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Occupational safety in the construction industry

Identifying important accident types, barrier failures, causal factors and safety management factors

Thesis for the degree of Philosophiae Doctor

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Accident prevention begins with having a clear understanding of factors that play key roles in causation.[1]

[1] Hinze, Pedersen and Fredley (1998).

Abstract

The Norwegian construction industry experienced many serious accidents in the years 2009-2014, including several fatalities. Several measures were implemented to reduce the number of occupational injuries, including measures to increase the knowledge about accidents and opportunities for accident prevention. The main objective of this thesis was to identify key events and factors in construction safety that indicates where to prioritise safety measures and types of measures to develop. This was done by asking three research questions: (1) Which accident types and barrier failures are frequent in construction accidents? (2) Which causal factors are important in construction accidents? (3) Which factors and combinations of factors are important in producing safety performance in construction projects? The materials analysed were 176 relatively serious accidents, 69 fatal accidents, and data from 12 construction projects.

Lists of frequent detailed accident types were identified for fatal injuries and serious non-fatal injuries. Among the fatal injuries there were more vehicle accidents, explosions, and fall from height when unprotected, than among the non-fatal accidents. Among the non-fatal injuries there were more fall from roof/platform/floor, contact with moving parts of a machine, and fall from scaffolds. The differences can be explained by differences in the types and amounts of energy involved. The lists of the most frequent accident types for fatal injuries and serious non-fatal injuries should be used for prioritising hazards in the construction industry. At the same time, the results show that hazards are different regarding injury severity and construction types, suggesting a need for specific lists for different construction types and injury severity. It also shows the importance of having safety management systems anchored to the specific hazards involved in each construction project.

The analysis of barrier failures using Haddon's (1980) countermeasure strategies demonstrated many missed opportunities for implementing these strategies at different stages in the accident process. Elimination is often impractical/impossible, but many other barrier strategies could have counteracted the accidents, most notably preventing the release of the hazard, modifying the rate or spatial distribution of release of the hazard, separating in time or space the hazard and the vulnerable target, and physical barriers. The research also found that when one barrier failed or was not used, there was no other barrier to interrupt the accident sequence, so called defence-in-depth. Moreover, many accidents occurred in work situations where barriers were lacking and where the barrier system was dependent on the human barrier

element. The results show that there is a significant potential for reducing accidents in construction by systematic barrier management.

The seven causal factors most identified in the accident analyses were (in rank order): (1) worker actions, (2) risk management, (3) immediate supervision, (4) usability of materials or equipment, (5) local hazards, (6) worker capabilities, and (7) project management. Worker actions was identified to be a causal factor in 82% of the accidents. Often, combinations of actions by the injured worker and other workers contributed to the accident. Worker actions were influenced by several other factors, most notably immediate supervision. Immediate supervision was identified in 54% of the accidents, most notably inadequacies in controlling unsafe conditions and actions, and inadequacies in planning the work in a manner to reduce risk and identifiable hazards. The results demonstrate how important front-line construction workers and supervisors are in both causing and preventing accidents. Risk management was found to be a factor in 56% of the accidents, most notably poor or lacking risk assessments, poor routines for assessing risk in working operations, inadequate systematic health and safety work/internal control, and not following the safety and health plan. These inadequacies are largely about inadequacies in risk management at different levels and underline the importance of risk being addressed at different levels by different actors.

The study of safety management in 12 construction projects showed that: (1) projects with high safety performance had a far higher average score on safety management factors than projects with low safety performance; (2) high safety performance can be achieved with both high and low construction complexity and organisational complexity, but these factors complicate the coordination of actors and operations and makes it harder to achieve high safety performance; (3) it is possible to achieve high safety performance despite many relatively poor safety management factors, and it is possible to produce low safety performance despite many relatively good safety management factors; (4) eight safety management factors were found to be "necessary" for high safety performance, namely roles and responsibilities, project management, safety management and integration, safety climate, learning, site management, staff management, and operative risk management. Site management, operative risk management, and staff management were the three factors most strongly associated with safety performance.

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Abbreviations

COSC: Cooperation for safety in construction

GDP: Gross domestic product.

LTI-rate: Lost time injuries (LTI) per 1 million working hours.

MTI-rate: Medical treatment injuries (MTI) per 1 million working hours.

NLIA: Norwegian Labour Inspection Authority

OHSM: Occupational health and safety management

phi: The phi coefficient (the mean square contingency coefficient) is a measure of association for two binary variables.

RUO: Registered unwanted occurrences.

SCM: Swiss Cheese Model

SH-plan: Safety and health plan

SMS: Safety management system

TRI-rate: Total recordable injuries (TRI=LTI+MTI) per 1 million working hours.

WTR: Willingness to report.

List of articles:

Article 1: Winge, S., and Albrechtsen, E. (2018). Accident types and barrier failures in the construction industry. *Safety science*, *105*, 158-166.

Article 2: Winge, S., and Albrechtsen, E. (Under Review) Accident types and barrier failures in 69 construction fatal accidents in Norway 2011-2017. Manuscript under review in *Policy and Practice in Health and Safety*.

Article 3: Winge, S., Albrechtsen, E., and Mostue, B. A. (2019). Causal factors and connections in construction accidents. *Safety science*, *112*, 130-141.

Article 4: Winge, S., and Albrechtsen, E., Arnesen. J. (Accepted). A comparative analysis of safety management and safety performance in twelve construction projects. Manuscript accepted for publication in *Journal of Safety Research.*

1 Introduction

1.1 Background

On the 8 May 2013 a bridge collapsed during construction in Trondheim, Norway. Two people were fatally injured, one employed by a subcontractor working under the bridge, the other driving a car on the road under the bridge which was open for traffic. Many workers were injured. The investigation by the main contractor concluded that the bridge building framework had a faulty design and collapsed, and that the controls implemented by the client and the main contractor did not identify these deficiencies (Kongsvik et al., 2018). Multiple deficiencies in the contract and safety management system were also found. The accident was the most serious out of many serious accidents in the Norwegian construction industry in the years 2009-2014, including many fatalities. The accident was not typical for construction accidents but was seen by many as a symptom of poor safety management and safety culture in the Norwegian construction industry.

The number of official construction fatalities increased from 42 in the years 2003-2008 to 59 in 2009-2014 – an increase of 42% (Figure 1). Since 2014, the numbers have decreased. These official numbers do not include hired workers employed by temporary employment agencies or workers from other industries being killed at in construction projects. Since 2009 the Norwegian Labour Inspection Authority (NLIA) has registered these workers. These workers are included in the accident analysis in this research project and are represented by the dark bars in Figure 1. Despite this limitation in classification of injuries, construction was the industry in with the highest number of fatalities in Norway in 2014-2018 (NLIA, 2019). The construction industry is also recognised internationally as one of the most hazardous industries in which to work (Lingard and Rowlinson, 2005; Pinto et al., 2011; Khosravi et al., 2014). Sunindijo and Zou (2011) found that the construction industry employs about 7% of the world's work force but is responsible for 30–40% of fatalities. In Europe (EU-28), the construction industry had most fatal accidents (N=716) of all industries in Europe (EU-28) in 2016 (Eurostat, 2018). The incidence rate for fatal construction accidents (per 100.000 employees) was the fourth highest after mining and quarrying, agriculture, forestry and fishing, and water supply.

Because of the many serious construction accidents in Norway 2009-2014, there was a widespread attitude among stakeholders in the construction industry and in the NLIA that measures at different levels were required. One measure was the establishment of a cooperation between central stakeholders in the Norwegian construction industry – the Cooperation for safety in construction (COSC). COSC has a vision zero approach to fatal- and other serious injuries, and is represented by clients, architects, engineering consultants, contractors, labour organisations and the authorities. One measure taken by the COSC was to provide more knowledge about accidents for prioritising and for developing preventive measures and strategies. One of the tasks of the authorities (NLIA and the National Institute of Occupational Health) in COSC is to produce annual analysis about the occupational health and safety (OHS) situation in the construction industry. This PhD was started to contribute to the need for knowledge about accidents and accident prevention for the construction industry and the authorities. So far, four reports have been published, in which this PhD project has made several contributions (Winge et al., 2015; Mostue et al., 2016 and 2017; Gravseth et al., 2018). This research project was funded by the NLIA and The Norwegian Research Council as a Public-Sector PhD scheme.

This thesis focusses on the Norwegian construction industry and compares the results to international studies. The Norwegian construction industry is a major contributor to both the gross domestic product (GDP) and the accident statistics. The contribution of the construction industry to the GDP in Norway was estimated to be 16% in 2017 (Prognosesenteret, 2017).

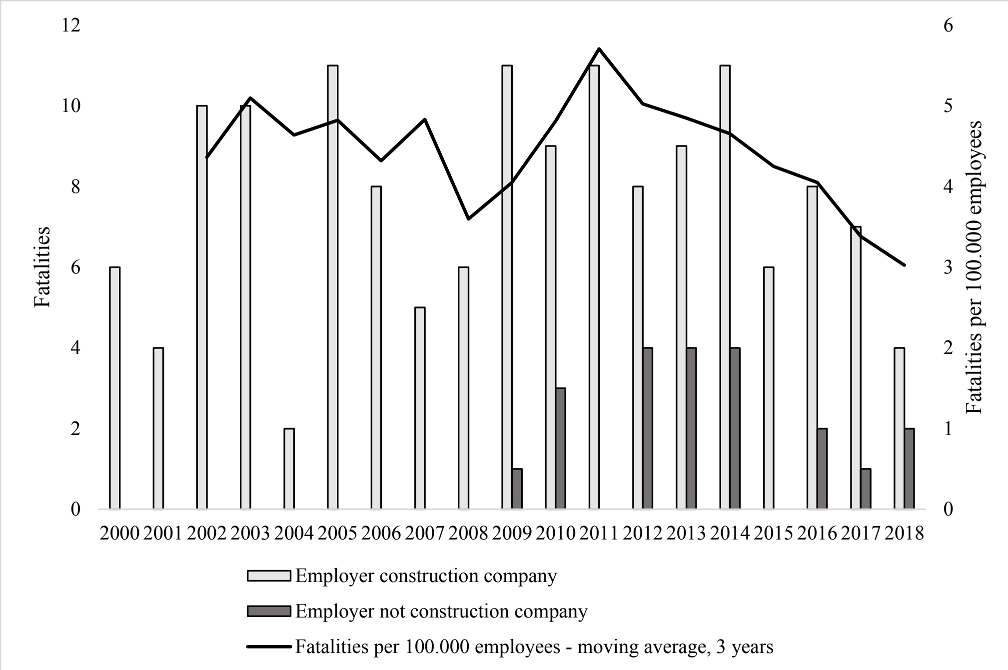

Figure 1. Number of occupational fatal injuries in the Norwegian construction industry and fatalities per 100.000 employees 2000-2018. Since 2009, workers injured during construction work, employed by non-construction companies, are included (dark colour). Sources: NLIA (2019) (injuries) and Statistics Norway (2019) (employees).

1.2 Structure of the thesis

In the remainder of chapter one, the research questions underlying the main objective will be presented. A brief description of the research context is also presented. The theoretical framework and main concepts are presented in chapter two. A review of literature on main topics is presented in chapter three. Chapter four presents a description of the research designs and the different research methods that have been employed in the empirical work of the thesis. A short summary of the research findings is presented in chapter five, which is followed by a discussion and conclusion in chapter six. An extended presentation of the empirical work and the research findings is to be found in the appendix, where the four research articles that constitute the fundament of the thesis are attached. The basic structure of the articles and the thesis is also presented in Table 1.

1.3 Objective and research questions

The main objective of this thesis was to identify key events and factors in construction safety that indicates where to prioritise safety measures and types of measures to develop. The research objective and research questions were developed by the researchers involved based on expressed needs of knowledge by the construction industry and authorities, and on the broad literature review on core issues presented in Chapter 3. The main objective is operationalised through three main research questions.

1.3.1 RQ1: Which accident types and barrier failures are most frequent in construction accidents?

Most clients and contractors rarely experience fatal- or serious accidents. Understanding the sequences of events leading to accidents is a crucial element of risk prevention (Swuste, 2008). Knowledge about dominating types of accidents with serious consequences are important for prioritisation, developing countermeasures, and for checklists for safety inspections at construction sites. There is some research on construction accident types in construction (chapter 3.1) but most of the research uses broad categories of accident types. For prioritisation and prevention, it is important to identify relatively detailed accident types. For example, fall from height can be categorised into fall from roof, ladder, scaffold etc. In this research a detailed accident variable with 36 categories is employed to identify more detailed accident types.

Accident types are related to barrier failures. Specific hazards must be controlled by specific barriers. When a frequent accident type is identified, it is important to know which barriers fail and countermeasures that can be implemented. Haddon's (1980) countermeasures strategies are used to identify barrier failures and unrealised barrier opportunities. The research question addressed is: *Which accident types and failures are frequent in construction accidents?* This research question is addressed in article 1, where the main sample consists of 176 mostly serious non-fatal accidents, and in article 2 where 69 fatal accidents were studied.

1.3.2 RQ2: Which causal factors are important in construction accidents?

In a review of construction site safety literature, Khosravi et al. (2014) concluded that there is little research on the key causes and contributory factors of unsafe behaviours and accidents at construction sites. Accident prevention begins with having a clear understanding of factors that play key roles in causation (Hinze et al.,1998). It is important to identify common causal factors, prioritise important factors, and to develop countermeasures. Research question 2 is: *Which causal factors are important in construction accidents?* Accident causation is addressed in article 3, where the main sample consists of the same 176 accidents studied in article 1.

1.3.3 RQ3: Which factors and combinations of factors are important in producing safety performance in construction projects?

Accident models and accident prevention (and safety management) models have many similarities, because issues that are contributory to accidents must be tackled in accident prevention. Safety management in construction is demanding, since construction projects are technologically and organizationally complex (Lingard, 2013). The research investigates what characterise projects with high safety performance and what characterise projects with low safety performance. Contextual factors like project complexity and organisational complexity can also influence the safety performance. Research question 3 is*: Which factors and combinations of factors are important in producing safety performance in construction projects?*

Table 1. Overview of research articles and methodology

Main objective: Identify key events and factors in construction safety that indicates where to prioritise safety measures and types of measures to develop				
	Article 1	Article 2	Article 3	Article 4
Title	Accident types and barrier failures in the construction industry	Accident types and barrier failures in 69 construction fatal accidents in Norway 2011-2017	Causal factors and connections in construction accidents	A comparative analysis of safety management and safety performance in construction projects
Research questions	Which accident types and barrier failures are frequent in *serious* construction accidents?	Which accident types and barrier failures are frequent in *fatal* construction accidents?	Which causal factors are important in construction accidents?	Which factors and combinations of factors are important in producing safety performance in construction projects?
Research design	Descriptive Explanatory Comparative (injury samples)	Descriptive Explanatory Comparative (injury samples)	Descriptive Explanatory Set-theoretical connections "Correlational"	Quasi-experimental Explanatory 12 Case studies Comparative analysis (QCA)
Material and data collection	Database on accidents, inspections etc. (NLIA). Documents about accidents (Notices, inspection reports, investigation reports, letters, judgements) Accident statistics from Statistics Norway	Database of accidents, inspections etc. (NLIA). Documents about fatal accidents (Notices, inspection reports, investigation reports, letters, judgements)	Database of accidents, inspections etc. (NLIA). Documents about accidents (Notices, inspection reports, letters, judgements)	Database Documents (Inspection reports, HS plans, progress plans) Statistics and indicators in injuries, occurrences, working hours etc. 21 Semi-structured interviews of project leaders and safety experts
Sample(s)	Main study sample: 176 accidents/184 injuries investigated by NLIA. Four "control samples" of injuries representing different severity	Main study sample: 69 fatal accidents (72 fatalities). Compared to main study sample in article 1 and 3 of 176 accidents (184 injuries).	176 accidents (184 injuries) investigated by NLIA (same as article 1)	12 construction projects (11 projects where one was divided into 2)
Data analysis	Coding, categorisation, frequencies Comparing injury samples Chi-square tests	Coding, categorisation, frequencies Comparing injury samples Chi-square tests Correlational (phi)	Coding, categorisation, frequencies Set theoretic connections (necessity and sufficiency) Correlational (phi)	Qualitative Comparative Analysis (QCA) Calibration Truth tables Set theoretic connections (necessity and sufficiency) Quine-McCluskey Algorithm

1.4 The "nature" of construction

Many researchers emphasise that construction is one of the most dangerous industries (e.g. Ringen et al., 1995; Lingard and Rowlinson, 2005; Swuste et al., 2012; Lingard, 2013; Mohammadi et al., 2018). Pinto et al. (2011) reviewed studies concerning risk factors influencing safety in construction, and identified a number of relevant causes influencing safety performance in the construction industry; poor work and safety organization; company size; lack of coordination among specialized groups; economic- and time pressure; lack of information about hazards and accidents; poor communications: poor involvement of workers in safety matters; constantly changing worksite; workers´ specialization; workers are responsible for his own protection; inadequate training and fatigue of practitioners; bad equipment selection, use or inspection; poor safety awareness of top management and project managers; lack of prevention/protection equipment's; construction jobs can be far apart; long-term health risks from the stress of on-and off-again employment.

There are many inherently hazardous work operations involving high amounts of energy in construction, for example working at height, large moving vehicles, lifting heavy loads, explosives and electricity. The hazards need to be managed, barriers must be implemented, and the site must be managed as workers, materials and equipment are constantly moving and the site is constantly changing.

Construction is a project-based industry where the production has limited duration and where many actors often are involved. All parties in construction, e.g. clients, designers, consultants, main contractor, subcontractors, suppliers and workers, have a role to play in ensuring safety (Lingard and Rowlinson, 2005). Coordinating the activities of different contributors to the design and construction of a facility can be challenging because each participant will be influenced by their interactions with other project participants, while also pursuing their own individual or organisational business interests (Lingard, 2013). The prevalence of subcontracting is often mentioned as a factor contributing to poor safety performance. It is the frontline worker at the bottom of the contractual chain that bear the most significant consequences when things go wrong (Swuste et al., 2012).

Choudhry and Fang (2008) describe construction as an organic type of organisation where the nature of the work, working environment, and job site conditions change rapidly. Mechanistic organizations allow for the exclusion of decision-making roles, and rules and procedures to be followed, while organic types rely on decision-making roles, the use of the workforce, and training facilities for workers to carry out non-standardized operations. Managing safety in circumstances with many hazardous work operations, in a dynamic and changing work environment with many parties, is complicated.

2 Theoretical framework

The purpose of this chapter is to present the overarching theoretical approach that ties the theoretical issues from the articles together, and to describe the concepts and presumed relationships between them.

2.1 Overarching theoretical model and conceptual framework

There is an abundance of potential factors that can help describe and explain accidents, accident prevention and safety performance in construction projects. A good theoretical model can be a good tool for structuring and displaying important concepts in a research project, and how they are connected. The relation between a theory and a model can be that the theory tries to *explain* a phenomenon, while the model tries to *represent* a phenomenon (Bhattacherjee, 2012). There is an abundance of models and theories in safety science (Le Coze et al., 2014). Many of these models focus on more or less similar factors. Hovden et al. (2010, p. 955) argue that: "Accident models affect the way people think about safety, how they identify and analyse risk factors and how they measure performance".

The theories and conceptual framework of this research has many similarities to Reason's (1997) model for organisational accidents (Figure 2). The model is therefore used to present the overarching theories and concepts in this research. Then, the other frameworks that are employed in this research are presented. Finally, all the frameworks and main concepts are summarised in a model that represent the three research questions in this research.

All analytical frameworks used in this research can be linked to Reason's model. Some have influenced Reason's model while other are influenced by the model. For this research, the Reason (1997) model is a good trade-off between being generic and detailed, and a good starting point for presenting the research. Another merit of the model is that its concepts and language is pragmatic and hence suits this research approach which is mainly applied research and policy research (see Guthrie, 2010). Some clarifications about the relation between the model and the approaches used in this research must, however, be made.

Reason (1997) dichotomise accidents into individual accidents and organisational accidents. Based on Reason's descriptions of the two types, most construction accidents will have characteristics from both types. Most construction accidents will not fit 100% in Reason's description of organisational accidents, but when it comes to explaining and preventing construction accidents, it is better to analyse occupational construction accidents as organisational accidents than individual accidents. Hopkins (2012) argues that the Reason model is an "extremely useful way to think about accident causation" (ibid. p., 5), even though most major accidents are more complex than construction accidents. In his book from 2016, Reason also use the model to analyse "organisational accidents" (unwanted occurrences) in healthcare, which have many similarities with occupational accidents in construction, showing that Reason thinks the model is applicable not only to major accidents. What makes Reason's (1997) model applicable to occupational safety in construction is that all the six elements in the model are basic in understanding construction accidents and safety management. In occupational construction accidents there are almost always *hazards*, *failures* in the defences, and *harm* (injuries). *Unsafe acts* are involved in many accidents, and the accidents take place at a *workplace* where frontline workers are influenced by the organisation of the site and the materials and equipment used. And there are always contractors and clients involved that must follow laws, regulations, procedures etc. (*organisational factors*) about controlling the other elements in the model.

To the left in the model are the main questions, *what, how* and *why,* for the different stages in accident investigations and the accident causation. Article 1 and 2 are mainly concerned with the upper part of the model (*what* happened and *how* it happened) – the hazards, barrier failures and injuries. Article 3 and 4 are mainly concerned with the causal factors – the unsafe acts, workplace factors and organisational factors (the *why* question). Article 3 study these as causal factors in construction accidents, while article 4 study them as management factors related to safety performance. Article 1 and 2 are hence mainly descriptive, while article 3 and 4 are mainly explanatory.

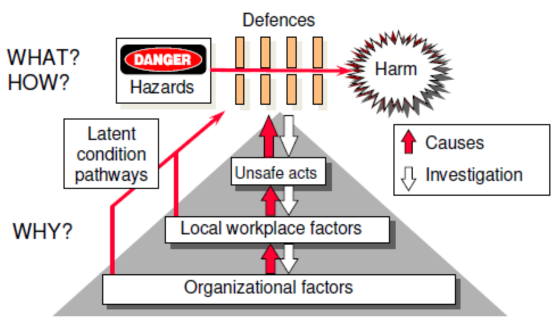

Figure 2. Stages in the development and investigation of an organisational accident (Reason, 1997, p. 17).

2.2 Hazards, barriers, accidents and injuries

Reason (2016) argues that organisational accidents have at least three common features: hazards, failed defences and losses. The upper part of the model illustrates the basic elements of an accident according to the energy-barrier perspective (Gibson, 1961; Haddon 1970; 1980), and the Swiss Cheese Model (SCM) with the holes in the barriers. For an accident to occur, there must be a be a; (1) hazard, coming into contact with an, (2) object (worker), as the result of, (3) failures in one or more defences/barriers, and (4) the events and hazards that leads to the final accident phase (Trost and Nertney, 1995). These four elements are basic in article 1 and 2.

2.2.1 Energy, hazard, accident and injury

Energy is the physical capacity to do work, and hence necessary for production. Haddon (1973) addressed the notion that injury occurs through the transfer of energy (e.g. kinetic, thermal, chemical, electrical, and ionising radiation). An injury occurs when "… energy is transferred in such ways and amounts, and at such rates, that inanimate or animate structures are damaged" (Haddon, 1973, p. 41). A hazard is a "... potential source of injury or damage to health of people, or damage to the environment or material assets" (Kjellén and Albrechtsen, 2017, p. 476). The terms accident and injury are often used synonymously. An accident does not necessarily result in an injury, but every injury is a result of an incident that can be termed as an accident. In some accidents, there are more than one injury, so the numbers of accidents and injuries are somewhat different. In this research, both injuries and accidents are used deliberately. This research is about *occupational* accidents and injuries. ILO defines *occupational accident as:* "An occurrence arising out of, or in the course of, work which results in a fatal or non-fatal injury" (ILO, 2015, p. IV).

2.2.2 Barriers

In Reasons' model for organisational accidents (Figure 2), there is a model in the model, illustrating the defences/barriers, namely the Swiss Cheese Model (SCM). In Reason's model, defences are "means by which protection can be achieved" (Reason 1997, p. 7). These defences include hard defences (e.g. physical barriers, alarms, PPE, system design) and soft defences (e.g. legislation, rules, procedures, training, administrative controls, and front-line operators). Reason (1997) reserves the term barrier for energy barriers. In this thesis the term barrier includes both hard and soft barriers.

There is no generally accepted definition of the term barrier (Sklet, 2006). The term comes from Haddon's "... generic strategies that encompass all of the tactics that may be used to reduce damage" (Haddon 1980, p. 8). These strategies are also called "energy barriers" (Trost and Nertney, 1995). In this research, we apply Kjellén and Albrechtsen's (2017, p. 130) definition of a barrier as "… a set of system elements (human, technical, organisational) that as a whole provide a barrier function with the ability to intervene into the energy flow to change the intensity or direction of it". A *barrier function* is "the ability of a barrier to intervene into an accident sequence to eliminate or reduce loss", and the *barrier system* is "… a set of interacting, human, technical and organisational elements that make up the barrier function". Some barriers are specifically made for safety, for example, guardrails and hard hats, others are part of a production system or structure, for instance building materials and scaffold floors.

In this research, Haddon's (1980) ten countermeasure strategies are used to identify barrier failures (Table 2). Haddon's purpose was to suggest preventive strategies at an "intermediate level of generalisation" (p. 8). Haddon's strategies encourage a fundamental way of thinking about the processes by which injuries occur and the ways in which they can be prevented (Runyan and Baker, 2009). The first strategy helps us consider measures that can eliminate basic hazards, while the other nine help us consider measures that can interrupt the injury process at different stages.

