren voor de veiligheid van organisaties.

Dit onderzoek ontwikkelt een kwantitatieve benadering van veiligheidsmanagement en werkt het systematisch en kwantitatief uit. De kwantitatieve focus schakelt over van de traditionele discrete (binaire) toestanden van (ongewenste) gebeurtenissen naar de huidige (continue) prestatie van veiligheidsfuncties, of barrières. Deze studie past Safety II-denken toe, onze visie op veiligheidsmanagement kijkt naar welke veiligheidsbarrières goed functioneren. Veiligheidsmanagement richt zich op de uitvoering van de dagelijkse werkzaamheden en de veiligheidsproblemen daarin. We verwachten dat de gecombineerde perspectieven van Safety-I en Safety-II het veiligheidsonderzoek zullen bevorderen naar een meer gevorderd niveau.

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