The SCM illustrates the principle of defence-in-depth and that there can be holes in these defences. Some holes are due to active failures and other to latent conditions. The defence-in-depth principle aims at increasing safety through layers of independent barriers. Defence-in-depth is primarily used in safety design where major accident risks are involved (Kjellén and Albrechtsen, 2017). We also must consider that barriers can deteriorate and need to be monitored and maintained (Rosness et al., 2010). Trost and Nertney (1995) describe three types of limitations in barriers. One limitation is that *barriers are not practical* due to the energy source, cost of the barrier etc. Another limitation is that *barriers fail*, for instance that physical barriers erode, and procedural barriers deteriorate through weak change control. A third limitation is when *barriers are not used*.

Table 2. Haddon's 10 countermeasure strategies for reducing loss. Based on Haddon (1980) and Kjellén and Albrechtsen (2017).

Related to the hazard	Related to the separation of the hazard from the object (worker)	Related to the vulnerable object (worker)
		
1.Prevent the creation of the hazard	6.Separate, in time or space, the hazard and the vulnerable target	8.Make the object more resistant
2.Modify relevant basic qualities of the hazard	7.Separate the hazard and object by physical barriers	9.Limit the development of loss
3.Reduce the amount of the hazard		10. Stabilise, repair and rehabilitate
4.Prevent the release of the hazard		
5.Modify the rate or spatial distribution of release of the hazard from its source		

2.3 Accident causality

Below the defences in Reason's model (Figure 2), we find the causal factors. Latent conditions are the organisational factors and workplace factors. Latent conditions can increase the likelihood of active failures through the creation of local factors promoting errors and violations. The term "causal" (factor) is rarely defined or discussed in construction safety literature. In this research, the term "causal factor" is used pragmatically and generically to refer to an aspect of a case that is relevant in some way to the explanation of the outcome (see Ragin, 2008).

2.3.1 Latent conditions: Organisational factors and workplace factors

Organisational factors and workplace factors are also called latent conditions. Organisational accidents are often caused by a complex interaction of latent conditions and unsafe acts. Unsafe acts are not necessarily involved in accidents as illustrated by the "latent condition pathway" in Figure 2.

The causal start of an organisational accident (Reason, 1997) are *organisational factors* like strategic decisions, allocating resources, planning, scheduling, communicating and managing. They can also be treated as management factors, as in article 4. In the ConAC model (Haslam et al., 2005) employed in article 3, "originating influences" include for example risk management, project management and safety culture. Organisational factors influence *workplace factors* (e.g. inadequate tools and equipment, time pressure, insufficient training, under-manning, poor communications) that can promote errors and violations (unsafe acts). In the ConAC model, workplace factors can be found as "immediate factors" and "shaping factors", for example supervision, housekeeping, design, and supply/availability of materials and equipment.

2.3.2 Unsafe acts

The latent conditions influence the individual's likelihood to do errors and violations (unsafe acts). In Reason's model there are two types of unsafe acts - errors and violations - of which there are subcategories. In this research material, information about these categories were mostly not sufficiently detailed in the accidents and are therefore not analysed. The term "human error" is also problematic and is used by many with quotation marks. Dekker (2014) writes that "The attribution of 'human error' depends on the perspective you take. What is a 'human error' to some people, is normal to others" (ibid., p. xx). In this research we adapt a broader understanding of unsafe acts based on the development and employment of the of the Construction Accident Causation (ConAC) framework (Haslam et al., 2003; 2005; Behm, 2009; Behm and Schneller, 2013). In this thesis, the term "unsafe acts" is used in article 2, and "worker actions and behaviours" in article 3, since that is the term used in the ConAC framework employed in article 3. Both terms are defined as all acts at the "sharp end" that have an impact on the accident, such as mistakes, unsafe acts, violations of procedures and taking shortcuts.

Human behaviour in organisations can be viewed through the person perspective and the system perspective (Reason, 2000). The **person approach** focuses on workers at "the sharp end" and sees "unsafe acts" as being caused primarily by mental processes, such as carelessness, forgetfulness, inattention and recklessness. The associated countermeasures are directed mainly at reducing unwanted variability in human behaviour, e.g. poster campaigns that appeal to people's sense of fear, writing another procedure (or adding to existing ones), disciplinary measures, threat of litigation, retraining, naming, blaming, and shaming. The **system approach** sees the same acts as consequences rather than causes, focussing on the conditions where individuals work and tries to build defences to prevent errors or mitigate their effects. The basic premise in the system approach is that humans are fallible, and errors are to be expected, even in the best organisations. Errors are seen as consequences rather than causes. These include recurrent "error traps" in the workplace and the organisational processes that give rise to them. A basic idea is that of system defences. When an unwanted event occurs, the important issue is not to blame someone, but how and why the barriers failed. Preventive measures in the system perspective typically focus on working conditions, such as time pressure, inadequate equipment, impractical procedures, rather than on individuals and their attributes.

2.3.3 The Construction Accident Causation (ConAC) framework

In article 3, we employed the Construction Accident Causation (ConAC) model (Figure 3) (Haslam et al. 2003; 2005) to identify causal factors in a sample of 176 construction accidents. The framework was also one of the frameworks used to develop the analytical framework employed to study safety management in article 4.

One of the merits of the ConAC framework is that it "… adopts a similar framework to that presented by Reason (1997) but places it in the context of the construction industry" (Lingard and Rowlinson, 2005, p. 30). The ConAC framework was developed inductively through a combination of focus groups and a detailed study of 100 construction accidents in the UK. The framework has three levels of factors;

1) *immediate* factors (e.g., worker actions) are influenced by,
2) *shaping* factors (e.g., supervision), and the shaping factors are influenced by
3) *originating* factors (e.g., risk management)

The shaping and immediate factors are divided into three types of factors;

1) *worker/team* factors
2) *site* factors, and
3) *material and equipment* factors

The double arrows at the centre of the model represent multiple two-way interactions. The understanding of causality in the ConAC model is that: "All accidents are multi-causal, with a rare combination of factors needing to coincide to give rise to an incident. Underlying each of the causal factors are a range of influences determining the extent to which they undermine safety" (Haslam et al., 2003. p. 58). Gibb et al. (2006) compares the layers (slices of cheese) in Reason's swiss cheese model to the layers of immediate circumstances, shaping factors and originating influences in the ConAC model. This is similar to Reason et al.'s (2006) understanding, that it "… is now broadly recognised that accidents in complex systems occur through the concatenation of multiple factors, where each may be necessary but where they are only jointly sufficient to produce the accident" (p. 2). Causality is important in this thesis and is therefore dealt with several places in the thesis.

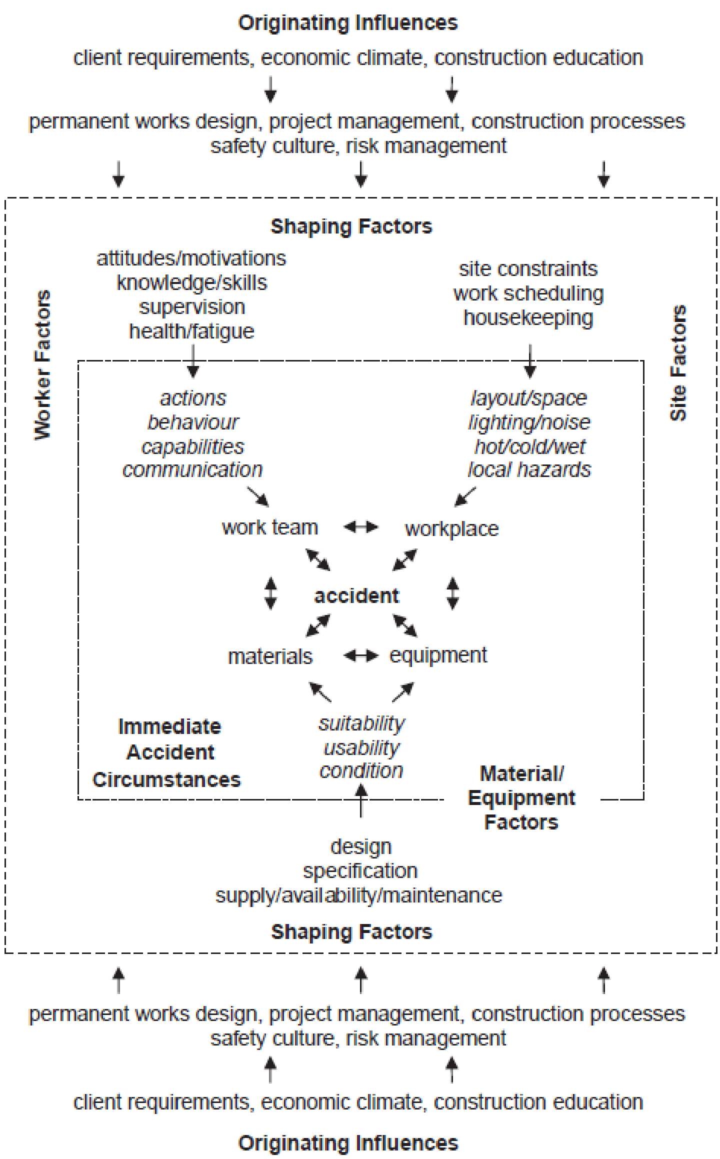

Figure 3. The Construction Accident Causation Framework (Haslam et al., 2003; 2005).

2.3.4 Generations of accident theories

Khanzode et al. (2012) describe four generations of accident theories, their features, causation themes and types of factors (Table 3). In Reason's model we can see similarities with the human factors/ergonomics, the energy-barrier approach from injury epidemiology and socio-technical models. The ConAC model employed in article 3, and which has influenced the analytical framework in article 4, also have many similarities with systems theory, STS-theory and macroergonomic theory.

Table 3. Generations of accident theories and causation themes (based on Khanzode et al. (2012).

Gen.	Causation theme	Types of factors examined	Theory	Important features
1	Person (unsafe acts)	Individual-related	Accident proness theory	Personal traits responsible for accident. Differential involvement in accident. Behavioural interventions.
2	Person (unsafe acts) and system (unsafe conditions).	Individual- and job-related	Domino theories	Unsafe act and condition as immediate predecessors of accident. Interventions focused on unsafe acts
3	System-person sequence (energy interactions)	Job-related (leading to energy interactions)	Injury epidemiology theory	Uncontrolled energy transfer. Control at pre-injury, injury and post-injury stages
4	System. System-person sequence.	Organisation-related. Job-related. Individual-related.	System theories	Holistic. Integrated safety systems.
			Socio-technical systems (STS) theory	Interacting. Job-design based on STS principles
			Macroergonomic theory	Holistic like system models. Organisation-centred

2.4 From accidents to safety management

Article 1-3 focus on the sequence of events and causal factors, while article 4 focus on safety management in construction projects. Accident models and accident prevention models have many similarities, because issues that are contributory to accidents must be tackled in accident prevention. Toft et al. (2012, p. 1) put it this way:

> *Accident prevention is the most basic of all safety management paradigms. If safety management is effective, then there should be an absence of accidents. Conversely, if accidents are occurring then effective safety management must be absent. Therefore, understanding how accidents occur is fundamental to establishing interventions to prevent their occurrence.*

The relation between causation and prevention can be seen this way: A contributory causal factor in an accident, e.g. poor risk assessment, point to poor *risk management,* which is an element in safety management. Accident models are therefore sometimes used as prevention models, and the other way around. In Reasons' (1997) model (Figure 2), the same latent conditions can contribute to several different accidents. The latent conditions can, however, be identified before incidents occur through proactive safety management. Proactive safety management involves regular monitoring of the systems' generic systemic processes such as planning, scheduling, training, communicating, designing, building, operating and maintaining. Regarding the ConAC-model (Haslam et al., 2005), Behm and Schneller (2013) hypothesise that the ConAC model "… could be utilized proactively in a construction organization's safety management systems to identify levels of unacceptable risk" (p. 593).

2.4.1 Safety, safety management (SM), and safety management systems (SMS)

Safety is the freedom from unacceptable consequences, while safety management is the *process* to realise certain safety functions (Li and Guldenmund, 2018). Heinrich et al. (1980) defined safety management as the "… systematic control of worker performance, machine performance, and the physical environment" (ibid. p. 4). A safety management system (SMS) is "… commonly defined as the management procedures, elements and activities that aim to improve the safety performance of and within an organisation" (Li and Guldenmund, 2018, p. 96). SMSs have evolved from individual management systems into integrated management systems. Todays' SMSs are not just a reflection of traditional accident models, but also a part of the organisational management system in organisations together with other management systems. Hale (2003b, p. 3) writes: "In systems terms, safety management should be seen as an aspect system, not a subsystem, of the organisation (…). Safety management only work well when it is seen as an integral aspect of the task of all those working in and for the organisation.

Li and Guldenmund (2018) argue that a complete model for a SMS should contain an: (1) events model; (2) barriers; and (3) the management system (Figure 4). Events models (scenarios) depict accident causation mechanisms that could be used to develop accident scenarios. They help to develop accident scenarios, which is important in article 1 and 2. Barrier models are based on the events models. Barriers have a risk control function, which is directly connected to the management system. The management system delivers the management factors to "complete" the barriers, i.e. to provide enough resources and controls to ensure their proper functioning. The management system includes every factor that affect the performance of safety barriers.

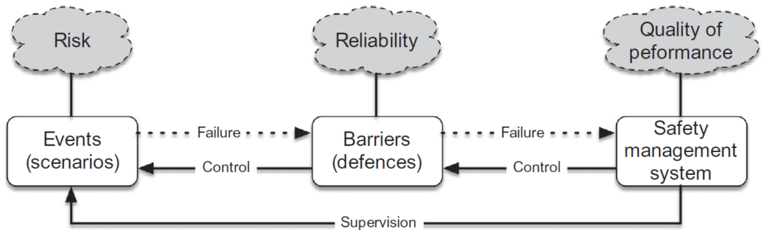

Figure 4. The relation between events (scenarios), barriers and safety management (from Li and Guldenmund, 2018, p. 103).

Safety management and risk management is often seen in terms of a hierarchy of system levels (Rasmussen, 1997; Hale, 2003a), with the (1) operational (work) process at the lower level, being controlled by a (2) combination of technology and human behaviour, which is in turn controlled by (3) management provision of resources, information and instruction (Hale et al., 2010). Hale (2003a; 2005) argued that we know "quite securely" the structure of a good safety management system. Hale's safety management system (SMS) is generic in the sense that the elements can be applied in various industries or organisations. Hale's suggested SMS includes;

1) An anchorage to the specific hazards of the production
2) A life cycle approach
3) Problem-solving at three levels (operational, tactical, strategic)
4) Systems at the tactical level delivering the crucial resources and controls for safety-critical tasks at the operational level, and
5) Feedback and monitoring loops ensuring assessment against performance indicators at each of the three levels.

Hale's safety management system (SMS) is generic in the sense that the elements can be applied in various industries or organisations. When SMS is about occupational safety it is called occupational health and safety management (OHSM). ISO's (2018) standard for occupational health and safety management systems (ISO 45001) (ISO, 2018) specifies requirements for OHS management systems. Effectiveness and the ability to achieve the outcomes of an OHS system are dependent on a number of key factors: top management leadership and commitment, communication, consultation and participation of workers, allocation of necessary resources, OHS policies, effective process for identifying hazards and controlling risks, continual performance evaluation and monitoring of the OHS management system, integration of the OHS management system into the organisation's business processes, OHS objectives that align with the OHS policy, and compliance with legal and other requirements.

2.5 Summary of main concepts

Figure 5 summarises the main concepts and connections related to the three research questions. The upper square (RQ1) shows the accident process. An occupational *injury* occurs when a *hazard* come into contact with a *worker* and when *barriers* fail. The accidents and injuries could have been prevented or mitigated by Haddon's (1980) countermeasure strategies/energy barriers that are illustrated with the broken lines and circles. Of the eight barriers studied in this research, five of them are related to the hazard, two separate the hazard and victim, and one is protecting the worker. The accidents in this research resulted in fatal- or non-fatal serious injuries. The hazards related to the accidents can be categorised into *accident types*. The accidents in this research resulted in injuries (fatal or non-fatal). The accidents and injuries are also categorised into accident types related to the hazards involved.

Causal factors (RQ2) and safety management (RQ3) can influence the accident process in an accident and the extent of accidents in for example a construction project. The *causal factors* (RQ2) are identified by using the ConAC framework that are grouped into worker- and team factors, site factors, material- and equipment factors, and originating factors. To the right, we find *safety management factors* (RQ3) that control hazards by e.g. safety barriers and which includes factors that affect the performance of safety barriers, e.g. risk management, staff management, site management, learning and roles and responsibilities. Safety management factors and contextual factors, was studied using an analytical framework developed based on based on previous research, e.g. Hale (2005) and the ConAC model (Haslam et al., 2005).

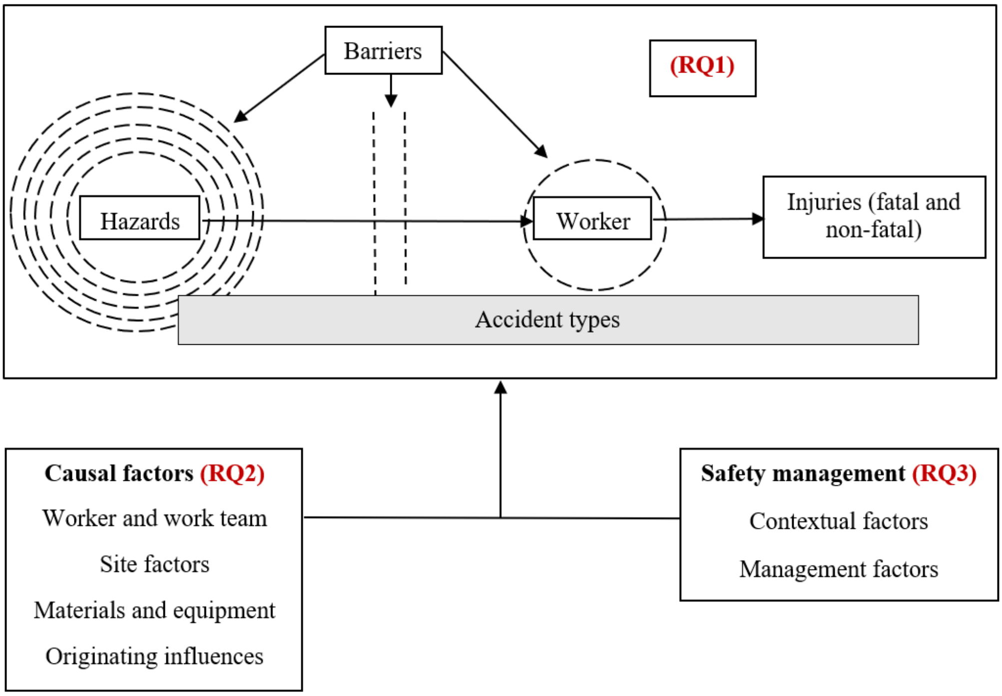

Figure 5. Summary of main concepts, relations between them and research questions (RQ).

3 Literature review

So far, the broad theoretical approach and important concepts have been presented. This chapter reviews literature that was basic for the formulation of the research questions presented in chapter 1.

3.1 Accident types

There are some statistics and studies showing distribution of incident types. Buskin and Paulozzi (1987) studied 231 fatalities in the construction industry in Washington State between 1973 and 1983. They found that falls, cave-ins, and electrocutions resulting from heavy equipment (boom type) contacting overhead power lines accounted for 45% of the fatalities. Heavy construction had a death rate twice that of the other two construction subgroups (building and special trades construction). Sorock et al. (1993) studied 200 construction-related fatalities in the New Jersey construction industry 1983 to 1989 and found that the leading cause of death was falls (46%). In a study of work-related deaths among construction workers in North Carolina 1988-1994, Lipscomb et al. (2000) found that work-related deaths were most often "caused by" motor vehicles (21%), falls (mostly roofs and scaffolds) (20%), machinery (15%), electrocutions (14%), and falling objects (10%). Three major causes of work-related motor vehicle accidents were identified including injuries to pedestrians in highway work zones and in backovers on construction sites, and injuries to drivers caused by shifting loads while transporting construction materials. In a study of 153 construction fatalities in Kocaeli, Turkey (1990-2001), Colak et al. (2004) found that the "cause of death" was fall from height (45%), vehicle accidents (14%), and electrocution (14%). In a study of 235 construction fatalities in east China (1991-1997), Xia et al. (2000) found that falls were the leading cause of death (46%) followed by collisions, struck by/against something, electrocutions, and excavation cave-ins. These accident types represented 94% of all fatalities. In a Dutch study of "accident types" in the construction industry, Ale et al. (2008) used a more detailed accident type variable. The most frequent accident types were contact with falling/collapsing object, followed by fall from height-roof/floor/platform, struck by moving vehicle, and fall from moveable platform. Differences in the distribution of accident types between fatal and non-fatal accidents can also be read from their results. In a study of work-related fatal and non-fatal injuries among US construction workers (1992-2008), Dong et al. (2010) found that falls (from roofs, ladders and scaffolds) (32%), was the leading cause of death in construction, followed by transportation accidents, contact with objects, and exposure to harmful substances or environments. They also found that patterns of leading causes for non-fatal injuries differ from those for fatal injuries. They underline that the numbers should be interpreted and used with caution, because some construction workers are misclassified in non-construction industries. For instance, workers from temporary work agencies are classified in "services". In Europe (EU28) 716 construction fatalities were registered in 2016 (Eurostat, 2019). The most frequent "deviations" were; fall of persons (29%); breakage/fall/collapse of material agent (19%); and loss of control of machines, equipment, tools (17%).

Kjellén (2018) analysed fatal accidents (N=60) to develop a safety performance indicator suitable for real-time management of major accident hazards in construction. He found that about 70% of the accidents belonged to three main categories: (1) fall from height, (2) driver or person outside the cabin fatally injured by moving construction machine/vehicle, and (3) person fatally injured by load or equipment during material handling. The three main categories were divided into subcategories and analysed to identify barriers to prevent adverse consequences.

It is challenging to compare the different studies and statistics since there are different variables and categories used for describing accidents, e.g. "deviations", "cause", "accident/injury types" and "central events". However, based on a review of construction safety literature using mortality data, Swuste et al. (2012) concluded with a list of the most frequent "central events" (Table 4). They also concluded that "… between countries there is consensus on this list" (p. 1341).

Table 4. The hierarchy of the central events in construction (From Swuste et al., 2012, p. 1335).

Central events
1. Falling from a height
2. Contact with falling or collapsing objects
3. Contact with electricity
4. Contact with moving machinery parts
5. Falling from a moving platform
6. Contact with hoisted, hanging, swinging objects
7. Hit by a vehicle
8. Squeezed between or against something
9. Contact with objects thrown from a machine

An issue regarding lists of accident types for prioritisation is whether *one* list of accident types is sufficient, or whether the distribution of accident types wary across injury samples representing for example different injury severity and different construction types.

Regarding injury severity, according to a popular version of the iceberg model, near misses, minor accidents and major accidents stem from the same causes (Rosness et al., 2010). This led to a belief that measures reducing the frequency of minor accidents will reduce the frequency of major accidents by a similar proportion. This belief also seems to be widespread in the construction industry today. Some studies have found differences between serious and less serious accidents. Salminen et al. (1992) found that fatal accidents differed both in the type of accident and the distribution of accident factors from non-fatal accidents. Hale (2002) found that the belief in the popular version of the iceberg model is not supported by the limited research undertaken and argued therefore that we cannot necessarily prevent major accidents by studying and tackling the minor accidents. Carrillo-Castrillo et al. (2013) found different causation between slight and non-slight accidents in the manufacturing sector. They also found significant differences in accident causation depending on the mechanism of the accident.

Differences are also found in construction. Li and Bai (2008) found significant differences between fatal and injury accidents in the construction zones, e.g. that head-on was the dominant type for fatal accidents while rear-end was the dominant injury accident type, and that a large percent of fatal accidents involved trucks while a majority of injury accidents involved light-duty vehicles only. Based on the results they recommended to target safety countermeasures at different severity of accidents.

In summary, there is some research on accident types in construction, but the research has some limitations. First, most studies use variables with broad categories (e.g. fall) that are not specific regarding prioritisation and developing countermeasures. Second, there is little research on the relation between injury severity and accident types. Third, there is little research on differences in accident types across construction types like building, civil engineering and refurbishment. The aim of this research is to contribute with further research to these research questions.

3.2 Barrier failures

In the Netherlands, an occupational risk model with was developed based on analysis of around 9,000 occupational accident investigations by the Dutch Labour Inspectorate. A set of

36 different accident scenarios (accident types) and 400 barrier failures were identified (RIVM, 2008). Bellamy et al. (2010) found that the most common barrier failures were related to danger zones, physical safeguards, placement of equipment, and roof edge protection. Ale et al. (2008), also using the same approach in construction, found that the most frequent barrier failures for fall from height (from roofs, floors or platforms) were roof edge protection, followed by user ability failure, and fall arrest failure. For falling objects, ensuring the safe zone is safe and preventing the object from falling in the first place was found to be the most important, especially by proper connection/anchoring.

Jørgensen (2016) state that there is hardly any systematic documentation of the safety barriers needed against "simple accidents" (traumatic events with usually no more than one victim in contrast to major accidents). Haddon's (1980) strategies encourage a fundamental way of thinking about the processes by which injuries occur and the ways in which they can be prevented (Runyan and Baker, 2009). In the review literature on construction safety (Pinto et al, 2011, Swuste et al, 2012; Khosravi et al., 2014; Nadhim et al., 2016; Zhou, 2015; Mohammadi et al., 2018) the terms *barrier* or *defence* is hardly mentioned. Literature on common barrier failures in construction accidents is therefore largely a "blank spot". Identifying barrier failures linked to frequent accident types using Haddon's (1980) strategies is therefore seen as a contribution to how accident sequences can be interrupted at different stages.

3.3 Causal factors

In accordance with Reason's model of organisational accidents (Figure 2), accident types, barrier failures and injuries are not seen as causal. The term causal factor/condition is reserved for the person level (unsafe acts), workplace level, and organisational levels.

3.3.1 Unsafe acts

The human element is particularly important in a labour-intensive industry as the construction industry (Lingard and Rowlinson, 2005). Depending on operational definitions, it is often concluded that "human error" is a determining factor in 70-80% (Rasmussen, 1997) or 80-90% (Hale & Glendon, 1987; Phillips, 2005) of accidents. A study of occupational accidents (Salminen and Tallberg, 1996) found that "human errors" were involved in 84% of serious accidents and 94% of fatal accidents. In the studies using the ConAC framework (Haslam et al., 2005), "worker actions and behaviours" were found to be a causal factor in 49% (UK), 53% (Australia), and 63% (USA) of the accidents (Gibb et al., 2014). In a study of 26 fatal construction accidents, Hale et al. (2012) found violations in 23 of the accidents and errors in 21 of the accidents.

The studies described illustrate how important front-line construction workers are in preventing and causing accidents. When frontline workers are part of the barrier system, we must expect accidents to happen "… due to inherent variability in human performance" (Kjellén & Albrechtsen, 2017, p. 142). Identification of unsafe acts is not about blaming frontline workers. Today, it is widely acknowledged that worker behaviour is largely a result of the system workers are part of (Reason, 1997) and symptomatic of trouble deeper within a system (Dekker, 2014).

3.3.2 Workplace factors and organisational factors

Hale et al. (2012) developed a framework for identifying underlying causes of fatal construction accidents. They studied 26 fatal accidents that was compared to another sample of 50 accidents. At the workplace level, they found a concentration of failures in planned risk control, competence, commitment to choose safety above other goals, and ergonomic design and usability of the hardware. The main areas of workplace failures were reflected in failures in management processes - weakness in monitoring and supervision largely in the sense of failures to correct unsafe behaviour and use of equipment. At the corporate systems level they found that contracting strategy, the control of the supply chain, and the influence of top management leadership appeared as important factors. There are some literature reviews of factors influencing safety performance in construction. Swuste et al. (2012) focussed on whether it is possible to influence safety in the building sector, Khosravi et al. (2014) identified factors influencing unsafe behaviours and accidents, Zhou et al. (2015) gave an overview of safety management studies in construction, while Mohammadi et al. (2018) identified factors influencing safety performance.

Khosravi et al. (2014) included 56 studies in a literature review to identify factors influencing unsafe behaviours and accidents on construction sites. They found *high evidence* of association for organisation (e.g., safety climate/culture, information management, and policy/plan) and project management (e.g., commitment/support, management style and review/feedback). They found *moderate evidence* of association for supervision (e.g., effective enforcement, supervision style and communication), site condition (e.g., unsafe condition and hazardous operation), individual characteristics (e.g., attitude/motivation, psychological distress and age/experience) and contractor (e.g., size and subcontractor rate). And they found *low evidence* for association for work groups (e.g. group norm and attitude, group interaction, team work) and society (e.g. societal culture, knowledge, economy, social support and social challenges).

In a review of 90 papers, Mohammadi et al. (2018) identified 13 factors influencing safety performance in construction: motivation, rules and regulation, competency, safety investment and costs, financial aspects and productivity, resource and equipment, work pressure, work condition, culture and climate, attitude and behaviour, lesson learned from accidents, organization, and safety programs and management systems. They concluded that safety performance is not only determined by management activities within project levels, but also by the interactions among factors at different hierarchical levels. They suggested that more research is needed to investigate the interaction between the identified factors and determine how they are able to affect safety performance.

3.3.3 The ConAC studies

Haslam et al. (2003; 2005) developed the ConAC framework inductively through a combination of focus groups and a detailed study of 100 construction accidents. They found problems arising from workers or the work team in 70% of the accidents, workplace issues in 49%, shortcomings with equipment in 56%, problems with suitability and condition of materials in 27%, and deficiencies with risk management in 84% of the accidents.

Cooke and Lingard (2011) used the ConAC framework in an analysis of 258 fatal construction accidents in Australia based on coronial investigations. Frequent factors identified were mainly immediate factors, for example, worker actions/behaviour, site layout/space and suitability of materials and equipment.

Behm and Schneller (2013) used the ConAC model interviewing employees, witnesses, supervisors and safety engineers in 27 construction accidents. The most frequent factors found were risk management, worker actions and behaviour, and worker capabilities including knowledge and skills. They also analysed if the factors were correlated to other factors in the framework and found that worker actions were negatively correlated with worker capabilities, indicating that these factors acted independently. Further, they found that worker actions were correlated with attitudes and motivations, attitudes and motivation were correlated with safety culture, worker actions were correlated with availability of equipment and materials, site conditions were correlated with work scheduling and work scheduling was correlated with construction processes.

Gibb et. al (2014) compared the results on 23 of the ConAC factors from research in the UK, Australia, and USA, and found similarities and dissimilarities in the ranking of factors between the three studies. A comparison of results from the studies and this research is presented in chapter 5. The average percentage of each factor from the studies showed that the most frequent immediate factors were worker actions, suitability of materials/equipment and worker capabilities. The most frequent shaping factors were knowledge/skills and attitudes/motivations, and the most frequent originating factors were risk management, project management and permanent works design.

Based on a literature review, Khosravi et el. (2014) concluded that there is some research on causal factors in construction accidents. Few studies use a holistic framework to identify causal factors that can help prioritise and develop effective interventions. The aim of this research is to contribute to this knowledge.

3.4 Safety management

One important function of safety management is to counteract the causal factors described in the previous section. Heinrich et al. (1980, p. 4) defined safety management as the "… systematic control of worker performance, machine performance, and the physical environment". A safety management system (SMS) is "… commonly defined as the management procedures, elements and activities that aim to improve the safety performance of and within an organisation" (Li and Guldenmund (2018, p. 96).

Hale (2003a; 2005) argues that we know "quite securely" the structure of a good safety management system, including, (1) an anchorage to the specific hazards of the production, (2) a life cycle approach, (3) problem-solving at three levels (operational, tactical, strategic), (4) systems at the tactical level delivering the crucial resources and controls for safety-critical tasks at the operational level, and, (5) feedback and monitoring loops ensuring assessment against performance indicators at each of the three levels.

The research on effectiveness of occupational health and safety management (OHSMS) is however ambiguous (Zwetsloot, 2013). In a literature review, Gallagher et al. (2001) concluded that OHSMSs can deliver more healthy and safe workplaces under the right circumstances. In another review, Robson, et al. (2007) concluded that the body of evidence was insufficient to make recommendations either in favour of or against OHSMSs. In a review of the effectiveness of safety management systems, Thomas (2011) concluded that organisations with a certified SMS had significantly lower accident rates. There was however a lack of agreement about which components of a safety management system contributed the most to safety performance. The ISO 45001 (Occupational health and safety management systems) (ISO, 2018) also states that effectiveness and the ability to achieve the outcomes of an OHS system are dependent on a number of key factors, for example top management leadership and commitment, communication, consultation and participation of workers, allocation of necessary resources, risk management, continual performance evaluation and monitoring, integration of the OHSM system into the organisation's business processes (ISO, 2018).

Zwetsloot (2013) argue that the difficulties in demonstrating the effects of OHSMS on safety performance can be explained that many do not consider "contextual factors" like the ambitions and commitment of management, the participation of workers, and the continual adaptation to changing circumstances. Zwetsloot (2013) also argues that the system is more than the sum of its parts and the interactions between the elements are just as important as the elements.

A literature review of 49 studies of safety management and quality management in construction projects found that the literature overall supported the use of integrated safety and quality management (Loushine et al., 2006). The characteristics found to contribute to improved construction safety were management commitment, employee involvement, a formal safety management program, training, audits and observation, continuous improvement, and communication

Hallowell and Gambatese (2009) identified from previous research 13 critical elements of an effective construction safety program: a written and comprehensive safety and health plan, upper management support, job hazard analyses and hazard communication, safety and health orientation and training, frequent worksite inspections, emergency response planning, record keeping and accident analyses, project-specific training and regular safety meetings, safety and health committees, substance abuse programs, safety manager on site, subcontractor selection and management, and employee involvement in safety and evaluation. Hallowell and Calhoun (2011) quantified the interrelationships between these 13 elements and concluded that the most central elements in an effective program were the site safety manager, worker participation and involvement, a site-specific safety plan, and upper management support and commitment. Another important conclusion was that many of the strategies found to be effective in isolation also provided a high level of synergistic effects that enhance the effectiveness of other elements.

In a review of 90 papers, Mohammadi et al. (2018) identified 13 factors influencing safety performance in construction: motivation, rules and regulation, competency, safety investment and costs, financial aspects and productivity, resource and equipment, work pressure, work condition, culture and climate, attitude and behaviour, lesson learned from accidents, organization, and safety programs and management systems. They also concluded that safety performance is not only determined by management activities within project levels, but also by the interactions among factors at different hierarchical levels.

Summarised, the research on safety management in construction shows several factors associated with safety performance. Some studies also show that certain combinations of factors increase the effect on safety performance. Based on a literature review, Mohammadi et al. (2018) suggested that more research is needed to investigate the interaction between the identified factors and determine how they are able to affect safety performance, which is one of the aims of this research.

The literature reviewed use different terms like safety management, occupational health and safety management, and safety programs. In this research, we use the term safety management to include all the terms.

4 Methodology

4.1 Type of research

Guthrie (2010) presents four main types of research; pure-, applied-, policy-, and action research. Pure research is concerned solely with scientific outcomes of interest to the scientist. Applied research is concerned with topics that have potential for practical application, but without a particular way of implementing the results. Policy research is based on practical issues of interest to those who make decisions about them. Action research is concerned with working on particular practices in order to improve them.

George and Bennett (2005) argue that one of the "chief goals" with political science is to provide policymakers with "generic knowledge", "that will help them form effective strategies" (ibid. p. 7). The same can be said about much safety science research, including this research. The position is in line with Hale (2014, p. 67), who writes that, for him "… safety science is an applied subject whose ultimate justification must be that it makes things in the field safer and healthier". The goal with this research is to contribute with knowledge that have potential for practical application and is based on practical issues of interest to decision makers in the construction industry (clients, contractors, workers' unions and authorities) and regulators (mainly the Labour Inspection Authority, NLIA). This research therefore mainly belongs to the applied- and policy research types as described by Guthrie (2010). Parts of it are mostly applied research, while other parts are mostly policy research. It is also an objective to contribute to knowledge in the field of research, and to employ, develop and document the methodological approaches employed to contribute to the development of research within the field.

4.1.1 Ontology and epistemology

Ontology is about what kinds of things there are, what it is made up of, what processes are going on, what are their properties, how do they interact and so on (Benton and Craib, 2011). Reason's (1997) model of organisational accidents (Figure 2) illustrates the ontology of this thesis. The upper part of the model is concerned with *what* happened and *how* it happened – the hazards, defences and injuries. These concepts are close to the empiricist traditions with its focus on energy, production and technology. The lower part of the model is concerned with *why* the defences failed, and focuses on the unsafe acts, workplace factors and organisational factors. This part is closer to the rationalist approach with the focus on humans' and organisations' intentions and actions, individually and within organisations.

Objectivism asserts that organisations and cultures influence individuals to comply with requirements and that the organisation can be a constraining force on individuals (Bryman, 2014). Organisations and cultures are seen as objective realities. Constructivism is an ontological position that "... asserts that social phenomena and their meanings are continually being accomplished by social actors" (Bryman, 2014, p. 29). In recent years constructivism also include the notion that "… the researcher always presents a specific version of social reality, rather than one that can be regarded as definitive (ibid.). The generations of safety models presented in chapter 2.3.4 illustrates that a version of the social reality cannot be seen as definitive. It is therefore important to have in mind that the models and approaches used in this thesis will develop and possibly be replaced. In this thesis, approaches and results are seen as having elements of both objectivism and constructivism and that there will be new generations of safety models and that the models will see further development.

Since this research is an applied- and policy type of research, it is based on a belief that there is a material world, that it can be studied, and that it is open to change based on knowledge. The social realists' commitment to changing unsatisfactory realities (Benton and Craib, 2011) is basic in safety science. Regarding organisations and organisational factors in safety, this research shares the view of social realism that: "Society and persons are distinct 'levels', both real, but interdependent and interacting with each other" (Benton & Craib 2011, p. 133).

Epistemology refers to the philosophy "… that investigates the possibility, limits, origin, structure, methods and validity (or truth) of knowledge" (Delanty and Strydon, 2003, p. 5). Since this research belongs to the applied- and policy research types (Guthrie, 2010), it builds on an epistemological view that science is "… the systematic attempt to express in thought the structures and ways of acting of things that exist and act independently of thought" (Bhaskar, 1975, p. 250 in Bryman, 2014, p. 25). There are however epistemological differences related to the ontology of the *what*- and *how*-questions, compared to the *why*-questions in Reason's (1997) model. It is easier to assess the *what*- and *how*-questions, than the *why*-questions. It is easier to judge that a person fell from height, compared to judging whether risk management was a contributory cause in an accident. More on this issue in chapter 4.4.1.

Causality is important to the ontology and epistemology of this research. Causality was problematic for the classical empiricists. Hume held that we have no impression of causation. Experience shows us one thing after another, connections between them are not experienced (Kasser, 2015). A basic ontological and epistemological belief in this thesis is that causality exists and can be studied and observed. Hinze et al. (1998) argue that accident prevention begins with having a clear understanding of factors that play key roles in causation. These views are largely in accordance with scientific realism.

Accident causality, risk management and safety management are often seen in terms of a hierarchy of system levels in safety (see e.g. Rasmussen, 1997; Reason, 1997; Hale, 2003a), where the; (1) operational (work) process at the lower level, being controlled by a; (2) combination of technology and human behaviour, which is in turn controlled by; (3) management provision of resources, information and instruction (Hale 2010). The thesis therefore shares the position that society is a "complex of mechanisms and processes constituted by the combination of mechanisms drawn from several of the other levels" (Benton and Craib, 2011, p. 129). This view is in harmony with Bhaskar's solution to the structure/agency problem, that "structures are causally efficacious in that the both enable and constrain actions" (Benton & Craib 2011, p. 133).

This type of research (applied- and policy research) is based on a pragmatic understanding of causality. The understanding of causality is in line with Ragin (2008) who states that a "causal condition" is used generically to refer to an aspect of a case that is relevant in some way to the explanation of the outcome. Causal factors in accidents and safety management is studied in article 3 and 4.

4.1.2 Qualitative and quantitative

Goertz and Mahoney (2012) treat the quantitative and qualitative traditions as loosely integrated alternative cultures, with its own values, beliefs and norms. They describe that quantitative research draws on mathematical tools associated with statistics and probability theory, while qualitative research is often based, explicitly or implicitly, on set theory and logic. The *data* used in article 1-3 were basically qualitative in that documents (notes, reports, letters) collected by the NLIA were analysed. The *approach* was quantitative in that data was collected from many cases using "variables" to quantify the frequency of categories regarding the accident sequence (e.g. accident types and barrier failures), and causal factors (e.g. unsafe acts and poor supervision). Article 1 and 2 were also quantitative in the sense that the main study sample was compared to other samples to estimate differences by using chi-square tests and correlation analysis (phi). Article 3 used a set-theoretic approach and correlations (phi) to study connections between different causal factors.

Article 4 was different from article 1-3 in that it combined different data collection techniques. Different methods (mixed methods) was combined to "cancel out" weaknesses by using only qualitative or quantitative techniques (Guthrie, 2010). In the study of safety management and safety performance in 11 construction projects (12 cases) we applied different types of data to study the issue by different angles: (1) numbers about project size (working hours), companies involved, injuries, injury rates and near accidents; (2) semi structured interviews with projects leaders and OHS experts; and (3) document analysis of safety and health plans, OHS inspection reports and OHS logs. The article also used Qualitative comparative analysis (QCA) (Ragin, 1987; Ragin, 2008), which fits quite well into a "mixed methods" design (Rihoux and Ragin, 2008). QCA is described in chapter 4.3.8. QCA is, however, not just a mixed-method approach. Most aspects of QCA require familiarity with cases, which in turn demands in-depth knowledge. At the same time, QCA is capable of pinpointing decisive cross-case patterns, the usual domain of quantitative analysis. So, QCA is an attempt to *bridge* qualitative and quantitative approaches.

4.1.3 Inductive and deductive strategies

One question underpinning most studies in safety science is; "Can we learn from past incidents and accidents in order to project useful predictions into the future"? (Le Coze et al. 2014, p. 3). The most popular models, metaphors, theories in safety science are from earlier studies of accidents and safety management. The logic is that we think we can use these models and theories to predict factors that with high probability will be a cause in future accidents. The problem of induction, described by Hume, is that such universal claims cannot be justified by logic (Benton and Craib, 2011) – we can never be certain that the factors will be the same in the future. Another problem in safety science is that the situations studied often are causally complex with many factors influencing the outcome that makes it difficult to predict the outcome with a high degree of certainty. Probabilistic inductive arguments are therefore widely used. This research has elements of both deductive and inductive strategies but is mainly inductive in that it attempts to draw "… generalizable inferences out of observations" (Bryman, 2016, p. 22). There are however also deductive elements in all articles since they employ analytical frameworks that is produced by previous research to see if there are similarities between the previous research and this research. All articles are however more *iterative* than inductive/deductive, since the process more precisely can be described as "… weaving back and forth between data and theory" (Bryman, 2016, p. 23).

4.2 Materials and sampling

4.2.1 Introduction

An overview of the research design, data collection, samples and data analysis for the thesis and the four articles is presented in Table 1. This chapter presents an overview of the materials and sampling in the four articles. More details are found in the articles. Discussion of the external validity is undertaken in chapter 4.4.2.

The objective of article 1-3 was to study the sequence of events and causal factors in construction accidents. To do that, we needed a certain number of accidents with sufficient details about the accidents. Many countries produce accident statistics based on reports to the welfare authorities, Labour inspection authorities, insurance companies etc. Many national accident surveillance systems do not, however, capture sufficient information to be used effectively for prevention (Gibb et al., 2014). They do not produce the necessary qualitative details for producing more in-depth knowledge about accident scenarios, barrier failures, worker actions and other causal factors that are necessary for prioritisations and developing measures. Cooke and Lingard (2011) argue that "National compensation-based statistics relating to work-related injury and death do not generally permit detailed analysis of causes beyond the identification of the mechanism (e.g., struck by moving object, fall from height) and agency of injury (e.g. mobile plant or transport). In order to guide prevention efforts, there is a need to better understand the causes of workplace injuries and deaths" (Ibid., p. 279).

Accidents investigated by the Norwegian Labour Inspection Authority (NLIA) was the only source available on construction accidents in Norway with a sufficient number of accidents, and sufficient details to study the accident sequence and causal factors. Narratives from investigations of accidents can be a good source of information about the accident sequence and causal factors: "Even with short narratives researcher generally have found information deduced from narrative data to be more accurate and complete than data about the same events as recorded in administrative sources" (Bondy et al., 2005, p. 374).

4.2.2 Article 1 and 3

Article 1 and 3 used the same sample which consisted of 176 mostly serious accidents (184 injuries) that was extracted from the NLIAs database. The employer's notification obligation in the Norwegian Work Environment Act says that: "If an employee dies or is seriously injured as the result of an occupational accident, the employer shall immediately and by the quickest possible means notify the Labour Inspection Authority and the nearest police authority" (Ministry of Labour and Social Affairs, section 5-2). "Serious injury" is defined as any harm, (physical or mental), that results in permanent or prolonged incapacitation. There is guidance on NLIA's website describing nine characteristics that indicate serious injury, e.g. injuries to head, skeleton, internal organs, loss of body part, poisoning, unconsciousness, metabolism/frost injury, hypothermia, and injuries that lead to hospitalisation (NLIA, 2018). When the NLIA is notified of an accident, the NLIA decides whether to complete an investigation based on assessments of potential severity and available inspectors. The criteria for selecting accidents for the main study sample were that (1) at least one construction company was involved, that (2) it happened during construction work, and (3) that it was inspected by the NLIA in 2015. Most construction accident statistics do not include workers employed by non-construction companies that are injured in construction accidents, e.g. temporary employment agencies. Criteria 1 and 2 ensure that these workers are included.

4.2.3 Article 2

The sample in article 2 consisted of 72 fatal injuries in 69 accidents that occurred 2011-2017. The sample was, like in article 1 and 3, extracted from the NLIAs database described above. There are however some differences between fatal- and non-fatal injuries. Regarding fatal injuries, the NLIA in addition captures fatal injuries not notified by the employer via other sources, mainly from health services, police or media or other sources. The number of fatal injuries is believed to nearly 100% complete.

To capture all construction fatalities, sampling was undertaken in three steps. First, all the 57 construction fatalities from the official statistics were registered. Second, three of the 57 fatalities were removed from the sample because the work carried out had nothing to do with construction. Third, to capture workers fatally injured in construction accidents not employed by construction companies, we analysed all fatal occupational accidents in the period to capture construction fatalities registered in other industries. We registered 18 workers fatally injured in construction accidents not employed by construction companies, that was included in the sample. So, the study sample consists of 72 fatal injuries (57-3+18) injured in 69 accidents. The workers not employed by construction companies represent 25% of the sample.

4.2.4 Article 4

The study was performed in cooperation with Statsbygg, a government client organisation. Statsbygg build and rehabilitate state public buildings, such as court buildings, prisons, museums and university buildings. Statsbygg is actively involved in safety management in projects and have project staff present at the sites and are following up production and OHS regularly. The sampling was carried out in dialogue with OHS experts in Statsbygg based on their familiarity with projects. The cases were selected based on three criteria:

(1) Projects initially assessed to have relatively high or low safety performance were selected, because it is advantageous to include cases with a "positive" or a "negative" outcome in comparative methods (Berg-Schlosser, De Meur, Ragin & Rihoux, 2009).

(2) Projects relatively similar in size (working hours), building type, and contractual arrangements were selected to keep these factors as constant as possible.

(3) Projects that were finished or more than halfway finished were selected making it possible to compare safety performance.

Materials from eleven different projects were collected. One project was much larger than the others. This project experienced many problems in the first part of the executions stage regarding project management and safety management. It was paused for some weeks and several measures were implemented to improve the management of the project. Since the two parts of the execution stage were very different regarding safety management, it was decided to analyse the project as two cases. The number of cases analysed is therefore 12. The data collection took place after the projects were finished, or in some cases more than halfway, making it possible to assess results from most of the construction period. It was therefore not practicable to use safety climate surveys or other leading indicators. Because of limitations in the safety indicators, and difficulties using leading indicators, we chose to do a researcher-based assessment of safety performance based on five sources. We also did a researcher-based assessment of safety management and contextual factors. The materials used are presented in Table 5.

Table 5. Materials used to assess safety performance, safety management and contextual factors.

Safety performance	Safety management- and contextual factors
The total recordable injury rate (TRI-rate).	The client's safety and health plan including roles, progress plans, measures, procedures etc.
Analysis of all registered dangerous situations (RUOs and SDs).	Log on OHS related information
Reports from OHS audits/inspections	Reports from OHS audits/inspections
Interviews with client project leaders about their assessments of the extent of hazards and dangerous situations relative to the project size.	Interviews with client project leaders about safety management and contextual factors
Interviews with OHS-inspectors about their assessments of the extent of hazards and dangerous situations relative to the project size.	Interviews with OHS-inspectors about safety management and contextual factors

4.3 Data analysis

An overview of the research design, data collection, samples and data analysis for the thesis and the four articles is presented in Table 1. This chapter presents the methodological approaches and techniques for analysing the data in the four articles.

4.3.1 Incident concentration-analysis

"Incident concentration-analysis" (Kjellén and Albrechtsen, 2017) is an approach to identify clusters of incidents with common characteristics, e.g. hazards, deviations, barrier failures, time and place. The approach was used in article 1 and 2 to identify concentrations of accident types and barrier failures and other key characteristics. The concentrations indicate where to prioritise safety measures and types of measures to prioritise. The approach is similar to "descriptive epidemiology", which seeks to summarise conditions based on person, place, and time by analysing the pattern of health outcomes (e.g. accidents) (Aschengrau and Seage, 2007).

Incident-concentration analysis in industrial settings is carried out in several "dimensions". The basic assumption is that each industrial system has its own clusters of accidents, mainly decided by the types of energies involved in the production. The steps in the incident concentration analysis used in this research were to:

1) Establish uni- and bi-variate distributions for different dimensions
2) Select concentrations making up a significant portion of the total number of records (e.g. 5-10 out of 50 records) with similar characteristics
3) Analyse these concentrations in more detail

4) Look for similarities in activities, sequence of events and energy involved.

4.3.2 Content analysis

To identify the incident concentrations, content analysis was used. The data in 1-3 and, and some of the data in article 4 is based on secondary data – documents and reportage based on accounts from NLIA inspectors and companies. Using documents requires content analysis. Content analysis is the systematic analysis of such data to infer meanings that are relevant to the research problem (Guthrie, 2010). We used different analytical frameworks to *classify* the data into categories and *evaluate* (interpret) the meanings of the content. For example, an accident type variable with 36 categories (Hale et al., 2007) was used to identify detailed accident types. Haddon's (1980) ten countermeasures strategies was used to classify barrier failures types. Trost and Nertney's (1995) categories was used to identify three barrier failure limitation types. And the ConAC framework (Haslam et al., 2005) was used to identify 23 types of causal factors. And we developed an analytical framework iteratively to identify 16 types of safety management factors and contextual factors connected to safety performance. These frameworks are described below.

4.3.3 Identifying accident types

There are several variables for categorising "accident types" (e.g. Eurostat and ILO), and each "accident type" is linked to a specific hazard. An accident type variable helps to identify how a hazard affects a worker. In Norway, the same accident type variable is used in the samples described above which makes it possible to compare the distributions of accident types across the samples. To identify more detailed accident types, a variable developed for occupational accidents by the WORM project (Workgroup Occupational Risk Model) in the Netherlands (Hale et al., 2007) was utilised. This variable is based on the bowtie and the aim behind the variable is to "… describe all types of occupational accidents in a set of generic descriptions, or scenarios, linking the development of each type of accident to the possible barriers …" (ibid. p. 1701). The objective behind the development of the variable was to support companies in their risk analysis and prioritisation of prevention. The variable has 36 different "scenarios" and is also used in the "Storybuilder" tool (Bellamy et al., 2007) and in a study of construction accidents in the Netherlands (Ale et al., 2008).

4.3.4 Identifying barrier failures and limitations

In article 1 and 2, Haddon's (1980) ten countermeasure strategies are used to identify barrier failures (Table 2). These strategies are not mutually exclusive, and combinations of measures are often recommended. Kjellén and Albrechtsen (2017) order Haddon's strategies (1980) so that the primary strategies are related to the hazard (energy source) (strategy 1-5), separation of the hazard and object (strategy 6, 7), and the vulnerable object (strategy 8-10) (Strategies 9 and 10 were beyond the scope of this analysis

We employed Trost and Nertney's (1995) three types to categorise limitations in barriers. One limitation is that *barriers are not practical* (NP) due to the energy source, cost of the barrier etc. Another limitation is that *barriers fail* (BF), for instance that physical barriers erode, and procedural barriers deteriorate through weak change control. A third limitation is when *barriers are not used* (NU). We also identified categories of barrier element failures (e.g. edge protection, roof collapse, objects inadequately attached) inductively based on the qualitative descriptions of the accident sequence in the material.

4.3.5 Identifying causal factors

In article 3, the ConAC framework was used to identify causal factors. Previous studies using the ConAC model found it problematic that the classification of factors was open to interpretation (Cooke and Lingard, 2011; Behm and Schneller, 2013), which was also our experience. Behm (2009) and Behm and Schneller (2013) developed operational definitions guided by previous research by Haslam et al. (2003; 2005). This study employed these definitions, but made some clarifications based on and how the terms were operationalised in this study and empirical findings.

Like the other studies using the ConAC framework, the researchers coded the accidents and their related factors based on their judgement of "reasonable confidence" that a factor was present in an accident (Haslam et al. 2005). Haslam et al. (2005) assess that the outer originating influences are rarely clearly identifiable in incident investigations. Therefore, like Behm and Schneller (2013), this study did not attempt to trace incident influences on these outer originating influences in the framework. This study employs the same 23 factors Gibb et al. (2014) employed when comparing the Australia, UK and US studies.

The method for using the ConAC framework was inspired by the methods described by Behm and Schneller (2013), adapted to the secondary data employed in this study:

1) Identify immediate circumstances (e.g., worker actions)
2) Identify the shaping factor(s) associated with the immediate factor (e.g., supervision)
3) Identify originating influence(s) influencing the shaping factor(s) (e.g., risk management)
4) Repeat the sequence for each immediate circumstance

A spreadsheet developed by Behm and Schneller (2013) was employed to describe how each factor was linked to the accident (Figure 6). The figure shows the part of the spreadsheet about the work team factors to illustrate the analysis process.

	Factor/Influence	How linked to accident?
☐	Work Team	
	☐ Communication	
	☐ Capabilities (knowledge/skill)	
	☐ Actions/behaviours	
	☐ Attitudes / motivations	
	☐ Supervision	
	☐ Health/fatigue	
	☐ Permanent works design	
	☐ Project Management	
	☐ Construction Processes	
	☐ Safety Culture	
	☐ Risk Management	

Figure 6. Spreadsheet developed by Behm and Schneller (2013) for identification of causal factors (Shows only the part of the spreadsheet about the work team factors).

Four analysts studied the documents related to the accidents. To ensure internal validity, quality assurance measures were carried out in five steps: (1) The first author (Winge) studied the previous studies and gave training to the others. (2) A few accidents were analysed according to the method described above by the analysts jointly before the accidents were divided among the analysts for reading documents and coding. (3) There were regular meetings of the analysts where accidents and factors were discussed. (4) After all the accidents had been assessed and coded, two analysts divided the accidents in two groups and carried out quality assurance of the coding of all the accidents (not accidents they had originally coded). (5) During analysis of the accidents, the first author compared the coding and recoded where there

4.3.6 Identifying safety management factors and contextual factors

In article 4, the analytical framework for measuring and comparing safety performance and the safety management factors in 12 construction projects, was developed in an *iterative* manner to facilitate a dialogue between theory and evidence as described by Ragin (2014). A preliminary framework was developed based on previous research, regulations and standards. The preliminary analytical framework was tested on documentation collected from eight projects and revised. The framework was also tested as interview guide for semi structured "pilot interviews" with three projects leaders (for client). After the interviews, the framework was revised to the final version with the 16 categories.

4.3.7 Set theory, *necessary* conditions and *sufficient* conditions

In article 3, we also identified causal connections between different factors, and in article 4 combinations of factors connected to safety performance. To assess causal connections between factors and outcomes, set theoretic approaches were employed.

Goertz and Mahoney (2012) argue that "… qualitative research is (often implicitly) rooted in logic and set theory" (p. 2). Set theory treats concepts as sets of categories in which cases can have membership. Concepts (e.g. worker behaviour or safety performance) "… are treated as categories in which particular cases may or may not have membership or have a certain degree of membership" (Goertz and Mahoney, 2012, p. 18). For a more comprehensive introduction to set theory and logic, see Schneider and Wagemann (2012).

One merit of the set theoretic approach is that it allows for assessing *necessity* and *sufficiency* of conditions in data sets (Table 6). In this approach the "independent variable" is called *condition* (X), and the "dependent variable" is called *outcome* (Y). To express that X is *sufficient* for Y, terms often used are "ensures", "guarantees", "is always followed by", "inevitably", "generates", and "produces". To express that X is *necessary* for Y, terms often used are "only if", "essential", "indispensable", "enables", "prevents", "permits", and "allows". The aim is often to construct a list of conditions that are individually *necessary* and jointly *sufficient* for an outcome.

A condition (X) is *sufficient* if, whenever it is present across cases, the outcome (Y) is also present (If X, then Y). Sufficient conditions can produce the outcome alone, but there are also other conditions with this capability. The logic behind *necessary* conditions can be viewed as the mirror image of that for a sufficient condition (Schneider and Wagemann, 2012). A condition (X) is necessary if, whenever the outcome (Y) is present across cases, the condition (X) is also present. A necessary condition must be present for the outcome to occur. The reasoning involved in identifying necessary factors is counterfactual – making an argument about what would have happened had this factor been otherwise (Hopkins, 2014).

Table 6. Description of sufficient and necessary conditions

Type	Description	Logic	Capacity	Terms	Examine cases that share same;	Attempt to identify their shared;
Sufficient	Whenever the condition is present, the outcome is also present	If X, then Y	Can produce the outcome alone	"only if", "essential", "indispensable", "enables", "prevents", "permits", "allows".	Conditions (X)	Outcome (Y)
Necessary	Whenever the outcome is present, the condition is also present.	If Y, then X	Must be present for the outcome to occur	"ensures", "guarantees", "is always followed by", "inevitably", "generates", "produces".	Outcome (Y)	Conditions (X)

Set-theoretic connections are often illustrated by Venn-diagrams where each circle represents cases with a given characteristic. Figure 7 illustrates from left to right that conditions (binary categories) can be; (1) sufficient (If X, then Y), (2) necessary (if Y, then X), (3) X as a sufficient and necessary condition, and (4) no connection.

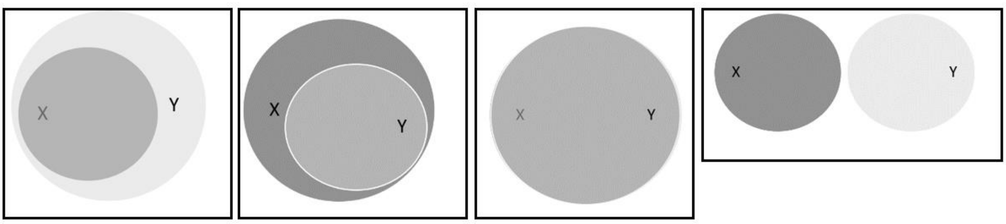

Figure 7. Venn diagrams illustrating (from left to right) (1) X as a sufficient condition (if X, then Y), (2) X as a necessary condition (if Y, then X), (3) X as a sufficient and necessary condition, and (4) no connection.

The connection between immediate supervision (X) and worker actions (Y) found in article 3 is used for illustration (Figure 8). Most (91%) of the immediate supervision-accidents (X) are also worker actions-accidents (Y). This gives support to the logical argument "if X, then Y", or if poor immediate supervision, then poor worker actions. X covers most (59%) of Y, indicating that the empirical relevance (coverage) is strong. The 59 accidents (41%) that are not X, indicate that X is not *necessary* for Y and that there must be other conditions that can also explain Y.

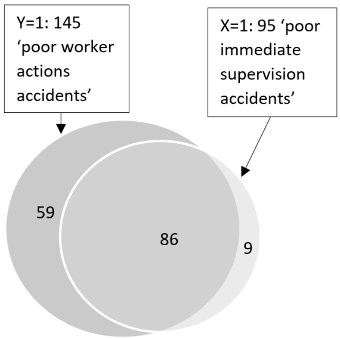

Figure 8. Venn diagram illustrating the connection between "poor immediate supervision" (X) (n = 95) and "poor worker actions" (Y) (n = 145).

In article 3, it was not possible to assess necessary and sufficient conditions for accidents as such, since variation in the outcome (dependent variable) is necessary to do that, and there are no "non-accidents" in the material. However, causal connections between factors in the ConAC framework were assessed, for instance, which factors that influence worker actions and local hazards.

	Causal conditions absent (X=0)	**Causal condition present (X=1)**	
Outcome present (Y=1)	A	B	
Outcome absent (Y=0)	C	D	

Figure 9. Two-by-two table

For binary variables, the assessment of sufficiency and necessity of conditions are carried out in two-by-two tables. If a condition is sufficient, there are cases in cell B and no cases in cell D (Figure 9). The logic behind necessary conditions can be viewed as the mirror image of that for a sufficient condition (Schneider and Wagemann, 2012). A condition (X) is necessary if, whenever the outcome (Y) is present across cases, the condition (X) is also present. A necessary condition must be present for the outcome to occur. If a condition is necessary, there are cases in cell B, and no cases in cell A (Figure 9). Table 6 summarises the strategies for assessing sufficiency and necessity.

In data sets, connections between factors are rarely perfectly consistent. Some cases will usually deviate from the general patterns so that conditions can be quasi-necessary or quasi-sufficient (Legewie, 2013). Consistency and coverage are parameters used to assess how well the cases in a data set fit a relation.

The calculation of consistency is described in Table 7. *Consistency* resembles significance in statistical approaches where 0 indicates no consistency and 1 indicates perfect consistency. The consistency value for conditions should be higher than 0.75 (Schneider and Wagemann, 2012). If a relation is established to be consistent, the coverage should be calculated. *Coverage* assesses the degree to which a condition accounts for instances of an outcome, or empirical relevance (Ragin, 2008). The analogous measure in statistical models would be r^2, the explained variance contribution of a variable (Thiem, 2010), with values between 0 and 1.

Table 7. Assessing consistency and coverage for sufficient and necessary conditions. Based on Ragin (2008) and Schneider and Wagemann (2012).

Sufficiency				Necessity			
	X=0	X=1	Coverage		X=0	X=1	Consistency
Y=1	A	B	B/(A+B)	Y=1	A	B	B/(A+B)
Y=0	C	D	-	Y=0	C	D	-
Consistency	-	B/(B+D)	-	Coverage	-	B/(B+D)	-

Why did we choose a set theoretic approach to study connections between factors? One merit of this approach that it allows for assessing sufficiency and necessity. Ragin (2008) argues that "correlations is a good tool for studying general cross-case tendencies" (p. 21) but "attends only to relative differences" and "conflates different kinds of causal assessment" (p. 22). He demonstrates that a correlational analysis in a 2x2 cross table can be deconstructed into two asymmetric set-theoretic analysis, one focussing on sufficiency, the other on necessity. The correlation focuses simultaneously and equivalently on the degree to which instances of the cause produce instances of the outcome (the number of cases in cell B relatively to the sum of values in cells B and D) *and* on the degree to which instances of the absence of the cause are linked to the absence of the outcome (the number of cases in cell C relative to the sum of cases in cell A and C) (Figure 9). The phi coefficient is a correlation coefficient for two binary variables. Two binary variables are considered associated if most of the data fall along diagonal cells. Ragin (2008) also concludes that empirical evidence can give strong support to a set-theoretic argument despite a relatively modest correlation.

4.3.8 Qualitative comparative analysis (QCA)

In article 4 we aimed at identifying how safety management factors, contextual factors, and combinations of factors, were associated with safety performance by studying 12 construction projects. We employed Qualitative comparative analysis (QCA) (Ragin, 1987; Ragin, 2008), which is an approach for comparing cases, producing case knowledge and identifying associations between conditions (causal factors) and the outcome. QCA is an approach that attempt to bridge qualitative and quantitative analysis. QCA has gained increased in popularity in recent decades, especially in the disciplines of comparative politics, business and economy, sociology, and management and organisation (Roig-Tierno et al., 2017). Comparative studies of "good" and "bad" construction projects is also an opportunity to study both what goes wrong (safety I) and what goes right (safety II) in safety management in construction projects (Hollnagel, 2014).

The number of conditions in QCA must be kept quiet low; three to eight conditions are recommended (Ragin, 2008). The problem is that as the number of binary conditions increases, the number of possible combinations of these variables increases exponentially, so-called limited diversity (Ragin, 1987). One strategy for including more conditions is to conduct separate QCAs for different sets of conditions (Gerrits and Verweij, 2018). We decided to conduct two QCAs, one including "contextual conditions" and one for "safety management factors".

QCA is a set-theoretic approach (described above) where concepts are understood as sets in which cases have membership. There are two types of sets. So far, we have described crisp sets (binary categories). Crisp sets allow only full membership (1) and full non-membership (0). The other type of sets, is a fuzzy set. Fuzzy sets allow for partial membership in addition to full membership and non-membership where the point of maximum ambiguity (fuzziness) is .5. A fuzzy set can be seen as a continuous variable that has been calibrated to indicate degree of membership. Researchers must use substantive and theoretical knowledge to calibrate membership. In this research we used both crisp sets and fuzzy sets.

As QCA is a relatively new technique, we explained its basic logic and steps in article 4 (for a detailed treatment of QCA, see Ragin, 2008, and Schneider and Wagemann, 2012). Data analysis was performed using the fsQCA 3.0 for Windows software (Ragin and Davey, 2017) and its software manual (Ragin, 2017).

4.3.8.1 Causal complexity

The aim of a set theoretic approach studying necessary and sufficient conditions is often to construct a list of conditions that are individually *necessary* and jointly *sufficient* for the outcome (Sartori, 1970, in Goertz and Mahoney, 2012). One merit with QCA is that it is designed to study causal complexity (Ragin, 2008). And it is assessed to be very well suited to researching complexity, for example construction projects (Gerrits and Verveij, 2018). There are three aspects of causal complexity: (1) There can be multiple conditions that are necessary for the outcome. (2). A combination of *necessary* conditions (configuration) can be *sufficient* for producing the outcome. (3). There can be multiple configurations that can produce the outcome (equifinality). This is illustrated in Figure 10.

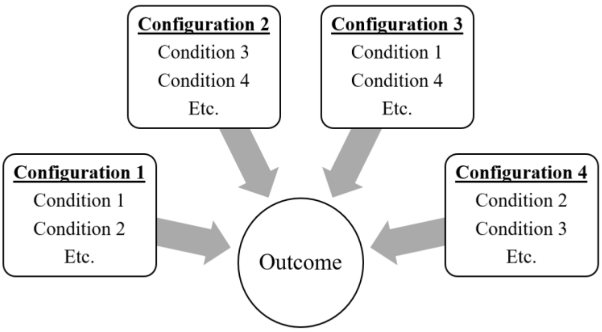

Figure 10. Illustration of causal complexity: That multiple necessary conditions (configurations) can be sufficient for producing the outcome, and that there can be several sufficient configurations (equifinality).

The set theoretic thinking is (often implicit) central in much safety science research. Reason et al. (2006) and Hopkins (2014) argue that accidents in complex systems occur through the interaction of multiple factors, where each may be *necessary* but where they are only jointly *sufficient* to produce the accident. No failure, human or technical, is sufficient alone to cause an accident. Hopkins (2014) writes that necessary factors is the basis of the Swiss cheese model: "An accident occurs because the holes in the barriers all line up. Had any one of the barriers operated as intended, the accident would not have happened. Each of the barrier failures was thus necessary for the accident to occur" (p. 11).

The aim of QCA analysis is to identify combinations of conditions that are *sufficient* for the outcome (if X, then Y). This process requires six steps:

Table 8. Steps in Qualitative Comparative Analysis (QCA)

N	Task	Description
1	Calibration	Use substantive and theoretical knowledge to calibrate membership for conditions and outcome
2	Raw data matrix	Produce a raw data matrix where outcome and conditions are calibrated for each case
3	Truth table	Produce truth tables for the occurrence and non-occurrence of the outcome where each row in the truth table represents one logically possible configuration.
4	Minimising the truth table	Minimise the number of rows for each truth using logical minimisation (Quine-McCluskey Algorithm) and produce the solution formula.
5	Parameters	Reporting the parameters of fit (consistency and coverage) for the solution formula
6	Interpretation	Interpret the results

4.3.8.2 Raw data matrix and truth tables

The truth table is at the core of QCA. A truth table lists all possible logically possible configurations. We use one of the truth tables from article 4 as example (Table 9). The outcome is Safety Performance (SP), and the causal conditions are Construction Complexity (CC), Organisational Complexity (OC), Contract Management (CO), and Operative Risk Management (RM).

Each row in the truth table represents one logically possible configuration (Ragin, 1987). The fuzzy conditions need to be dichotomised to match calibrated fuzzy cases into a truth table. A fuzzy set score below 0.5 is dichotomised to 0, and a fuzzy set score above 0.5 is dichotomised to 1. The truth table shows the configurations as dichotomies, but the calibrated cases remain fuzzy. Since we include four conditions that can score either 0 or 1, there are 16 logically possible combinations of the four conditions. The truth table for the outcome *high* safety performance shows that there are cases in eight out of the 16 possible configurations. Column number 2-5 indicate the qualitative status of the four conditions (present 1 vs. not present 0). Column "SP" indicates whether the given row is sufficient for the outcome "high safety performance" (score of 1) or not sufficient (0). The decision about sufficiency is based on each row's consistency score ("Cons."). Consistency expresses the degree to which empirical evidence supports the claim that a set-theoretic relation exists. Values below 0.80 indicate substantial inconsistency. This yields four rows which include six cases that are considered *sufficient* for high safety performance, and four rows including six cases that are considered *not sufficient* for high safety performance. The "Cases" column shows the labels of cases that are members of a given row.

Table 9. Truth table for contextual conditions with high safety performance.

Row	CC	OC	CO	RM	SP	Cons.	Cases
1	1	1	1	1	1	0.93	A
2	1	1	0	1	1	0.90	D
3	0	0	1	1	1	0.90	B, F
4	0	1	1	1	1	0.88	C, E
5	1	1	0	0	0	0.65	K
6	0	0	1	0	0	0.65	J
7	0	0	0	0	0	0.52	G, H, I
8	0	1	0	0	0	0.40	L

A separate QCA is carried out for the occurrence and non-occurrence of the outcome because the concepts often contain various qualitatively different notions, so-called causal asymmetry (Ragin, 2008).

4.3.8.3 Logical minimisation

After truth tables have been produced for the occurrence and non-occurrence of the outcome, the rows of each truth table can be made simpler using logical minimisation (Quine-McCluskey Algorithm): "If two Boolean expressions differ in only one causal condition yet produce the same outcome, then the causal condition that distinguishes the two expressions can be considered irrelevant and can be removed to create a simpler, combined expression" (Ragin, 1987, p. 93).

4.4 Scientific quality

This chapter addresses key issues regarding scientific quality. See also the discussion regarding limitations in the articles and chapter 6.4.

4.4.1 Internal validity

Since identifying causal factors and connections/associations are at the core of this research, internal validity is an important quality criterion. In qualitative research, internal validity is about establishing the right causal relationships (Yin, 2003), while in quantitative research internal validity is determined by how well a study can rule out alternative explanations for its findings (Bryman, 2014).

Regarding causal factors, Kjellén and Albrechtsen (2017) describe two methods for identifying causal factors; analytic methods and expert judgements.

Analytic methods are used when there are logical relations among the factors (Kjellén and Albrechtsen, 2017). Analytical methods are fact-based and held to be objective. Hopkins (2014) argue that the reasoning involved in identifying *necessary* factors is counterfactual, and that in some instances it is a matter of logic, for example when technical causes are involved. The identification of accident types and barrier failure types in article 1-3 were in most cases relatively straightforward to identify based on the descriptions of the accident sequence made by the labour inspectors. It is for example, in most cases, clear that the injured person was for example falling from height, hit by a vehicle, or that edge protection was lacking, or that equipment broke.

Expert judgements are subjective judgements used to identify and interpret causal factors when "objective facts" are lacking. Cause is not something you find, but something you construct (Dekker, 2014) Expert judgements normally must be made regarding unsafe acts, workplace factors and organisational factors. Such causal connections become probabilistic statements rather than logical deductions (Hopkins, 2014). For example, we can judge that better planning of the operation *probably* would have prevented the accident (article 3), or that better risk management would probably have produced better safety performance (article 4).

In article 3 we, like Haslam et al. (2005), coded the accidents and their related factors based on a judgement of "reasonable confidence" that a factor was present in an accident. We experienced that it was easier to identify factors at the sharp end on site than at the blunt end of, for example, project management or design. Like Haslam et al. (2005), we judged that the outer originating influences are rarely clearly identifiable in incident investigations. Therefore, like Behm and Schneller (2013), this study did not attempt to trace incident influences the outer originating influences in the framework (see Figure 3).

Using checklists is a method for ensuring that "all" relevant causal factors are considered (Kjellén and Albrechtsen, 2017). Several checklists have been applied in the articles. A limitation in using checklists/analytical frameworks is that the framework employed, and the factors included will influence the outcome. Lundberg et al. (2009) has expressed this as "What-you-look-for-is-what-you-find". One of the reasons for using the ConAC framework in article 3 was that it is holistic, include relatively many factors, and that the operational definitions of the factors are broad, including many aspects. To increase internal validity, the operational definitions created by Behm and Schneller (2013) were used and described in more detail from this study. A limitation using accident data collected by others (inspectors and companies), is that some issues are not investigated and are underestimated, for example design, housekeeping and fatigue.

In article 3 quality assurance measures were carried out in five steps to improve internal validity, including training of researchers, analysing a few accidents jointly, regular meetings between researchers, quality assurance of the coding of all the accidents by two researchers, and quality assurance and recoding (when discrepancies) during analysis.

The methods employed for assessing connections between factors in article 3 do not necessarily confirm causation. In the analysis, connections were established from an immediate factor to a shaping factor, and from the shaping factors to originating factors. However, there are many connections in the data set that are not validated in this way. To establish likely causal connections, it is necessary to study each connection in depth using other methods like for example process tracing (e.g., Goertz and Mahoney, 2012; George and Bennett, 2005).

The QCA approach employed in article 4 also do not confirm causation between the conditions and the outcome. However, since there were relatively few cases, it was possible to trace the causal process more in depth than in the accident studies, using process tracing (see Goertz and Mahoney, 2012; George and Bennett, 2005). The combination of several data sources and methods by triangulation (Denzin, 1970) and mixed methods (Tashakkori and Teddlie, 2010) was judged to increase the internal validity in article 4.

Regarding measurement of safety performance, there is much evidence of under-reporting of workplace injuries (Shannon et al., 2001) and health and safety indicators can be subject to manipulation and misinterpretation (Oswald et al., 2018). Great care therefore needs to be taken when using safety indicators to evaluate organisational safety policy and practices. Therefore, interviews, document and researcher assessments (triangulation) were also undertaken to assess safety performance.

4.4.2 External validity

It is preferable for a scientific study to give knowledge about something more and beyond its immediate case study (Coffey and Atkinson, 1996; Yin, 2003). The goal in qualitative research is to generalise the findings to a theoretical proposition rather than a specific population (Yin, 2003, p. 10). To what extent can the results be generalised?

Available documentary data often do not meet formal sampling requirements, and identification of the entire population can therefore be difficult (Guthrie, 2010). To assess the representativeness of the study sample used in article 1 and 3 regarding accident types, the sample was compared to four other construction injury samples representing different degrees of severity (Table 10). The results showed that the main study sample was significantly different from the other three samples regarding accident types, and hence not representative for accidents with high or low injury severity. The analysis showed that the distribution of accident types varied across the samples regarding severity, construction types and probably other characteristics. It is therefore problematic to assess external validity by comparing the sample to other samples representing different severity. We can therefore not talk about *one* sample of construction injuries. The short answer regarding external validity is therefore that we do not know the representativeness of the sample. One strength about the sample is however that it included all accidents investigated by the NLIA for one year and the number of accidents is relatively large. The sample thus provide a reasonable picture of the nature of relatively serious construction accidents and injuries.

Table 10. Overview of samples of injuries in the Norwegian construction industry

Sample name	Description	Data period	Injuries in the sample	Number injuries per year	Estimated average severity (order)
"Main study sample"	Accidents investigated by the NLIA in 2015	2015	184 (176 accidents)	-	Medium/high (2)
"Fatal"	Fatal injuries	2000-2014	131	10 (average 2012-2016)	High (1)
"Inspection"	Injuries reported to the NLIA	2011-2016	1758	293 (average 2011-2016)	Medium (3)
"Insurance"	Injuries (insurance claims) reported to the Labour and Welfare Administration (LWA)	2015	1783	1 783	Medium (4)
'survey"	Labour force survey (LFS) 2013	2013	41	9 000 - 10 000	Low (5)

The main study sample in article 2 was 69 fatal construction accidents that occurred 2011-2017. One limitation with the official construction accident statistics in Norway, and many other countries, is that it includes only workers employed by construction companies. Measures were therefore taken to include fatalities involving hired workers employed by temporary employment agencies or workers from other industries doing work at construction projects. We identified 18 workers fatally injured in construction accidents, not employed by construction companies, that was included in the sample. They represent 25% of the sample. It is assumed by the NLIA that almost all occupational fatal injuries are captured in NLIAs database. It can therefore be argued that the sample is almost 100% representative since it includes "all" construction fatalities in Norway for the period.

In article 4, 12 construction projects were studied. The study was performed in cooperation with Statsbygg, a Norwegian government client organisation who build and rehabilitate public buildings. Statsbygg is a large client, building many large buildings, and mostly a have a strong safety performance. The client and projects are therefore not "representative" of construction projects. The purpose of the research was hence to generalise the findings to a theoretical proposition rather than a specific population (Yin, 2003).

4.4.3 Reliability

Reliability is defined as the ability to replicate the same results using the same techniques. In qualitative research, this largely involves describing the data gathering and all parts of the project so thoroughly that any reader could understand what has been done and how the findings and conclusions were reached (Yin, 2003).

There are many judgements and assessments made by the researchers based on data in this research. We have been very conscious about our role in data collection, analysis, interpretation and describing the results. It is no doubt that the researcher background, experience, values etc. can influence the results.

Several analytical frameworks have been used in this research. In order to increase reliability, data collection, core concepts, analytical frameworks, analysis methods and techniques are described with sufficient detail in the articles so that it should be possible to replicate them. This is especially important regarding judgements about causal influences (see chapter 4.4.1).

In article 1 and 2 we used frameworks for categorisation of data for accident type variables (Hale et al., 2007), countermeasure strategies (Haddon, 1980) and barrier limitations (Trost and Nertney, 1995) that are described in the articles and referred to so that it is possible to replicate the studies. In article 3, we used the ConAC framework (Haslam, 2005). Like previous studies, we found it problematic that the classification of factors was open to interpretation. We therefore used and developed further operational definitions described by Behm (2009) and Behm and Schneller (2013) and described them in article 3. This makes it easier for future research using the ConAC framework and easier to replicate previous research. In article 4, we developed an analytical framework based on several previous studies, where operational definitions of the factors, based on previous studies and our research, were described, which make them possible to replicate.

5 Results

In this chapter, a review of the main results of the four research articles are presented. The review is the basis for the discussion of the main findings in the next chapter.

5.1 Article 1: Accident types and barrier failures in 176 accidents

5.1.1 Accident types and construction types

The findings related to the first research question are published in article 1 and 2. In article 1, the main study sample of 176 accidents/184 injuries investigated by the NLIA (relatively serious), the most frequent accident types were fall (48%), hit by object (24%), and cut by sharp object (13%). The main study sample was compared to four other samples of construction injuries representing different degrees of severity (fatal injuries; all injuries reported to the NLIA; injuries reported to the welfare authorities; and a survey based on interviews of a representative sample of workers). The results showed that accident types were distributed significantly different across the samples, indicating a relation between severity and accident types.

The coarse accident type variables employed to compare the five samples is too coarse for precise prioritisations. It was, for example, important to identify how and where the 48% injured workers in fall accidents occurred, whether they fell from for example scaffolding, ladders, or floors. To identify more detailed accident types, an accident type variable with 36 different categories developed by the WORM project (Hale et al., 2007) was employed. The most dominant accident types were different types of fall accidents, contact with falling objects, and contact with moving parts of machine (Table 11). The distribution of accident types for injuries in the main study sample (N=184) was compared to fatal injuries (year 2000-2014, N=131). The main difference between the two samples was that many accidents in the main study sample (non-fatal) were related to tools and machines (e.g. saws, angle grinders, and nailing machines), working in height, and flying/ejected objects (e.g. piece of wood or nails), while many of the accident types in the sample of fatal injuries were related to large falling objects (for instance rocks or concrete elements), explosions, and large vehicles. The results showed that the differences in accident types between the study sample and fatal accidents can be explained by differences in types of work and type and amount of energy involved.

The distribution of the accident types was also significantly different across construction types. In *Building*, the most frequent accident types found were fall from height (roof/floor/platform and scaffold), hit by objects (equipment and materials), and cut by sharp object (mainly saws). In *Civil Engineering,* the most frequent accident type was hit by object (mostly heavy objects like concrete slab/block, rocks, poles and plates), fall from height (scaffolds, platform, lift, beam, and into a hole), and accidents involving blasting, trench collapse, and dump trucks. *Civil Engineering* had a larger proportion of fatalities/likely fatalities than the other construction types, suggesting that the hazards involved in *Civil Engineering* accidents are different from the other construction types and that there are often large amounts of energy involved. The accidents in *Engineering Construction* were similar to accidents in *Building*. In *Refurbishment*, there were many falls from height (66%), mostly falls through the roof and from scaffolding structures. The differences in accident types can be explained by the different types of construction work an hazards involved in the different construction types.

5.1.2 Barrier failures

The seven most frequent accident types described above were analysed more in depth, identifying more detailed patterns of scenarios and barrier failures (Table 11). For example, the most frequent important barrier element failures for the 30 falls from roof/floor/platform was openings/holes in structures, lack of edge protection/fall arrest, and collapse of roof/floor. The analysis using Haddon's (1980) countermeasure strategies, demonstrated that there were many missed opportunities for implementing these strategies at different stages in the accident process.

The analysis of barrier failures showed that many accidents are explained by the lack of physical barrier elements. The results indicate that there is significant potential for accident prevention in the construction industry by systematic barrier management.

Table 11. The seven accident types and central barrier element failures related to Haddon's strategies (1980) and barrier limitations (N=138 accidents and 169 barrier element failures). (NU=Not used. F=Partial or total failure. NP=Not practical. LE=Latent error. HE=Human error).

Accident type	n.	Central barrier element failures	n.	Haddon	Limitation
Fall from roof, floor, platform	30	Opening/hole in structure	12	7	NU
		Edge protection/fall arrest	9	7	NU
		Floor/roof collapse	4	4	F (LE)
Fall from scaffold	26	Floor deficiency	8	4	F (LE)
		Edge protection/fall arrest	6	7	NU
		Working on the outside of the scaffold or on/under railing	6	7	F (HE)
		Scaffold moving, overturning, collapsing	6	4	F (LE)
Contact with falling objects	25	Workers in the danger zone	25	6	F (HE)
		Objects inadequately attached	12	4	F (HE)
		Loss of control of load/equipment	6	4	F (HE)
		Lifting equipment broke	4	4	F (LE)
Contact with moving parts of a machine	21	Loss of control of saw/material	7	4	F (HE)
		Used hand instead of push stick	4	6	F (HE)
		Worker inattentive and "bumped into" the blade	4	7	F (HE)
		Condition of saw/saw arrangement inadequate	3	4, 7	NU
Hit by object during lifting	14	Workers in the danger zone	14	6	F (HE)
		Loss of control of the load	7	4	F (HE)
		Edge protection (working in height)	5	7	NU
		Lost control of crane	3	4	F (HE)
		Lifting equipment broke	3	4	F (LE)
Fall from ladder	13	Ladder not attached	10	4	NP
Fall from height – unprotected	9	Unprotected	9	7	NU
Total	138	Total	169	-	-

In summary, the most frequent accident types in the sample included: fall from roof, floor or platform; contact with falling objects; fall from scaffold; and contact with moving parts of a machine. A comparison of the study sample to other injury samples, showed that the distribution of accident types varied regarding severity and different construction types. This can be explained by differences in work type, hazard, and energy type and energy amount. The analysis of barrier failures showed that in many accidents there were no physical barrier elements, and that in other accidents there was only one physical barrier element, that failed.

5.2 Article 2: Accident types and barrier failures in fatal accidents

The results in article 1 showed that the distribution of accident types varied for different samples of injuries representing different severity. The purpose of article 2 was therefore to: (1) identify detailed accident types for fatal injuries; (2) identify barrier failures and unsafe acts related to the most frequent accident types; (3) compare the fatal accident types to non-fatal accidents types (from article 1), and (4) compare fatal accident types in different parts of the construction industry.

Figure 11 shows accident types using the accident type variable developed by the WORM project (Hale et al., 2007). There are differences between the fatal and non-fatal accident types. There were more fatal injuries among the vehicle accidents, working at height unprotected, and explosions. And there were more non-fatal injuries among fall from roof/platform/floor/ladder/scaffold, contact with moving parts of machine and contact with flying/ejected objects.

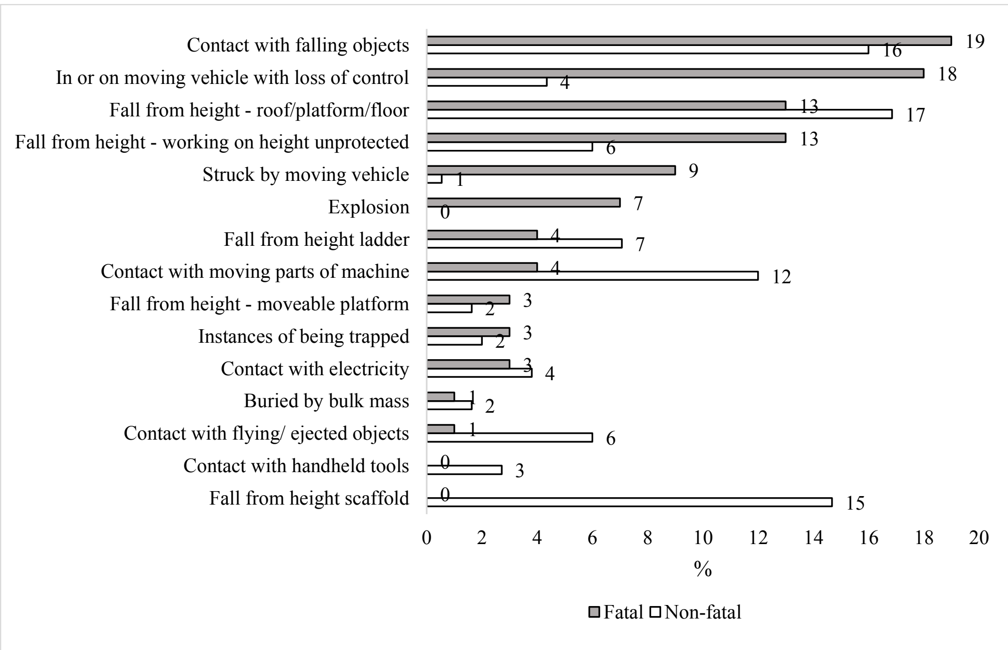

Figure 11. Most frequent accident types (%) for fatal injuries (N=68*) compared to non-fatal injuries (N=179*). (*Accidents categorised as "other" was removed from the calculations).

"Unsafe acts" by frontline workers were identified in 58 accidents, latent failures without unsafe acts by frontline workers in four accidents, while in seven accidents there was not sufficient information to assess unsafe acts. This means that unsafe acts were involved in 94% of the accidents where we had sufficient information to assess unsafe acts. Most of the unsafe acts were about deciding to carry out dangerous jobs without adequate safety barriers.

Table 12 shows the results of an analysis of the six most frequent fatal accident types, the number of accidents where unsafe acts were involved, and central barrier element failures. Multiple barrier element failures were identified in many accidents. The table shows that unsafe acts was involved in almost all of the accident types, that each accident type has its specific barrier element failures, and that the most frequent barrier failures are Haddon's number 4 (prevent sudden release of the hazard), 5 (modify the energy when it has been released), 6 (separate hazard and victim in time/space), and 7 (separate hazard and victim by physical means). Each of the six accident types, its characteristics, barrier failures and unsafe acts were analysed in detail.

Table 12. The six most frequent accident types, number of accidents (and injuries), number accidents with unsafe acts, central barrier element failures (Haddon, 1980), frequency of the barrier element failures (n), type of barrier failure related to Haddon (1980), and barrier limitations (Trost and Nertney, 1995). (NU=Not used. BF=Partial or total failure. NP=Not practical).

Accident type	Accidents and number of fatalities in parenthesis (n)	Accidents with unsafe acts (n)	Central barrier element failures	n.	Haddon	Barrier limitation
Contact with falling objects	13 (13)	11	Workers in danger zone	12	6	NU
			Collapse of structure	4	4	BF
			Technical failures	2	4	BF
In or on a moving vehicle with loss of control	12 (12)	10	No physical barriers preventing the vehicle from driving out	6	7	NU/NP
			Driver losing control of vehicle	5	4	BF
			Surface (unstable, slippery)	4	4	BF
			Seat belt not used	3	5	NU
Fall from height – roof/platform/floor	9 (9)	9	Fall protective equipment not used	4	5	NU
			Edge protection	3	7	NU
			Collapse of structure	2	4	BF
Fall from height – unprotected	8 (9)	7	No physical barrier preventing fall	6	7	NU
			Fall protective equipment not used	5	5	NU
			Collapse of structure	2	4	BF
Struck by moving vehicle	6 (6)	6	Workers in danger zone	6	6	NU
			Technical failures	2	4	BF
Explosion	3 (5)	2	Elimination of hazard	3	1	BF
Total	51 (53)	45	-	69	-	-

A comparison of the fatal- and non-fatal injuries across four construction types showed significant differences (Chi square: x2(4)=43.126, p≤.000). The Phi coefficient was .415 (p≤.000), showing a moderate strong connection between construction type and injury consequence. The results showed for example that more than half of the fatal injuries occurred in Civil Engineering, while almost half of the non-fatal injuries occurred in Building.

Another analysis showed large differences in accident types across the construction types. For example, fall dominated in Building and Engineering Construction, while bumping, crash, collision dominated in Civil Engineering.

5.3 Article 3: Causal factors in construction accidents

One limitation of article 1 and 2 was that they focused mainly on the hazards (accident types) and defences (barrier failures) (the *how* and *what* questions), and little on the causal factors at the workplace level and organisational level (see Figure 2). The purpose of article 3, *Causal factors and connections in construction accidents* (Winge, Albrechtsen and Aamnes Mostue, 2019), was to identify frequent causal factors at different hierarchical levels using a holistic accident causation model developed for construction accidents. The accident model employed, the ConAC model (Haslam et al. 2003; 2005), was presented in chapter 2.3.3.

Figure 12 summarises factors identified using the ConAC framework. In total, 1.039 causal factors were identified in the 176 accidents, an average of 5.9 factors per accident. There were on average 2.7 immediate factors, 1.8 shaping factors and 1.5 originating factors per accident. The left side of Figure 12 shows that worker- and team factors were identified in 90% of the accidents, site factors in 55%, material- and equipment factors in 56%, and originating influences in 66% of the accidents. The right side of the figure shows the percentage of accidents where the detailed factors were identified. Seven of the factors were identified in more than 30% of the accidents: the immediate factors worker actions, worker capabilities, usability of materials or equipment, and local hazards; the shaping factor immediate supervision; and the originating factors project management and risk management.

Figure 12. Percent of causal factors identified in 176 accidents (several factors possible for each accident). (White=immediate factors. Black=Shaping factors. Stripes=Originating influences).

5.3.1 Connections between factors

There is an abundance of possible connections between the 23 factors in this material, but all were not theoretical plausible. We used a set theoretic approach to identify consistent connections between the factors (see chapter 4.3.7).

Conditions and outcomes of frequent causal factors were analysed. Table 13 shows connections that were: theoretically plausible; consistent (> .75); empirically relevant (coverage > .30); involve the most frequent factors; and do not include factors that include same type of characteristics. Seven factors were identified as "sufficient", but not "necessary", for worker actions. Four of the factors also show a positive correlation, indicating a symmetric relationship between the factors. Figure 13 simplifies and summarises the seven most frequent causal factors identified, and causal conditions that are consistent and empirically relevant.

Table 13. Connections between factors in rank order by coverage (empirical strength) (N=176). n=cases where both factors are present. Consistency > .75. Coverage > .30. S/N=Sufficient/Necessary. Correlations (*phi*).

Condition (X)	Outcome (Y)	n.	Consistency	Coverage	S/N	R.*	Sig.
Risk management	Immediate supervision	77	.79	.81	S/N	.553	.000
Immediate supervision	Worker actions	86	.91	.59	S	.231	.002
Risk management	Worker actions	86	.88	.59	S	.158	.036
Project management	Immediate supervision	49	.86	.52	S	.444	.000
Usability of materials or equipment	Worker actions	66	.89	.46	S	.152	.044
Local hazards	Worker actions	59	.83	.41	S	n.s.	n.s.
Immediate supervision	Work scheduling	38	.90	.40	N	.410	.000
Risk management	Construction processes	37	.84	.38	N	.330	.000
Worker capabilities	Worker actions	51	.91	.35	S	.156	.039
Project management	Worker actions	50	.88	.34	S	n.s.	n.s.
Risk management	Work scheduling	33	.79	.34	N	.258	.001
Knowledge/skills	Worker actions	46	.90	.32	S	n.s.	n.s.

*Correlations (phi): $p < .05$. Strength R: weak (0-.0.3), moderate (0.3-0.6), and strong (0.6-1.0). n.s. = Not significant.

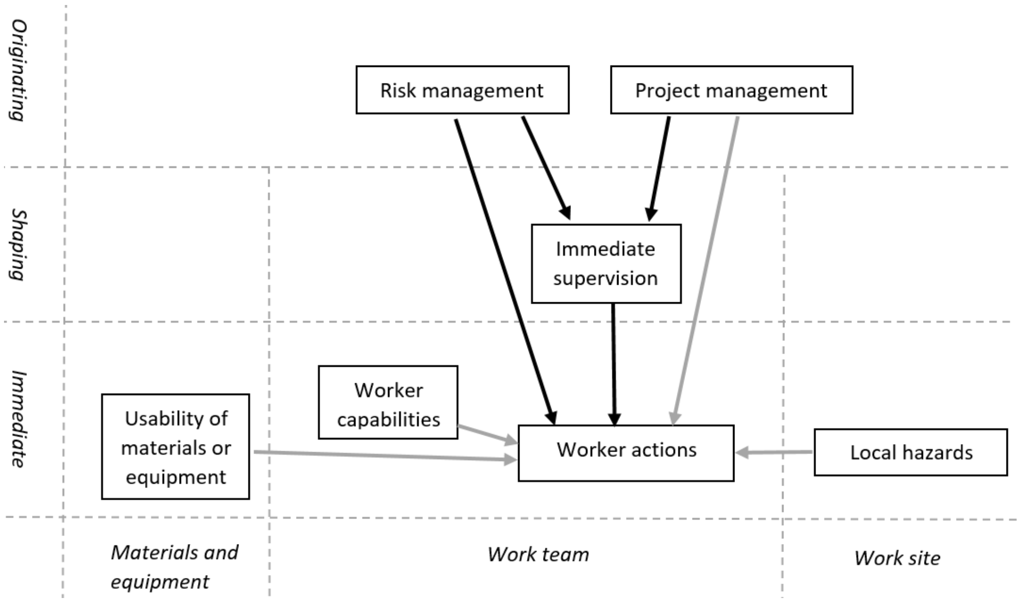

Figure 13. Factors consistently connected to poor worker actions (coverage > .3) and poor immediate supervision, and connections between these factors. Black arrows indicate strong connections (coverage > .5).

The three factors most identified in article 3, worker actions, immediate supervision, and risk management, seem to be key causal factors.

Worker actions was identified to be a factor in 145 accidents (82%). Subcategories of poor worker actions were identified inductively. The most frequent categories found were (in rank order) (1) using wrong type/use of equipment, (2) working at heights without adequate safeguarding, and (3) staying in the danger zone. In 24% of the worker actions-accidents, other workers than the injured worker contributed to the accident. Often, combinations of actions by the injured worker and other workers contributed to the accident.

Poor immediate supervision was identified in 95 accidents (54%). Out of these 95 accidents, inadequacies in controlling unsafe conditions and actions were judged to have been involved in 38%, and inadequacies in planning the work in a manner to reduce risk and identifiable hazards were judged to have been involved in 29% of the accidents. Immediate supervision is a shaping (intermediate) factor in the ConAC framework, and Figure 13 illustrates that immediate supervision is an outcome of the originating factors risk management and project management, and a "cause" of poor worker actions.

Poor risk management was identified to be a factor in 56% of the accidents. The most frequent categories of deficiencies in risk management were (1) poor systematic health and safety work/internal control, (2) poor routines for assessing risk in working operations, (3) not following the safety and health plan, and (4) poor or lacking risk assessments. There were combinations of such deficiencies in most of the risk management accidents.

In summary, the research identified several frequent causal factors in the 176 accidents, most notably worker actions, immediate supervision and risk management. Important causal connections between factors were also identified, for example between risk management and immediate supervision, and between immediate supervision and worker actions.

5.4 Article 4: Safety management and safety performance in construction projects

Article 1-3 focussed mainly on *accidents*, and its associated hazards, barrier failures and causal factors. In article 4, the aim was to identify safety management factors, contextual factors and combinations of such factors associated with high and low safety performance in 12 construction projects. Eight safety management factors were found to be "necessary" for high safety performance (Table 14), indicating that high safety performance cannot be achieved without high performance on these specific factors (if Y, then X). Site management, operative risk management and staff management were the three conditions most strongly associated with safety performance. A likely explanation is that the three factors are the more proximal than the other factors, with more direct influence on what is going on at the sharp end, and essential in the daily control of the safety at site. Risk management seem to be a key factor in safety management, being good in all high safety performance projects and poor in all low safety performance projects. As many of the safety management factors, operative risk management is not, however, a factor operating in isolation. An analysis of necessity indicated that project management and roles and responsibilities were consistent "necessary" conditions for operative risk management (consistency; .95 and coverage; .90 for both).

Table 14. Necessary conditions for the outcome <u>safety performance</u>. N=12. Consistency and coverage.

Factor	Consistency	Coverage
1. Construction complexity	.62	-
2. Organisational complexity	.59	-
3. Time	.71	-
4. Economy	.68	-
5. Contract management	.64	-
6. OHS planning	.55	-
7. Roles and responsibilities	.87	.81
8. Project management	.89	.83
9. Management commitment	.84	.82
10. Safety climate	.80	.87
11. Learning	.80	.79
12. Performance evaluation	.74	-
13. Operative risk management	.92	.91
14. Site management	.85	.93
15. Staff management	.81	.89
16. Hardware management	-	-

The average score for the 12 safety management factors (factor 5-16 in Table 14) was .53. for all projects, .77 for the high safety performance projects, and .30 for the low safety management project.

Two analyses of combinations of factors (QCAs) were undertaken. The first QCA analysed combinations of contextual factors and safety management factors. (Table 15). The table shows two configurations sufficient for *high* safety performance covering 80% of the outcome, and two configurations sufficient for *low* safety performance covering 78% of the outcome. Black circles (●) represent *present* factors, white circles (○) represent *absent* factors, and empty cells represent redundant factors, that is, factors that have been minimised away through pairwise comparison (see article 4 for details).

Table 15 shows that high safety performance can be achieved with both high and low construction complexity and organisational complexity. The analysis indicated, however, that high construction complexity and organisational complexity complicate safety management. What seemed to be important was how project complexity and organisational complexity was handled by operative risk management, and probably other safety management factors. In projects with high organisational complexity and high safety performance, the organisational complexity was adequately planned for, and extensively managed by, for example, involvement, cooperation and follow-up of the contractors.

Table 15. Consistent configurations for high and low safety performance (Complex solution). (Algorithm: Quine-McCluskey)

	High safety performance configurations (frequency cut-off; 1, consistency cut-off; .90)		*Low* safety performance configurations (frequency cut-off; 1, consistency cut-off; .87)	
Conditions	**HP1**	**HP2**	**LP1**	**LP2**
Construction complexity	○	●	○	○
Organisational complexity		●	○	●
Contract management	●			○
Operative risk analysis	●	●	○	○
Consistency	.91	.92	.92	.94
Raw coverage	.44	.49	.63	.32
Unique coverage	.30	.35	.46	.15
Cases	B, C, E, F	A, D	G, H, I, J	K, L
Overall solution consistency	.93		.91	
Overall solution coverage	.80		.78	

●, core condition (present); ○, core condition (negated); empty cells, redundant conditions.

The second QCA analysed combinations of safety management factors (Table 16). The results showed three configurations *sufficient* for high safety performance covering 90% of the outcome and one configuration producing *low* safety performance covering 93% of the outcome (Table 16). The results showed that it is possible to achieve high safety performance despite many relatively poor safety management factors (HP3). One of the cases in LP1 performed relatively well on many factors (roles and responsibilities, contract management, and parts of the project management), but still had low safety performance. The main deficiency was that the focus on, and commitment to, OHS as a process was low and poorly integrated into production management. The results indicate that it is necessary to emphasise the safety management process on its own to achieve high safety performance.

Table 16. Consistent configurations for high and low safety performance (Complex solution). (Algorithm: Quine-McCluskey)

	High safety performance configurations (frequency cut-off; 1, consistency cut-off; .89)			Low safety performance configuration (frequency cut-off; 1, consistency cut-off; .92)
Conditions	**HP1**	**HP2**	**HP3**	**LP1**
Staff management	●		○	○
Operative risk management	●	●	●	○
OHS planning		○	○	○
Roles and responsibilities	●	●	○	
Management commitment	●	●	○	○
Consistency	.93	.91	.89	.94
Raw coverage	.75	.63	.33	.70
Unique coverage	.16	.04	.11	.06
Cases	A, B, C, E	C, E, F	D	G, H, I, J, K, L
Overall solution consistency	.93			.93
Overall solution coverage	.90			.93

●, core condition (present); ○, core condition (negated); empty cells, redundant conditions.

6 Discussion and conclusion

6.1 Introduction

In this chapter, key findings related to the main objective will be discussed. The discussion is about how the findings contribute to the existing research literature, and theoretical and practical implications of the results. The chapter also discusses some methodological limitations about this research which leads to the conclusion of the thesis.

The main objective of this thesis was to identify and explain key factors in accidents and prevention in the construction industry. This was done by asking three main research questions:

RQ1: Which accident types and barrier failures are frequent in construction accidents?

RQ2: Which causal factors are important in construction accidents?

RQ3: Which factors and combinations of factors are important in producing safety performance in construction projects?

Given the holistic approach, multiple data sources, and quite extensive analytical frameworks, it is not surprising that the thesis have multiple findings. What binds them together are their relevance in describing and explaining construction accidents and safety management illustrated by the conceptual framework presented in chapter 2.5.

6.2 Accident types and barrier failures

Understanding the sequences of events leading to accidents is a crucial element of risk prevention (Swuste, 2008). Lists of frequent accident types and their barrier failures are therefore important for prioritisation, developing countermeasures, and for developing checklists for safety inspections at construction sites.

6.2.1 Accident types

The literature review showed that there is some research on accident types in construction accidents, but little research on detailed accident types, which is necessary for precise prioritisation. Large differences in accident types were found between the four samples representing different injury severity, and between the main study samples of fatal- and non-fatal injuries studied in article 1 and 2 (Figure 11). It is important to underline that the non-fatal injuries in this sample are relatively serious injuries. Among the fatal injuries there were more vehicle accidents, explosions, and fall from height when unprotected, than among the non-fatal accidents. Among the non-fatal injuries there were more fall from roof/platform/floor, contact with moving parts of a machine, and fall from scaffolds. The differences can be explained by differences in the types and amounts of energy involved as described by the energy model (Gibson, 1961; Haddon, 1973). The results illustrate that severity of injury is not only governed by chance but depends on energy interaction involved in the injury event (Shannon and Manning, 1980).

A popular version of the iceberg model suggests that near misses, minor accidents and major accidents stem from the same causes (Rosness et al., 2010). The model is still used by many OHS-advisors and managers in the construction industry. Construction companies commonly prioritise hazards based on the companies' accident statistics, and since serious injuries rarely occur, it is a risk that hazards with potential of fatality and serious injury are not sufficiently prioritised. The differences in accident types (hazards) between fatal and non-fatal accidents in this research suggest that the popular version of the iceberg model is not entirely correct. The results are broadly consistent with conclusions, and what can be read from, previous studies and statistics (Salminen et al. 1992; Jeong, 1998; Hale, 2002; Ale et al., 2008; Li and Bai 2008; Dong et al., 2010; Carrillo-Castrillo et al., 2013; Eurostat, 2017). The research suggests that hazards and causes of minor and major accidents are different, and that we therefore cannot necessarily prevent major accidents by studying and tackling the minor accidents (Hale, 2002), or that we cannot prevent minor accidents by studying and tackling major accidents.

To the authors' knowledge, no studies comparing accident types for different construction types are undertaken. We found differences in accident types across construction types in article 1 and 2. For example, for the fatal injuries, fall from height dominated in *Building* and *Engineering Construction*, while bumping, crash and collision dominated in *Civil Engineering.* The results also showed differences between the construction types regarding fatal- and non-fatal injuries. For example, it was found that *Civil Engineering* had most of the fatal injuries (52%) but a smaller share the non-fatal injuries (15%), while *Building* had 24% of the fatal injuries and 47% of the non-fatal injuries. This means that *Civil Engineering* must be prioritised when it comes to preventing the fatal injuries. The differences across the construction types can also be explained by differences in the types and amounts of energy involved in work operations (see Gibson, 1961; Haddon, 1973). The results suggest that different construction types must prioritise different types of hazards, and that lists of frequent accident types for prioritisation should be produced for the different construction types.

The literature review showed that accident types highlighted in many studies of fatal construction accidents were fall from height, falling/collapsing objects, electrocution, vehicle accidents, and contact with hoisted/hanging objects. It is problematic to compare the distribution of accident types from this research to other studies since different accident type variables are used, and judgements therefore must be made. In a literature review, Swuste et al. (2012) produced a list of frequent accident types based on mortality data from a literature review. The list of frequent fatal injuries in article 2 has similarities and dissimilarities with the list produced by Swuste et al. (2012). It is however clear that fall from height and falling objects are dominant among the fatal injuries both in this research and in the list presented by Swuste et al. (2012). Vehicle accidents are more dominant, while contact with electricity is less dominant in this research compared to Swuste et al. (2012).

The lists of the most frequent accident types for fatal injuries and serious non-fatal injuries can be used at different levels (national, project, company etc.) for prioritising hazards. The results, however, also show that the lists have limited external validity. The types of frequent accident types vary regarding construction types and samples representing different injury severity, suggesting a need for specific lists for different construction types and injury severity. It also shows the importance of having safety management systems anchored to the specific hazards involved for each specific project (Hale, 2003a).

6.2.2 Barrier failures

The literature review showed that there is little research on detailed accident types and its related barrier failures in construction. The analysis of barrier failures using Haddon's (1980) countermeasure strategies demonstrated many missed opportunities for implementing these strategies at different stages in the accident process. Haddon's strategies are first and foremost an approach that encourage a fundamental way of thinking about the processes where injuries occur and the ways they can be prevented. The approach encourages us to be creative and consider multiple opportunities for prevention that might otherwise go unrealised (Runyan and Baker, 2009). Many of the accidents studied could have been prevented by eliminating the hazard in the first place (Haddon 1), but elimination is often impractical/impossible (Trost and Nertney, 1995). The research shows that many of the other strategies could have interrupted the accident process, most notably prevent the release of the hazard (Haddon 4), modify the rate or spatial distribution of release of the hazard from its source (Haddon 5), separate in time or space the hazard and the vulnerable target (Haddon 6), and physical barriers (Haddon 7).

The results also showed that each accident type has its specific dominant barrier element failures. For example, in the fall from height-accidents, dominant failures were edge protection and floor deficiency. And in the falling objects-accidents, dominant barrier failures were worker in danger zone, collapse of structure and technical failures on lifting equipment. There are some similarities between this research and Ale et al. (2008), who identified frequent barrier failures for fall from height (roof edge protection, followed by user ability failure, and fall arrest failure), and falling objects (ensuring the safe zone is safe and preventing the object from falling in the first place was found to be the most important, especially by proper connection/anchoring).

The research showed that many accidents occurred in work situations where barriers were lacking and where the barrier system was totally dependent on the human barrier element. When frontline workers are part of the barrier system, we must expect accidents to happen "… due to inherent variability in human performance" (Kjellén and Albrechtsen, 2017, p. 142). In many safety critical systems, the last line of defence is often thought to be the human operator at the sharp end (Dekker, 2014). Systems that are strongly dependent on the human barrier element, like many construction work operations, are vulnerable.

The results also showed that few barrier opportunities were realised in most of the accidents, which is normal for occupational accidents (see Kjellén and Albrechtsen, 2017). When one barrier failed or was not used, there was no other barriers present to interrupt the accident sequence, so called defence-in-depth. Many of the accidents could have been prevented by implementing more barrier functions. The construction industry can learn much about barrier management from high-risk industries like nuclear industry, aviation and the oil- and gas industry. In high-risk industries with defence-in-depth, a lot must go wrong for an accident to happen (Reason, 1997). In the offshore oil and gas industry, for example, the philosophy is that there should be at least two physical barriers in place at all times to prevent a blowout (Hopkins, 2012). The research shows that there is a significant potential for reducing accidents in construction by systematic barrier management. Passive approaches like Haddon's (1980) strategies are often more effective than "behaviour-change strategies" (Runyan and Baker, 2009)

6.3 Causal factors and safety management factors

Article 1 and 2 addressed mainly the upper part of the conceptual model (Figure 5), while article 3 and 4 addressed mainly the lower part of the model – the causal factors and safety management. Figure 14 compares the percentages of each factor with three other studies that employed the ConAC model (Haslam et al., 2005; Cooke and Lingard, 2011; Behm and Schneller, 2013; Gibb et al., 2014). There are some differences between the four studies, but also many similarities. When the percentages for each factor from the four studies are merged, the most frequent factors, by far, are worker actions and risk management, followed by knowledge/skills, worker capabilities, and suitability of materials and equipment.

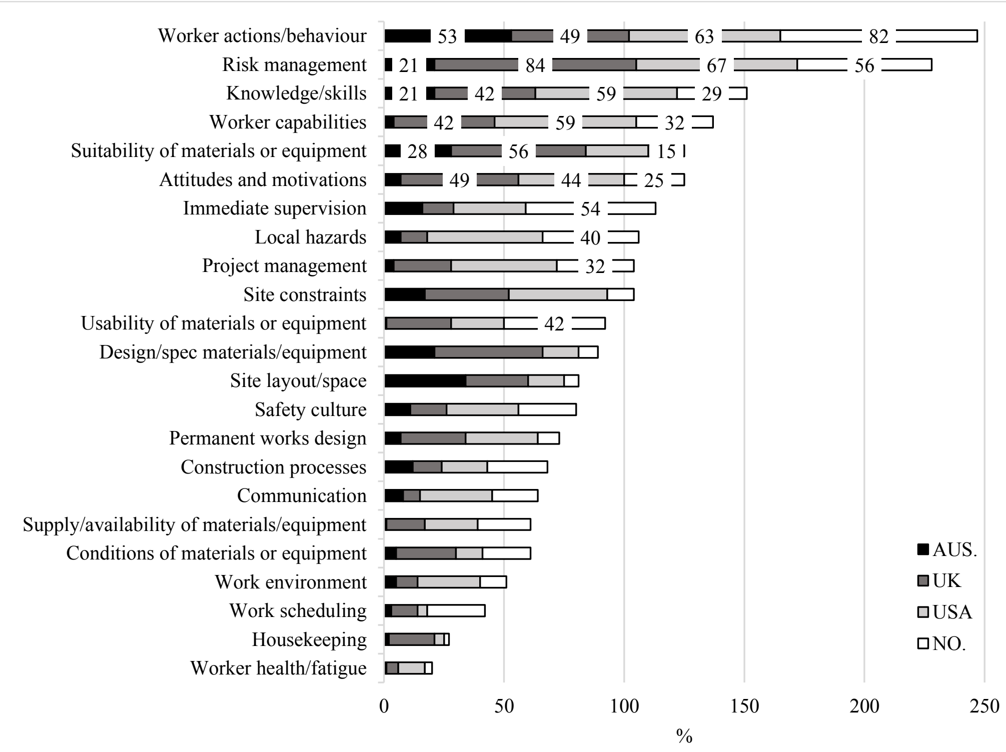

Figure 14. Percentage of causal factors found in the Norwegian study (NO.) compared to the studies in UK, Australia (AUS.) and USA (Based on Gibb et al., 2014 and Winge et al., 2019).

I now discuss some of the important causal factors, connections between them, and their connection to the results from the study of safety management in article 4. I start with the most distal causal factors and management factors and proceed to the more proximal factors.

6.3.1 Management commitment to OHS

Management commitment to OHS is not a factor in the ConAC framework and was not investigated in article 3. In article 4, management commitment to OHS was found to be "necessary" for high safety performance. In projects with high safety performance and adequate management commitment to OHS, the managers expressed clearly that safety was prioritised before production, and they actively participated in OHS and other OHS-related management factors like project management, safety climate, planning, and staff management. The results are consistent with literature reviews (Shannon et al., 1997; Mohammadi et. al., 2018). Hallowell et al. (2013) concluded that safety performance is exceptionally strong when top management is visibly involved in safety.

6.3.2 Project management

Inadequacies in project management (contractor arrangements, subcontracting, labour supply, work scheduling, time management, time pressures and individuals taking it upon themselves to do jobs/tasks) was found to be a causal factor in 32% of the accidents in article 3. Project management is defined differently in different studies and it is hence problematic to compare to many studies, except for the studies employing the ConAC framework. The previous studies using the ConAC framework, deficiencies in project management was also found to be one of the most frequent "originating" factors (Gibb et al, 2014). The most frequent problems were related to unclear organisational structures and responsibilities, cooperation and communication between workers and companies, lack of control on actors and worker behaviour in the project, time pressure and new types of jobs unfamiliar to the work team. In article 4, adequate project management was found to be "necessary" for high safety performance. Project management was found to be especially demanding and important in projects with high organisational complexity.

6.3.3 Risk management

Figure 14 shows that risk management was the originating causal factor most identified in this research and the other studies using the ConAC model (Gibb et al., 2014). This is not surprising, since accidents "… invariably involve an inadequately controlled risk, indicative of a management failing" (Haslam et al, 2005, p. 413). The types of deficiencies in this research were similar to those of Haslam et al. (2005) who found that the failures of risk management typically were lack of, or inadequate, risk assessments. Hale et al. (2012) also found a concentration of failures in planned risk control at the workplace level and planning and risk management at the "delivery systems" level. These inadequacies are largely about inadequacies in risk management at different levels and underline the importance of risk being addressed by different actors at different levels (Rasmussen and Svedung, 2000; Hale et al., 2012).

In article 4, aspects of risk management were included in two factors. First, as a part of the overall OHS-planning of the project (assessment of risks in advance with specific measures), and second, as operative risk management (planning of operations to reduce risk by people in direct control of the risk at the operational level). The analysis showed that most projects did not have an adequate OHS-planning, including assessment of risks in advance with specific measures. The research also showed that assessment of risks in advance with specific measures is very demanding because of the dynamic nature and new emerging risks. Conventional OHS risk management methods, assuming that that work can be decomposed into its parts, is of limited value in construction because system elements are in constant dynamic interaction with one another (Cooke-Davis et al., 2007). Because of the inadequate OHS-planning in most of the projects, many residual risks therefore had to be handled by operative risk management, which is one explanation why operative risk management was found to be "necessary" for safety performance. The results are consistent with a study of the use of Job Safety Analyses (JSA) in construction which concluded that JSAs are performed for many activities in which barriers and procedures should have been established prior to initiating the JSA (Albrechtsen et al., 2019). In article 4, operative risk management was good in all high safety performance projects and poor in all low safety performance projects. One project illustrates the importance of operative risk management. The project performed poorly on most safety management factors but had good operative risk management and achieved high safety performance. Operative risk management is not, however, a condition operating in isolation. The results indicated that project management and roles and responsibilities were consistent "necessary" conditions for good operative risk management.

6.3.4 Hazards, barriers and site management

Project management and risk management described above influence the situation at construction sites. In article 3 we found that "local hazards" (hazards specific to the site that should have been managed or planned for) were present in 40% of the accidents. In article 1 and 2, we found that in many accidents, few barrier opportunities were realised, and that the barrier system was totally dependent on the human barrier element. And in article 4 we found that most projects did not have an adequate OHS-planning, including assessment of risks in advance with specific measures. The preferred method of tackling hazards is to eliminate as many of the hazards in the working environment as practical (Trost and Nertney, 1995). Many of the hazards involved in the accidents analysed, could have been tackled earlier in the projects, but the frontline workers had to handle the residual risks and make safety critical decisions themselves. Many construction workers have to deal with hazards daily. Jørgensen (2016) call these hazards "simple hazards". Simple hazards are so common "… that people have largely learned to deal with them without getting injured". These hazards are "… therefore seen not as hazards to be eliminated, or tightly technologically controlled, in the same way as major hazards, but as within the control of the potential victims" (ibid., p. 48).

In article 4 we also found that site management was found to be "necessary" for high safety performance. The projects with adequate site management were well organised, had clearly defined danger zones, pathways, areas for storage, good housekeeping, and few hazards. The results also showed that site management and operative risk management strongly coincide. The results suggest that hazards and barriers at site must be managed by adequate barrier management, site management and operative risk management to produce high safety performance. The results are broadly consistent with previous research. Hallowell and Calhoun (2011) found that a site-specific safety plan is one of the most central elements in an effective safety program. Khosravi et al. (2014) found that "site condition" was moderately associated with accidents. The importance of site condition is apparent regarding work in heights. In a literature review of 75 studies of falls from height in construction, Nadhim et al. (2016) found that site condition was one of the most frequent factors. For example, falls from height could occur when there were unprotected walkways, improper guardrails, slippery or sloped surfaces.

6.3.5 Worker behaviour, supervision and staff management

Article 3 showed that project management and risk management described above were connected to immediate supervision and worker actions (Figure 13). In accordance with the ConAC framework, it was found that immediate supervision (inadequacies in controlling unsafe conditions/actions and planning the work to reduce risk) is a shaping (intermediate) factor, an outcome of risk management and project management, and a "cause" of poor worker actions. That immediate supervision is an important factor is consistent with several other studies in construction (Mohamed, 2002; Rowlinson et al., 2003; Choudry and Fang, 2008; Kines et al., 2010; Hardison et al., 2014; Fang et al., 2015). Rowlinson et al. (2003), for example, concluded that the foreman is the key interface between worker and management and plays a key role in ensuring that safety management systems operate effectively. And

Mohamed (2002), concluded that the more aware of occupational health and safety (OHS) supervisors are, the more positive is the OHS climate. The results also showed that the usability of materials and equipment, worker capabilities, and local hazards were connected to worker actions.

Article 1 and 2 showed that many accidents occurred in work situations with few barriers and where the barrier system was totally dependent on the human barrier element. Article 2 showed that "unsafe acts" by frontline workers were found to be a contributory factor in 94% of the fatal accidents. And article 3 showed that "Worker actions and behaviours" was a causal factor in 82% of the non-fatal accidents. Depending on operational definitions, it is often concluded that "human error" is a determining factor in 70-80% (Rasmussen, 1997) or 80-90% (Hale and Glendon, 1987; Phillips, 2005) of accidents. A study of occupational accidents (Salminen and Tallberg, 1996) found that "human errors" were involved in 84% of serious accidents and 94% of fatal accidents. It is important to underline that identifying "unsafe acts" is not about blaming frontline workers. Blaming workers does nothing to reduce the inherent risks within the workplace (Reason, 2000). Today, it is widely acknowledged that worker behaviour is largely a result of the system workers are part of (Reason, 1997), as demonstrated in this research, and symptomatic of trouble deeper within a system (Dekker, 2014).

In article 4, adequate staff management was found to be a "necessary" factor for high safety performance. In projects with adequate staff management, the share of skilled (trained) workers was high, the companies and workers had often worked together in previous projects, the safety climate was good, and supervision and safety behaviour were adequate. The results are similar to Choudhry and Fang (2008), who concluded that management involvement and toolbox talks are the most effective factors for site safety. They also concluded that management can help workers to improve safety behaviours through the influence of rules and regulations, training and increased communication. Hale et al. (2012) also studied staff management (manpower management) but did not find it to be an important causal factor.

We concluded earlier that there is a significant potential for reducing accidents in construction by systematic barrier management. Barriers are measures implemented against identified hazards. It is however demanding to foresee all hazards that can arise (Tinmannsvik, 2008), especially in dynamic and complex construction projects. In the previous section, we described how frontline workers have to deal with hazards daily, so called "simple hazards" (Jørgensen, 2016). This research, and other studies described above, demonstrates how important front-line construction workers and supervisors are in both causing and preventing accidents in hazardous situations. Lingard and Rowlinson (2005) argue that the human element is particularly important in a labour-intensive industry as the construction industry. Studies of petroleum installations have shown that workers can influence safety in at least three ways, by (1) being barrier elements, (2) using robust work practice, and by (3) improvisation (Skjerve, 2008). Robust work practise is about all the small measures workers can do to protect themselves and others against hazards that can arise in the execution of the work (Tinmannsvik, 2008). Robust work practice rarely specifies exact hazards but focus on the workers' ability to make judgements about each situation. Reason (2016) also argues that "purely systematic counter-measures are not enough to prevent tragedies" (ibid., p. 87). It is also important to make frontline workers more "mindful", i.e., more error-wise and alert to hazards and risks. Mindful safety practices imply that workers are encouraged to review situations from different perspectives: to be open to the possible relevance of new information and/or to be open to the need for reinterpretation of old information, and colleagues that watch after each other and correct each other (Skjerve, 2008). This is in accordance with a Danish study that emphasise the importance of network and friendship between workers (Baarts, 2004).

Summarised, worker behaviour and the extent of "unsafe acts" can be influenced by multiple measures directed at the systems as well as the workers, for example skills and knowledge, mindfulness, robust work practices, modifications of working conditions, adequate staff management and selection of contractors, suppliers and personnel.

6.3.6 Factors and combinations of factors important in safety management in construction projects

In article 4, eight safety management factors were found to be "necessary" for high safety performance: (1) roles and responsibilities, (2) project management, (3) OHS management and integration, (4) safety climate, (5) learning, (6) site management, (7) staff management, and (8) operative risk management. Site management, operative risk management, and staff management were the three conditions most strongly associated with safety performance. A likely explanation is that the three factors are the more proximal than the other factors, with more direct influence on what is going on at the sharp end, and essential in the daily control of the safety at site.

Safety performance is not only the result of the causal influence of single factors described above, but also the result of a complex interplay between different management factors and contextual factors as demonstrated by the QCA analysis in article 4. The results showed a large difference in the average score on the 12 safety management factors between the high safety performance projects (.77) and the low safety performance projects (.30). The research on effectiveness of occupational health and safety management is ambiguous (Zwetsloot, 2013). Robson, et al. (2007) concluded that the body of evidence was insufficient to make recommendations either in favour of or against OHSMSs. The results from this research is however consistent with conclusions from the literature reviews by Gallagher et al. (2001) who concluded that safety management systems can deliver more healthy and safe workplaces, and Thomas (2011) who concluded that organisations with certified safety management systems had significantly lower accident rates. The result is also consistent with literature reviews from construction by Loushine et al. (2006) and Mohammadi et al. (2018) who concluded that construction projects with adequate safety management systems/programs have better safety performance.

The results also showed that high safety performance can be achieved with both high and low construction complexity and organisational complexity. The results indicate, however, that high construction complexity and organisational complexity complicate safety management. What seemed to be important was how project complexity and organisational complexity was handled by safety management, in this analysis represented by the factor operative risk management. Regarding construction complexity, the results are broadly consistent with Törner and Pousette (2009) who concluded that the inherent complexity of construction work restricts and complicates safety management and demands comprehensive safety management. Regarding organisational complexity, the results do not contradict that there is a statistical association between increased on-site subcontracting and increased risks of injuries (Azari-Rad et al., 2003). The results do, however, indicate that high organisational complexity complicates the coordination of actors and operations and the production of a high safety performance.

The results also showed that it is possible to achieve high safety performance despite many relatively poor safety management factors, and that it is possible to produce low safety performance despite many relatively good safety management factors. In the latter case, a project performed adequately on many management factors, but the focus on, and commitment to, safety as a process was low and poorly integrated into production management. The result indicates that it is not sufficient to have a relatively good production and project management, it is also necessary to emphasise the specific safety management process on its own to achieve high safety performance. The results support Hale's (2003b) view that safety management only work well when it is seen as an integral aspect of the task of all those working in and for the organisation. Hale (2003b) argue that safety management should therefore be an aspect system, not a subsystem, of the organisation.

The results showed that single *necessary* factors can be jointly *sufficient* to produce high and low safety performance. This is broadly consistent with the understanding of causality in many accident models, where accidents occur through the interaction of several conditions, where each may be *necessary* but where they are only jointly *sufficient* to produce the accident (Reason et al., 2006; Hopkins, 2014, Winge et al., 2019). This research also showed that some safety management factors influence other safety management factors, and that there can be different combinations of factors producing high and low safety performance, so-called *equifinality*. The results support that the combination of many factors play a key role in safety management (e.g. Shannon et al., 2001; Hale et al, 2005; Hallowell and Calhoun, 2011; Dyreborg et al. 2013). Zwetsloot (2013), for example, argues that the system is more than the sum of its parts and the interactions between the elements are just as important as the elements. Hallowell and Calhoun (2011) concluded that many of the strategies found to be effective in isolation (site safety manager, worker participation and involvement, a site-specific safety plan, and upper management support and commitment), also provided a high level of synergistic effects that enhance the effectiveness of other elements. Similarly, ISO 45001 (ISO, 2018) states that the effectiveness and ability to achieve outcomes of an OHS system are dependent on several key elements.

6.4 Limitations

In order to provide the construction industry and authorities with knowledge on construction safety that can be used for prioritisation and developing preventive measures, a relatively broad and holistic approach has been chosen, focussing on many factors. This approach has led to an employment of several data sources and methodological approaches, for example document analysis, interviews, incident concentration analyses, Qualitative comparative analysis (QCA), correlational analysis and set theoretic analysis. These approaches also have limitations which has been described in the chapter about scientific quality (chapter 4.4) and elsewhere. Some limitations deserve to be repeated: (1) The data used in article 1-3 are secondary (collected mostly by inspectors from the NLIA), and some factors were difficult to assess due to little information. Using the ConAC model in article 3, there was little information on some factors, for example, permanent works design and worker health/fatigue and housekeeping, which are clearly underestimated in this material. Other types of materials are needed to estimate the extent of these factors. Moreover, it is easier to identify factors at the sharp end on site than at the blunt end. (2) A limitation using lists of frequent accident types as in article 1 and 2, is that we lack exposure data for the types of work represented by the accident type categories. The frequencies do not indicate risk, only frequencies. (3) We found that the lists of accident types are different for samples of injuries representing different severity, and for samples representing different construction types. The lists therefore have limited generalisability and should therefore be used cautiously. (4) Using analytical frameworks with factors like in article 3 and 4 means looking for a set of causal factors, and not looking for other factors, which influences the results. Lundberg et al. (2009) has expressed this as "What-you-look-for-is-what-you-find". (5) The approach in article 4 is a client's perspective, and the cases could have been studied more in depth. It would have been preferable to study more documents and interview more managers and safety representatives at the sharp end. There is however always a trade-off between depth and width. (6) Assessment of safety performance and safety management performance was problematic in some of the construction projects since performance often varies during a project. (7) An experience doing research in this field is that it is problematic to compare results to much previous research, due to different definitions and poorly described definitions of important terms in much research. A necessary condition for the accumulation of knowledge in safety science is that key factors are clearly defined. (8) Aiming for both in-depth insight into cases and complexity, and to produce generalisations, might seem to be contradictory goals (see Ragin, 1987). The number of accidents studied in article 1-3, and the twelve projects studied in article 4, are relatively few for the production of generic results, and the results must therefore be treated with caution. The research is therefore seen as a building-block type of research (George and Bennett, 2005), and I encourage researchers to undertake similar studies with larger N which makes it easier to include more factors and study how they operate together. I also encourage more case studies and intermediate-N studies to increase our knowledge of connections between causal factors, management factors, accidents and safety performance.

6.5 Conclusions and recommendations for future research

The main objective of this thesis was to identify and explain key factors about accidents and accident prevention in the construction industry. Knowledge about these events, failures and characteristics indicates where to prioritise safety measures and types of measures to develop. The research objective and research questions were developed by the researchers involved based on expressed needs of knowledge by the construction industry and authorities, and on the broad literature review on core issues presented in Chapter 3. The research has identified several concentrations of these factors and complex interactions between them.

The lists of the most frequent accident types for fatal injuries and serious non-fatal injuries can be used on a national level for prioritising detailed accident types. It is however important to underline that hazards are different regarding injury severity and construction types, suggesting a need for specific lists for different construction types and injury severity. It also shows the importance of having safety management systems anchored to the specific hazards involved for each specific project (Hale, 2003a). There is little research on detailed accident types in construction, and further studies are recommended, for example on: (1) detailed accident types for different construction types, injury samples representing different severity, and geographical units; (2) exposure data on different hazards types so that real risks can be assessed; (3) tools for prioritising hazards on a national level based on exposure data and injuries.

The analysis using Haddon's (1980) countermeasure strategies demonstrated that there were many opportunities for implementing these strategies/barriers at different stages in the accident process. It can be concluded that few barrier opportunities were realised in many accidents. Mostly, when one barrier failed, there were no other barrier elements present to interrupt the accident sequence, so called defence-in-depth. Many accidents occurred in work situations where the barrier system was totally dependent on the human barrier element. When frontline workers are part of the barrier system, we must expect accidents to happen "… due to inherent variability in human performance" (Kjellén and Albrechtsen, 2017, p. 142). The construction industry can learn from high-risk activities. In high-risk industries with defence-in-depth, a lot must go wrong for an accident to happen. There is a significant potential for reducing accidents in construction by systematic barrier management. There is little research on barrier failures in construction, and further studies are recommended on barrier failure types for different accident types and construction types, combinations of barrier failures, and barrier management in construction.

The seven causal factors most identified in the accident analyses were (in rank order): (1) worker actions, (2) risk management, (3) immediate supervision, (4) usability of materials or equipment, (5) local hazards, (6) worker capabilities, and (7) project management. Worker actions was identified to be a causal factor in 82% of the accidents. Often, combinations of actions by the injured worker and other workers contributed to the accident. Identifying unsafe acts is not about blaming frontline workers. Worker behaviour and the extent of unsafe acts can be influenced by measures directed at the workers as well as the systems, for example modifications of working conditions, skills and knowledge, and selection of contractors and personnel. Worker behaviour was found to be influenced by several other causal factors, most notably immediate supervision, risk management, usability of materials or equipment, local hazards, worker capabilities and project management. Further studies on causal factors in construction accidents is encouraged, for example on frequent causal factors, connections between causal factors, and types of causation going on between factors using process tracing (George and Bennett, 2005) or similar methods.

Safety management in construction is demanding, since construction projects are technologically and organizationally complex (Lingard, 2013). In the study of 12 construction projects, the results showed large difference in safety management scores between the high safety performance projects and the low safety performance projects. The result is broadly consistent with previous studies that safety management systems can deliver more healthy and safe workplaces (Gallagher et al., 2001) and lower accident rates (and Thomas, 2011). The results also support that construction projects with adequate safety management systems/programs have better safety performance (Loushine, et al., 2006). Eight management factors were found to be "necessary" for high safety performance. This research also showed that there are several combinations of factors producing high and low safety performance, so-called equifinality. The results also support that combination of many factors play a key role in safety management (e.g. Shannon et al., 2001; Hale, 2005; Hallowell and Calhoun, 2011; Dyreborg et al. 2013). Further studies on safety management in construction is encouraged, for example similar research with larger N which makes it easier to include more conditions and study how they operate together, and more case studies and intermediate-N studies to increase our knowledge of associations between safety management factors, combinations of factors, and safety performance in construction projects.

Finally, it must be added that studying all these accidents and unsafe conditions is not only depressing. This research and previous research also show many opportunities for prevention and mitigation. The conceptual model presented in chapter 2, based on e.g. Reason's (1997) model for organisational accidents, is a good model not just to analyse accidents, but also for strategic accident prevention at different hierarchical levels. Identifying the frequency and characteristics of these concepts as the basis for prioritisation and developing countermeasures, is important. Because, understanding the sequences of events leading to accidents is a crucial element of risk prevention (Swuste, 2008), and accident prevention begins with having a clear understanding of factors that play key roles in causation (Hinze et al., 1998).

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Appendix: The four research articles

PAPER I

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Accident types and barrier failures in the construction industry

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A R T I C L E I N F O

Keywords:
Construction industry
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A B S T R A C T

The paper identifies frequent accident types in the construction industry, characterises the accident sequence, and identifies barrier failures for the most frequent accident types. 176 accidents in the Norwegian construction industry investigated by the Norwegian Labour Inspection Authority in 2015 are analysed. The most frequent accident types include: fall from roof, floor or platform; contact with falling objects; fall from scaffold; and contact with moving parts of a machine. A comparison of the study sample to other injury samples, showed that the distribution of accident types varied regarding severity and different construction types. This can be explained by differences in work type, hazard, and energy type and energy amount. An analysis of barrier failures showed that many accidents are explained by the lack of physical barrier elements. The results indicate that there is significant potential for accident prevention in the construction industry by systematic barrier management.

1. Introduction

The construction industry in Norway has one of the highest numbers of fatal injuries and incident rates compared with other industries. The average incidence rate for fatalities during 2012–2016 was 4.1 per 100,000 employees (Labour Inspection Authority, 2017). An increase in the annual number of fatalities, and some major, dramatic accidents, led to an initiative from stakeholders in the Norwegian construction industry to establish a tripartite cooperation with a vision-zero-approach. The cooperation expressed a need for further knowledge on frequent accident types and their causal factors. Clients and contractors produce injury statistics for their projects and hence have an overview of the less severe injuries. However, they rarely experience severe accidents themselves. As a result, none of the actors in the industry have a significant number of cases of severe accident types and their barrier failures.

The purpose of this study is (1) to identify frequent accident types and (2) to analyse barrier failures to establish a knowledge base for prioritising and developing preventive measures in the construction industry. Producing relevant knowledge about accidents is problematic as the national data on accidents and injuries (like other countries), does not '… generally permit detailed analysis of causes beyond the identification of the mechanism and agency of injury' (Cooke and Lingard, 2011, p. 279). The main study sample in this research consists of 176 severe construction accidents investigated by the Norwegian Labour Inspection Authority (LIA) in 2015. This paper is limited to studying mainly proximate causes and incident types. Contributing factors in the organisation are not addressed.

There exist some statistics and studies showing distribution of incident types. However, it is problematic to compare the different studies and statistics since there are different categories used for describing accidents, e.g. 'deviations', 'cause', 'accident/injury types' and 'central events'. However, 'fall from height' dominates in most studies and statistics. Other frequent 'accident types' are falling/collapsing objects, moving vehicles, moving machine parts, and electricity. In Europe (EU28), 782 fatal construction accidents were registered in 2014 (Eurostat, 2017). The most frequent 'deviations' were: fall of persons (26%); breakage/fall/collapse, etc. of material agent (20%); and loss of control of machines, equipment, tools, etc. (19%) (Eurostat, 2017). The distribution of 'deviations' for non-fatal accidents was somewhat different. In a study of deaths from injuries among construction workers in North Carolina 1988–1994, Lipscomb et al. (2000) found that work related deaths were most often 'caused by' motor vehicles (21%), falls (mostly roofs and scaffolds) (20%), machinery (15%), electrocutions (14%), and falling objects (10%). In a Dutch study of 'accident types' in the construction industry, Ale et al. (2008) found that the most frequent 'accident types' were fall from height (roof, floor, platform), contact with falling/collapsing objects, fall from ladder, fall from scaffold, and contact with moving parts of a fixed machine. Both the statistics from Eurostat (2017) and Ale et al. (2008) show differences in the distributions of fatal vs. non-fatal accidents. Based on a review of construction safety literature using mortality data, Swuste et al. (2012) concluded that the most frequent 'central events' were: falling from height; contact with falling or collapsing objects;

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Table 1
Overview of samples of injuries in the Norwegian construction industry.

Sample name	Description	Data period	Injuries in the sample	Number injuries per year	Estimated average severity (order)
'Main study sample'	Accidents investigated by the LIA in 2015	2015	184 (176 accidents)	–	Medium/high (2)
'Fatal'	Fatal injuries	2000–2014	131	10 (average 2012–2016)	High (1)
'Inspection'	Injuries reported to the LIA	2011–2016	1758	293 (average 2011–2016)	Medium (3)
'Insurance'	Injuries (insurance claims) reported to the Labour and Welfare Administration (LWA)	2015	1783	1783	Medium (4)
'Survey'	Labour force survey (LFS) 2013	2013	41	9000–10,000	Low (5)

contact with electricity; contact with moving machinery parts; falling from a moving platform; contact with hoisted, hanging, swinging objects; hit by vehicle; squeezed between or against something; and contact with objects thrown from machine.

The construction industry is not homogenous, which also implies that incident types and barrier failures can vary regarding the type of project (e.g. building, infrastructure, refurbishment), project phase and project size and complexity. Research has demonstrated that causal factors differ in different settings, for instance between countries (Cameron et al., 2008; Spangenberg et al., 2003), and construction project features (Manu et al., 2010).

The framework used in this analysis is based on three elements that are basic in many accident causation models, namely hazards, barriers/defences and loss (e.g. Haddon, 1980; Reason et al., 2006). The analysis focuses on proximate factors in the accident sequence. Distal, organisational factors are not covered in this paper.

2. Study samples

The main study sample consists of 176 construction accidents investigated by the Norwegian LIA in 2015. This sample gives sufficient descriptions of the accident sequence as well as a sufficient number of recent accidents. The study sample is limited to accidents investigated by the LIA for one year. In 2015, LIA carried out investigations of 189 construction accidents, involving 210 companies. Seven of the 189 accidents were excluded from the sample since they did not take place during construction work or at constructions sites, and six accidents were excluded due to lack of sufficient information about the accident. Hence, the main study sample is 176 accidents involving 184 injured persons, of which 4 were fatalities.

According to the Norwegian Work Environment Act, occupational accidents that have led to fatal- or severe injuries must be notified to the police and the LIA. Severe injury here means any harm, (physical or mental), that results in permanent or prolonged incapacitation. There is guidance on LIA's website describing nine characteristics that indicate severe injury, e.g. injuries to head, skeleton, internal organs, loss of body part, poisoning, unconsciousness, metabolism/frost injury, hypothermia, and injuries that lead to hospitalisation (Labour Inspection Authority, 2017). When the LIA is notified of an accident, the LIA decide whether to complete an investigation based on assessments of potential severity and available inspectors. These are the criteria for selecting accidents for the main study sample:

(1) At least one construction company involved
(2) Happened during construction work
(3) Inspected by the LIA in 2015

Most construction accident statistics do not include workers employed by non-construction companies that are injured in construction accidents, e.g. temporary employment agencies. Criteria 1 and 2 ensure that these workers are included.

One investigated accident can contain many documents and normally consists of the notification of the accident, accident reports from the LIA and the company, and other letters between the LIA and companies. When an accident is reported by mail or phone to the LIA, a checklist is used to collect information about the accident to decide whether an investigation is going to be carried out. During the investigation, the inspectors use another checklist to investigate if there have been any violations of the law and to collect information about the course of events. After the investigation, the inspectors produce an investigation report that in most cases includes a description of the accident sequence, causal factors, and violations of the law when identified. In most cases, the investigated company is decreed to produce an accident investigation report and a plan including measures to prevent similar accidents.

The amount of information on the accidents varies significantly. Some cases have only one document while others have 50. Some cases are sparsely described and six accidents were excluded due to lack of sufficient information. Other accidents have rich descriptions and are investigated by professional accident investigators.

This research includes all data collected from the reporting of the accident and the whole process related to the investigation. Four analysts were engaged in finding relevant documents and extracting relevant qualitative information from the accidents into a word document consisting of 84,000 words. Central issues were assessed and organised in variables in an Excel document.

2.1. Samples compared to the main study sample

The main study sample is compared to four other samples of construction injuries representing different degrees of severity (Table 1). The aim of the comparison is to assess representativeness of the study sample and relations between accident severity and distribution of accident types.

The official number of employees in the Norwegian construction industry in 2015 was 206,000 and the average number of fatalities per 100,000 employees in the 2012–2016 period was 4.1 fatalities. It is likely, however, that the level of injuries in construction is underestimated since staffing agencies or subcontractors that are not construction companies employ many of the injured workers.

The main study sample is described above. The 'fatal' sample is fatal injuries reported to the LIA by the employer, police or health services (Table 1). Sometimes the LIA captures fatalities via media or other sources. It is estimated that the fatal injuries represent nearly 100% of the fatal construction injuries. The 'inspection' sample is injuries reported to the LIA and is similar to the main study sample. One difference is that the 'inspection' sample includes *all injuries reported to the LIA* 2011–2016, while the study sample only includes reported injuries that were investigated in 2015. Another difference is that the 'inspection' sample includes only employees in construction companies, while the main study sample also includes employees in non-construction companies (e.g. hired workers) injured during construction work. The level of underreporting is unknown. The 'insurance' sample is occupational injuries that lead to medical treatment or lead to work disability reportable to the Labour and Welfare Administration (LWA). These are the public injury statistics in Norway. The injury notification forms, including accident type, must be filled in by the employer, but are sometimes filled in by the injured worker. The level of underreporting is unknown (Statistics Norway, 2016).

The 'survey' sample is based on telephone interviews of a representative sample of workers. One question asked if the interviewees had been injured in a work accident the last 12 months. 915 of these workers were construction workers of which 41 were injured. The same accident type variable was used as in the other samples, but the sample lacks some categories. About 50% of these injuries did not lead to sick leave, so the average severity is low.

3. Methods

Descriptive epidemiology is an often-used method in investigation of construction accidents on a national, regional, or company level (Swuste et al., 2012). Descriptive epidemiology seeks to summarise conditions based on person, place, and time by analysing the pattern of health outcomes (e.g. accidents) (Aschengrau and Seage, 2007). This research uses a similar approach to that used in industrial settings, so-called 'incident concentration-analysis' (Kjellén and Albrechtsen, 2017). The purpose of incident concentration analysis is to identify clusters of incidents with common characteristics. The concentrations indicate where to prioritise safety measures and types of measures to prioritise. Incident-concentration analysis in industrial settings is carried out in several 'dimensions'. The basic assumption is that each industrial system has its own clusters of accidents, mainly decided by the types of energies involved in the production. The steps in the incident concentration analysis used in this research are to:

(1) Establish uni- and bi-variate distributions for different dimensions.
(2) Select concentrations making up a significant portion of the total number of records (e.g. 5–10 out of 50 records) with similar characteristics.
(3) Analyse these concentrations in more detail.
(4) Look for similarities in activities, sequence of events and energy involved.

3.1. Framework for analysis of the accident sequence

The framework used in this analysis is based on three elements that are basic in many accident causation models – namely hazards, barriers/defences, and loss (e.g. Haddon, 1980; Reason et al., 2006). An accident involves hazards coming into contact with objects (e.g. workers) as the result of failures in one or more barriers (Haddon, 1973).

The cases in this analysis are construction workers injured in accidents, which represent the 'loss'. A clarification and operationalisation of the terms 'hazards' and 'barriers' is necessary.

3.1.1. Energy, hazards, and accident types

The first step in this analysis is to identify hazards that are frequently involved in accidents and how they affect workers. Haddon (1973) addressed the notion that injury occurs through the transfer of energy (kinetic, thermal, chemical, electrical, and ionising radiation). An injury occurs when '… energy is transferred in such ways and amounts, and at such rates, that inanimate or animate structures are damaged' (Haddon, 1973, p. 41). A hazard is a '… potential source of injury or damage to health of people, or damage to the environment or material assets' (Kjellén and Albrechtsen, 2017, p. 476). There are several variables for categorising 'accident types' (e.g. Eurostat and ILO), and each 'accident type' is linked to a specific hazard which is a source of energy. An accident type variable helps to identify how a hazard affects a worker. In Norway, the same accident type variable is used in the samples described above which makes it possible to compare the distributions of accident types across the samples. To identify more detailed accident types, a variable developed for occupational accidents by the WORM project (Workgroup Occupational Risk Model) in the Netherlands (Hale et al., 2007) is utilised. This variable is based on the bowtie and the aim behind the variable is to '… describe all types of occupational accidents in a set of generic descriptions, or scenarios, linking the development of each type of accident to the possible barriers …' (ibid. p. 1701). The object behind the development of the variable was to support companies in their risk analysis and prioritisation of prevention. The variable has 36 different 'scenarios' and is also used in the 'Storybuilder' tool (Bellamy et al., 2007) and in a study of construction accidents in the Netherlands (Ale et al., 2008).

3.1.2. Barrier failures

The second step in this analysis is to identify failed barriers and discuss preventive measures. There is no generally accepted definition of barriers (Sklet, 2006). In this paper, we apply Kjellén and Albrechtsen's (2017, p. 130) definition of a barrier as '… a set of system elements (human, technical, organisational) that as a whole provide a barrier function with the ability to intervene into the energy flow to change the intensity or direction of it'. A *barrier function* is 'the ability of a barrier to intervene into an accident sequence to eliminate or reduce loss', and the *barrier system* is '… a set of interacting, human, technical and organisational elements that make up the barrier function'. Some barriers are specifically made for safety, for example, guardrails and hard hats; others are part of a production system or structure, for instance building materials and scaffold floor. Some barriers are a mix of these functions. The categories of barrier element failures in this research are developed inductively based on the qualitative descriptions of the accident sequence in the material.

Haddon (1980, p. 8) identified '… generic strategies that encompass all of the tactics that may be used to reduce damage'. These strategies are also called 'energy barriers' (Trost and Nertney, 1995). The first strategy helps us consider measures that can eliminate basic hazards, while the other nine help us consider measures that can interrupt the injury process at different stages. Haddon's strategies encourage a fundamental way of thinking about the processes by which injuries occur and the ways in which they can be prevented (Runyan and Baker, 2009). The strategies focus mainly on passive measures that will have a more universal and lasting impact than behavioural strategies. These strategies are not mutually exclusive and combinations of measures are often recommended.

Table 2
Haddon's 10 countermeasure strategies for reducing loss. Based on Haddon (1980) and Kjellén and Albrechtsen (2017).

Related to the hazard (energy source)	Related to the <u>separation</u> of the hazard from the object (worker)	Related to the vulnerable <u>object</u> (worker)
1. Prevent the creation of the hazard	6. Separate, in time or space, the hazard and the vulnerable target	8. Make the object more resistant
2. Modify relevant basic qualities of the hazard 3. Reduce the amount of the hazard 4. Prevent the release of the hazard 5. Modify the rate or spatial distribution of release of the hazard from its source	7. Separate the hazard and object by physical barriers	9. Limit the development of loss 10. Stabilise, repair and rehabilitate

Table 3
Background data for the 176 accidents/184 injuries in the main study sample in percentages.

Sex of involved workers (%)		Age of involved workers (%)		Nationality of involved workers (%)		Potential fatality of accident (%)	
Male	98.3	15–19	8.4	Norway	62.0	Fatality	2.4
Female	1.7	20–24	13.8	Other Nordic countries	5.6	Likely	46.5
Tot.	100.0	25–39	29.9	Eastern Eur.	25.8	Possible	25.9
		40–54	34.1	Other Eur. countries	6.1	Not possible	25.3
		55–67	12.6	Non-Eur.	0.6	Tot.	100.0
		67 <	1.2	Tot.	100.0		
		Tot.	100.0				

Kjellén and Albrechtsen (2017) order Haddon's strategies (1980) so that the primary strategies are related to the hazard (energy source) (strategy 1–5), separation of the hazard and object (strategy 6, 7), and the vulnerable object (strategy 8–10) (Table 2). Strategies 9 and 10 are beyond the scope of this analysis.

Trost and Nertney (1995) describe three types of limitations in barriers. One limitation is that *barriers are not practical* (NP) due to the energy source, cost of the barrier etc. Another limitation is that *barriers fail* (BF), for instance that physical barriers erode and procedural barriers deteriorate through weak change control. A third limitation is when *barriers are not used* (NU). Most of the accidents in this material do not have details to assess deficiencies in the total barrier systems. The aim is to identify main failures in *physical barrier elements* that contributed to the accidents.

4. Results

Table 3 shows background data for injured persons and the accidents in the main study sample.

Only 3 of the injured workers were women. The average age was 38 years, 64% of the injured were between 25 and 55 years, and 22% were younger than 25. The material does not always give information about the conditions of employment, but at least 18% were hired workers and 9% apprentices or hired for a summer job. 38% of the injured persons had foreign citizenship, 26% were from Eastern Europe, with the majority from Poland.

A method used by Haslam et al. (2003) was also used in this research to indicate potential fatality. Information from the accidents was used to evaluate alternative outcomes and to assess the outcome if the injured person had been in a slightly different location or if a different part of the body had been involved. *Likely fatality* required only a minor change in circumstances and *possible fatality* required a number of circumstances to change. 47% were assessed to be *likely* fatalities, 26% *possible* fatal accidents, and 25% were *not possible* fatalities. Most of the accidents assessed not to be likely or possible fatalities, were accidents using a saw.

4.1. Accident types and severity

The accident types in the main study sample are compared to four other samples of injury data representing four different degrees of severity (Tables 1 and 4). The purpose of the comparison is to assess the representativeness of the study sample and relations between severity and accident types.

4.1.1. Distributions of accident types and representativeness

The distribution of injuries on the accident type variable across the samples was evaluated using a chi square goodness of fit test. One requirement for the test is that no more than 20% of the expected counts are less than five cases. The accident type 'chemicals' was the main contributor to counts less than five and was therefore excluded from the test.

The results show that the study sample was significantly different from the other three samples included in the test. The relations between the other samples were also tested and they were also significantly different from each other. The results clearly indicate that there is a relation between severity and accident types across samples representing different severity. Hence, the main study sample is not completely representative for the fatal injuries or the less severe injuries. However, the order of the accident types is fairly similar to the 'insurance' and 'inspection' samples, while the order of the fatalities is somewhat different. Our assessment is that the study sample is relatively representative for severe injuries. However, we should be cautious about concluding that the shares of the accident types are correct. The results indicate that fall accidents might be overrepresented, and that 'cut' and 'squeezed/caught' might be underrepresented in the study sample. A more thorough comparison of the study sample and sample of fatal injuries is undertaken in Section 4.3.

4.2. Construction types and accident types

This section compares the distribution of accident types in the main study across four different construction types. Table 5 describes the construction types and the number of accidents. No data exists for indicating the size of production or working hours for these constructions types, which makes it impossible to produce exposure data. Fig. 1 combines construction type and accident type.

Only the accident types 'fall, 'hit by object', and 'cut' have sufficient observations to be included in the analysis. A chi square test was carried out showing that the distribution of the accident types was significantly different across the four construction types ($x^2(9) = 19.747$, $p \leq .002$). In *Building*, the most frequent accident types are fall from height (roof/floor/platform and scaffold), hit by objects (equipment and materials), and cut by sharp object (mainly saws). The largest difference between *Building* and the other construction types is the relatively high number of 'cut by sharp object'. In *Civil Engineering,* the most frequent accident type is hit by object (mostly heavy objects like concrete slab/block, rocks, poles and plates). The second most frequent accident type is fall from height (scaffolds, platform, lift, beam, and into a hole). Other accidents involved blasting (2), trench collapse (2), and dump trucks (2). *Civil Engineering* has a larger proportion of fatalities/likely fatalities than the other construction types. The results suggest that the hazards involved in *Civil Engineering* accidents are different from the other construction types and that there are often large amounts of energy involved. The accidents in *Engineering Construction* are relatively similar to accidents in *Building*. The main difference being that they happened at other types of sites, for instance industrial sites, warehouses, power plants, and farms. The 12 fall accidents were relatively equally distributed between ladder, scaffold, and roof/floor/platform. In *Refurbishment*, there are many falls from height (66%). 11 of the workers fell through the roof while working on rooftops changing roofing, doing repair work or demolition work. The main triggering factors were that they slipped on the roof and fell, or that the roof collapsed. There were seven falls from scaffolding structures. These accidents mainly happened during refurbishment and/or painting of the front of buildings. The results indicate that the distribution of accidents is relatively different across most construction types.

4.3. Identifying more detailed accident types

This section identifies more detailed 'accident types' by using an accident type variable with 36 different categories developed by the WORM project (Hale et al., 2007). The distribution of accident types in the main study sample is compared to fatal injuries to give a broader basis for prioritisation (Fig. 2).

Table 4
Accident types (%) for injured persons in the construction industry for different samples. The order of the top five accident types in parenthesis.

	'Study sample'	'Fatal'	'Inspection'	'Insurance'	'Survey'
Fall	48 (1)	33 (1)	42 (1)	29 (1)	19 (3)
Hit by object	24 (2)	22 (2)	16 (3)	27 (2)	27 (2)
Cut by sharp object	13 (3)	1	19 (2)	19 (3)	30 (1)
Squeezed, caught	6 (4)	12 (4)	11 (4)	9 (4)	5 (4)
Electricity	4 (5)	3	6 (5)	8 (5)	–
Bumping, crash, collision	2	19 (3)	2	3	–
Overturn	2	4	2	3	–
Explosion, blasting, fire	1	6 (5)	1	1	–
Chemicals	1	0	1	2	–
Total	100	100	100	100	–
Chi square goodness of fit test with study sample	–	$x^2(7) = 54.241$, $p \le .000$. (Sig.)	$x^2(7) = 14.567$, $p \le .042$. (Sig.)	$x^2(7) = 27.680$, $p \le .000$. (Sig.)	–

Table 5
Construction type and number and per cent of accidents (Typology based on Haslam et al. 2003).

Construction type	Description	N.	%
Building	Residential (houses/apartments) and non-residential (commercial/industrial buildings)	73	41.5
Refurbishment	Refurbishment and renovation	35	19.9
Civil Engineering	Road, rail, bridges, etc.	27	15.3
Engineering Construction	Petro-chemical, power generation, heavy industrial	25	14.2
Other	–	16	9.1
Total	–	176	100.0

A chi square test was carried out for the two samples. To focus on the differences between fatal vs. non-fatal accidents, the four fatal injuries in the study sample were excluded here and included in the sample of fatal injuries in the chi square test. Only 10 types had an expected count of five or more for at least one of the groups (study sample and fatal), and hence 260 injuries were included in the chi square test. The test showed that the distribution of accident types for the study sample and the fatal injuries were significantly different ($x^2(9) = 65.910$, $p \le .000$). The main difference between the two samples was that many accidents in the main study sample (non-fatal) were related to tools and machines (e.g. saws, angle grinders, and nailing machines), working in height, and flying/ejected objects (e.g. piece of wood or nails), while many of the accident types in the sample of fatal injuries were related to large falling objects (for instance rocks or concrete elements), explosions, and large vehicles. The results show that the differences in accident types between the study sample and fatal accidents can be explained by differences in types of work and type and amount of energy involved.

A list of seven accident types is suggested for prioritisation for the construction industry and analysed below. The list includes the six most frequent types in Fig. 2. 'Contact with flying/ejected objects' was excluded because these accidents included many different types of objects in many different situations, and hence was not an 'incident concentration'. During the analyses, it was found that in 14 accidents, workers were hit by objects during lifting. These accidents were categorised as 'contact with falling objects' (7), 'fall' (4) and 'contact with swinging/hanging objects' (3). This also illustrates that using predefined categories in a mechanistic way might lead to excluding important clusters. It was decided to include 'hit by object in lifting operations' in the analysis despite not being one of 36 categories in the accident type variable. The list of seven accident types applies to severe accidents and are analysed below.

4.4. Analysis of prioritised accident types and barrier failures

In this section, more detailed patterns of scenarios and barrier

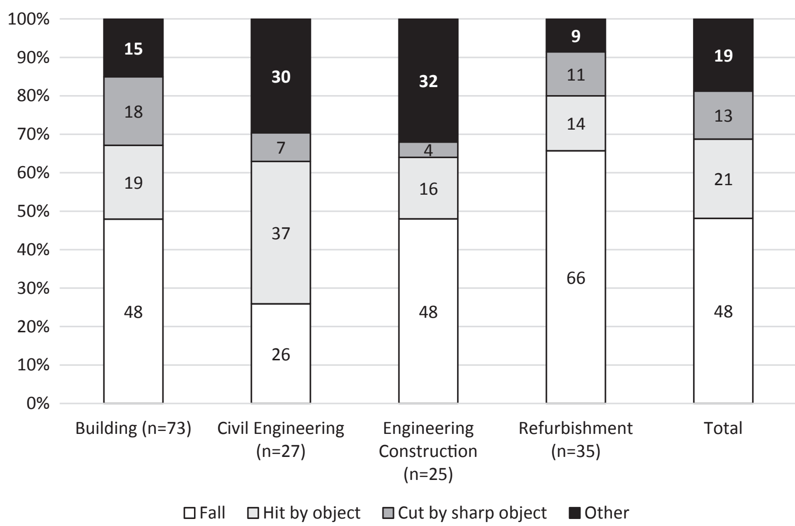

Fig. 1. Construction type and accident type combined (n = 160). (In 16 accidents, construction type is 'other'). Chi square test: $x^2(9) = 19.747$, $p \le .002$.

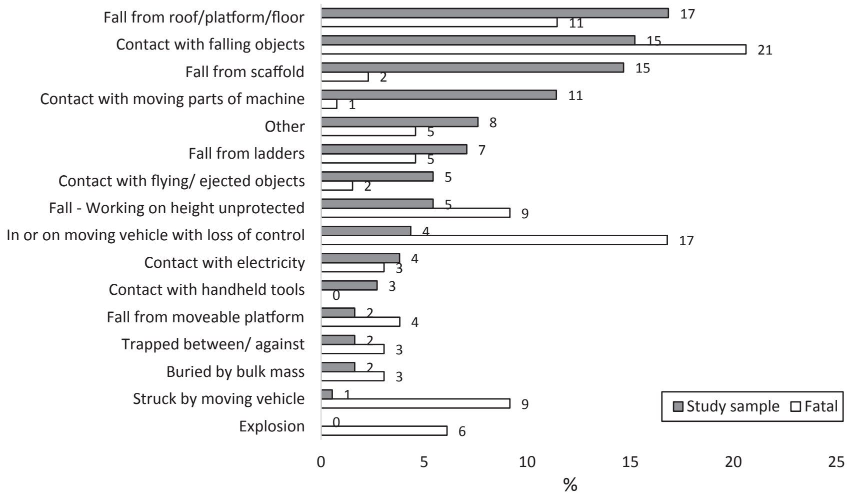

Fig. 2. Most frequent accident types (%) for injuries in the study sample (N = 184) compared to fatal injuries (2000–2014) (N = 131).

Table 6
The seven accident types and central barrier element failures related to Haddon's strategies (1980) and barrier limitations (N = 138 accidents and 169 barrier element failures). (NU = Not used. F = Partial or total failure. NP = Not practical. LE = Latent error. HE = Human error).

Accident type	n.	Central barrier element failures	n.	Haddon	Limitation
Fall from roof, floor, platform	30	Opening/hole in structure	12	7	NU
		Edge protection/fall arrest	9	7	NU
		Floor/roof collapse	4	4	F (LE)
Fall from scaffold	26	Floor deficiency	8	4	F (LE)
		Edge protection/fall arrest	6	7	NU
		Working on the outside of the scaffold or on/under railing	6	7	F (HE)
		Scaffold moving, overturning, collapsing	6	4	F (LE)
Contact with falling objects	25	Workers in the danger zone	25	6	F (HE)
		Objects inadequately attached	12	4	F (HE)
		Loss of control of load/equipment	6	4	F (HE)
		Lifting equipment broke	4	4	F (LE)
Contact with moving parts of a machine	21	Loss of control of saw/material	7	4	F (HE)
		Used hand instead of push stick	4	6	F (HE)
		Worker inattentive and 'bumped into' the blade	4	7	F (HE)
		Condition of saw/saw arrangement inadequate	3	4, 7	NU
Hit by object during lifting	14	Workers in the danger zone	14	6	F (HE)
		Loss of control of the load	7	4	F (HE)
		Edge protection (working in height)	5	7	NU
		Lost control of crane	3	4	F (HE)
		Lifting equipment broke	3	4	F (LE)
Fall from ladder	13	Ladder not attached	10	4	NP
Fall from height – unprotected	9	Unprotected	9	7	NU
Total	138	Total	169	–	–

failures within each of the seven prioritised accident types in the main study sample are identified. The categories of 'central barrier element failures' (Table 6) were developed inductively based on the qualitative descriptions of the accident sequence in the material. The barrier failures are also related to Haddon's (1980) countermeasure strategies (energy barriers) and Trost and Nertney's (1995) barrier limitations. In most of the accidents in this material, there is a lack of sufficient details to assess all of Haddon's strategies related to barrier failures. However, there are sufficient details to assess strategies number four (prevent the release of the hazard), six (separate, in time or space, the hazard and the vulnerable target) and seven (separate by physical barriers). In the discussion of possible measures against the different accident types, all of Haddons' strategies are discussed.

4.4.1. Fall from height

There were 81 falls from height, representing 46% of the accidents. The height of the fall was known in 68 of the 81 fall accidents. The average height of the falls was 3.9 m, the median 2–3 m, the maximum height 17 m and the minimum 0.5 m. 78% of the fall accidents were between two and five metres. In some of the fall accidents, the injured person fell in two or more stages, and in other accidents the injured person fell into shafts or the like that slowed down the fall. 73% of the fall accidents were assessed to be likely fatalities if there had been minor changes in the circumstances (one *was* a fatality).

4.4.1.1. Fall from roof, floor, platform. 'Openings and holes' were the most frequent barrier failures in fall from roof, floor and platform. The openings were mainly on rooftops, between floors, for ventilation systems, and for staircases. Most of these accidents happened during construction or refurbishment of buildings when there were temporary openings between floors or openings for staircases. Some of the openings were covered with plates etc. that did not support the weight and some plates were not sufficiently attached. In most of these accidents the injured persons were not aware of the openings. 'Edge protection' was assessed to be the main barrier failure in nine accidents. Some workers slipped and fell, others got interrupted by another event and took a step aside. In these accidents, no edge protection or fall arrest was implemented. 'Floor/roof collapse' was the main barrier failure in four accidents. In two of these accidents, the workers stepped on plates not attached, and in the other two, the workers fell through roof/floor that did not support the weight.

4.4.1.2. Fall from scaffold. 'Floor deficiency' was the main barrier failure in eight of the scaffold accidents. In four of them, the scaffold floor was in a poor condition (rotten) and in the other four, the scaffold floor was not properly attached and moved when the worker stepped on it. 'Edge protection' and 'fall arrest' was assessed to be the main barrier failure in six of the scaffold accidents. Some slipped, others 'forgot' that there was no protection and took a step aside. 'Working on the outside of the scaffold, or on/under the railing' occurred in six accidents. There were physical barrier elements in these situations, but the workers bypassed them. In some accidents, it seems that it was difficult for the workers to do the job standing on the scaffolding so they chose to do it outside or under the railing. 'Scaffold moving, overturning, or collapsing' was the main barrier failure in six accidents. Three accidents involved movable scaffolds that were moved while workers stayed on them. In three accidents, the scaffold overturned/collapsed. These six accidents have many dissimilarities and include barrier failures and deviations like moving scaffolds while workers stay on them, deficiencies in attachment, uneven ground, and too much weight on the scaffold so it collapsed.

4.4.1.3. Fall from ladder. In 10 of the accidents involving ladders, the main barrier failure was that the ladders were not properly attached on the top or bottom. In most of the accidents involving a ladder, it would have been safer to use scaffolds, platforms, or lifts. Most of these accidents happened to workers installing, controlling, or taking down electrical systems and heat pumps. These jobs are often short-term jobs where the customer provides the ladder. This group may be especially vulnerable to unsafe working conditions.

4.4.1.4. Fall from height – Unprotected. There were nine falls from height where the worker was unprotected, meaning that they were exposed to fall hazard without any physical safety barriers like edge protection, fall arrest equipment, or safety nets. In four of these accidents, the workers were working on structures without any protection (beams and transformer station) where they slipped and fell. In two accidents, the workers were first hit by objects (crane and railing) and then fell.

4.4.1.5. Barrier failures and measures against fall accidents. Many fall accidents are preventable by 'eliminating the hazard' (Haddon's strategy 1). This is often a task for designers and planners. Work at height can be avoided by doing jobs at ground level, for instance assembling edge protection and materials and using extendable tools. Many of the holes, openings, and unprotected edges could have been eliminated. The 'qualities of the hazard' (strategy 2) can be reduced by ensuring that there are no items with sharp edges etc. below the workers, and by 'soft landing systems'. The 'amount of the hazard' (strategy 3) can be reduced by lowering the height, reducing the number of workers exposed to fall hazards and the time they are exposed to fall hazards (e.g. job rotation), and reducing the hazardous area (e.g. size of openings and unguarded edges). The 'release of hazard' (strategy 4) can be prevented by a 'work restraint system' that prevents workers from getting into a fall position, good housekeeping, and by non-slippery surfaces to prevent slips and trips that can lead to falls. 'Separation in time or space' (strategy 6) can be achieved by keeping workers out of the fall danger zone when there are temporary openings and areas without edge protection. Some accidents occurred when workers entered scaffolds and platforms during erection, and when altering and disassembling scaffolds and platforms. All fall accidents could have been prevented by adequate physical barriers like edge protection and fall arrest equipment (strategy 7). The workers' ability to prevent and handle hazardous situations (strategy 8) can be increased by training and recruiting workers that are fit, healthy, experienced, and competent.

4.4.2. *Contact with falling objects*

Most of the 25 accidents where the workers came in contact with falling objects involved large and heavy objects overturning during construction or deconstruction. Heavy objects include: supporting beam, electricity pole, principal rafter, mesh reinforcement, and concrete wall element (fatal accident). Variation in the size, weight and the height of the fall of the objects influenced the potential of fatality. Most of these accidents were assessed to be *likely* or *possible* fatal accidents, and one *was* fatal.

Large objects exist in most construction projects and hence this hazard is hard to eliminate, modify, or reduce (strategies 1–3). Therefore, preventing release of the hazard (strategy 4) is important. Many of the accidents happened during assembling and disassembling of building structures and materials. In at least 12 of the accidents, the falling objects were inadequately attached. And in at least four of these accidents, strong wind was a triggering factor. A fatal accident happened due to inadequate temporary anchorage of a wall element and strong wind. In these accidents, the injured persons were (of course) in the danger zone (strategy 6). In most of the accidents, the workers did not assess that there was a 'falling objects hazard', and hence a danger zone.

4.4.3. *Contact with moving parts of a machine*

In 21 accidents, the injured persons were in contact with moving parts of a machine. 16 of the accidents involved different types of saw, 10 of them the so-called 'Norsaw'. The injuries in these accidents were mostly loss of fingers or deep cuts in fingers or arms. These are serious injuries, but none of them were assessed to be likely fatalities. In seven of the saw accidents, a kickback or that the piece 'jumped', caused the hand to fall onto the blade.

Hazards related to the saw can be eliminated (strategy 1) by using pre-cut materials. Saw manufacturers produce saws with modified blades and create saws that stop with flesh contact (strategy2). The amount of the hazard (strategy 3) can be reduced by avoiding wearing things that can come in contact with saw, for example, gloves, rings and long sleeves. The release of the hazard can be prevented (strategy 4) by ensuring stability of saw arrangement and materials. In three accidents, inadequacies in the condition of the saw/saw arrangements was found to be a contributing factor. In at least four accidents the injured person used the hand to push the piece of wood and moved the hand into the blade. These accidents could have been prevented by keeping the hand out of the danger zone and using push stick (strategy 6), or by physical barriers like safety guard (strategy 7). Accidents where pieces of wood were thrown from the blade could have been prevented by wearing safety glasses/face shield (strategy 7). In many of the accidents using a saw, the injured persons were young and/or apprentices and inexperienced. And in many, the workers had been doing the same task for a long time. The number of saw accidents can be reduced by recruiting more experienced workers, training, and reducing duration when single workers use the saw to avoid monotonous work (strategy 8).

4.4.4. Hit by object during lifting

During the analyses, it was obvious that accidents where workers were hit by objects during lifting were frequent. However, the type variable has no single category for such accidents. Hence, a free text search for 'crane', 'lifting', and 'hoisting' was carried out, capturing 14 accidents. These were originally categorised as contact with falling objects (7), fall (4), and contact with swinging/hanging objects (3). These 14 accidents involved moving materials or equipment using different types of lifting equipment like cranes, forklift trucks, and excavators.

In some of these accidents, another method for moving the objects could have been used, for instance moving the object by vehicle instead of lifting above ground (strategy 1). In all the lifting accidents, there was a sudden loss of control of the hazard involved (strategy 4). In seven accidents, there was a loss of control of the load. In some of these accidents, the load hit a worker. In others, the worker was trying to unfasten the load when it suddenly loosened and the worker was hit or squeezed. In three accidents, the lifting equipment (hook, strap) broke so that the load/lifting equipment hit the worker. In five accidents, the workers were working at height and were hit by lifted objects and injured in the fall. These are so-called 'domino accidents' with successive losses of control (Hale et al., 2007). Edge protection was also a barrier failure in these accidents. Ensuring control of the load and the condition and usability of the lifting equipment is important in preventing release of the hazard in lifting operations (strategy 4).

In all the 'lifting accidents', workers were hit by the load, crane, lifting equipment etc., or standing on platform hit by load. A central strategy is to keep workers out of the danger zone and using signallers to ensure that nobody stays in the danger zone (strategy 6).

5. Discussion and conclusion

By studying 176 construction accidents in depth, we aimed to contribute to a more comprehensive knowledge of frequent accident types, barrier failures, and characteristics of construction accidents.

5.1. Accident types

Lists of frequent accident types are important tools for prioritisation. The list of frequent accidents identified in this research adds to the relatively sparse literature on clusters of accident types and barrier failures in the construction industry. It is challenging to compare different studies and statistics on accident types due to use of different accident type variables. However, there seem to be many similarities between the list of frequent accident types identified in this research and other similar overviews (Ale et al., 2008; Eurostat, 2017; Lipscomb et al., 2000; Swuste et al., 2012). Fall from height dominates in most studies and statistics and other frequent 'accident types' are falling/collapsing objects, moving vehicles, moving machine parts, and electricity.

Swuste et al. (2012) concluded (based on a review of studies using mortality data), that there is consensus on a list of the most frequent 'central events' in construction between countries. Results presented in this paper, Eurostat accident statistics (Eurostat, 2017), and research by Ale et al. (2008), suggest differences in distribution of accident types for samples representing different severity. The results in this material demonstrated that many of the non-fatal accidents were related to tools and machines, working in height, and flying/ejected objects, while many of the accident types in the sample of fatal injuries were related to large falling objects, explosions, and large vehicles. These differences are explained by differences in the types and amounts of energy involved as described by the energy model (Gibson, 1961; Haddon, 1973). And the differences in the distribution of accident types across construction types identified in this research, is explained by the different types of work, and hence types and amounts of energies involved in the accidents. This has implications for safety management in the construction industry.

The results support arguments that the causes of minor and major accidents are different and that we can not necessarily prevent major accidents by studying and tackling the minor accidents (Hale, 2002; Reason, 1997), or that we cannot prevent minor accidents by studying and tackling major accidents.

5.2. Barrier failures

The analysis of physical barrier failures showed that in some accidents, there were no physical failures identified, only human failures. In many other accidents, there was only *one* physical barrier to keep a specific hazard under control. For instance, when guardrails were missing or the scaffold floor collapsed, there were no other barriers preventing the worker from falling and hitting the ground. Or when the anchoring of a large building element broke, no other barriers were there to prevent the element from falling. In situations with only one physical barrier element, it is of course important that these barrier elements do not fail. Many of these accidents could have been prevented by implementing more than one physical barrier. In many high-risk industries, for instance, the offshore oil and gas industry, the philosophy is that there should be at least two physical barriers in place at all times to prevent a blowout, so called defence-in-depth (Hopkins, 2012; Reason, 1997). The analysis using Haddon's (1980) countermeasure strategies, demonstrated that there were many opportunities for implementing these strategies at different stages in the accident process. The first strategy, to eliminate basic hazards could have been applied in many situations.

Even though many clusters of accident types and barrier failures have been identified in this research, the material demonstrates an abundance of occupational hazards. Jørgensen (2016) describes such hazards as 'simple hazards' that are so common in every work process that most people hardly think about them and have largely learned to deal with them without getting injured. In such settings, it is important to have several different safety barriers for different hazard sources (Bellamy et al., 2010). There is little research on barriers in the construction industry. Priemus and Ale (2010) focused on barriers in accident investigation and Jørgensen et al. (2011) focused on barrier awareness on an individual level. However, systematic establishment and maintenance of barriers can contribute to preventing accidents similar to the ones in this material. Even though there are differences between occupational 'simple hazards' in the construction industry, and hazards in other industries, the construction industry can learn from experience and guidelines for systematic barrier management from other industries (e.g. NPSA, 2017; OGP, 2014).

5.3. Limitations and future research

One strength of the main study sample is that is allows for analysing accident sequences in depth, while one limitation is that the number of accidents is relatively low (N = 176). Based on a comparison of the distribution of accident types to other samples of injuries, we assessed that the main study sample can be used to make some generalisations from the sample to relatively severe construction accidents. However, one should be cautious about concluding that the percentages of the accident types are exact. Another limitation with this type of research is that we lack exposure data for the types of work represented by the accident type categories. The frequencies do not indicate risk, only frequencies. A third limitation is that this research focuses primarily on identifying proximal factors in the accident process. Accidents are caused by a complex interaction of latent conditions and active failures (Reason, 1997). The next phase in this research project is to identify how immediate factors are related to shaping and originating factors as described by the Construction Accident Causality framework (Gibb et al., 2014; Haslam et al., 2005).

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PAPER II

Accident types and barrier failures in 69 construction fatal accidents in Norway 2011-2017

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Accident types and barrier failures in 69 construction fatal accidents in Norway 2011-2017

The purpose of this research was to contribute to the knowledge about frequent accident types and barrier failures in construction. We studied 69 fatal construction accidents in Norway 2011-2017. The most frequent accident types were: contact with falling objects; in or on a moving vehicle with loss of control; fall from roof/platform/floor; fall from height – unprotected; struck by moving vehicle, and explosion. The most frequent accident types of fatal injuries were different from a sample of frequent non-fatal injuries. The barrier analysis showed that few barrier elements were present in most accidents. Many of the accidents occurred in work situations where the barrier system was totally dependent on the human barrier element. 'Unsafe acts' by frontline workers were identified in 94% of the accidents. Prioritisation of frequent accident types, systematic barrier management, and prevention of unsafe acts are important strategies for preventing fatal construction accidents.

Keywords: construction; fatal accidents; accident types; barrier failures; deviations; unsafe acts.

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1 Introduction

The number of official construction fatalities in Norway increased from 42 in the years 2003-2008 to 59 in 2009-2014 - an increase of 42% (NLIA, 2019). These official numbers do not include hired workers employed by temporary employment agencies or workers from other industries working at construction projects. There was a widespread attitude in the Norwegian construction industry and in the Norwegian Labour Inspection Authority (NLIA) that 'something had to be done'. A formal cooperation, 'Cooperation for Safety in Construction' (COSC) was established between stakeholders in the construction industry for developing strategies for reducing the number of accidents.

Lists of frequent accident types and barrier failures are important for prioritisation and for using in checklists for safety inspections at construction sites. Clients and contractors do not have quantitative material to identify hazards and deviations regarding severe accidents. COSC therefore ordered an analysis of frequent accident types and barrier failures for prioritisation and for developing countermeasures. A first step was an analysis of a sample of 176 relatively severe accidents investigated by the NLIA in 2015 (Winge & Albrechtsen, 2018). This study sample was compared to other samples of construction injuries representing different severity, showing significant differences in accident types between the samples. To prioritise 'fatal hazards' it was therefore decided to study a sample of fatal accidents in depth. The purpose of this research was therefore to identify (1) detailed accident types for fatal injuries, and (2) barrier failures, unsafe acts and other deviations related to the most frequent fatal accident types. This was done by studying 69 construction fatal accidents (72 injuries) in Norway 2011-2017. The literature on detailed accident types and barrier failures for fatal construction on a regional/national level is sparse. Buskin and Paulozzi (1987) studied 231 fatalities in the construction industry in Washington State between 1973 and 1983. They found that falls, cave-ins, and electrocutions resulting from heavy equipment (boom type) contacting overhead power lines accounted for 45% of the fatalities. Heavy construction had a death rate twice that of the other two construction subgroups (building and special trades construction). Sorock, Smith, and Goldoft (1993) studied 200 construction-related fatalities in the New Jersey construction industry 1983 to 1989 and found that the leading cause of death was falls (46%). In a study of work-related deaths among construction workers in North Carolina 1988-1994, Lipscomb, Dement and Rodriguez-Acosta (2000) found that work related deaths were most often 'caused by' motor vehicles (21%), falls (mostly roofs and scaffolds) (20%), machinery (15%), electrocutions (14%), and falling objects (10%). Three major causes of work-related motor vehicle accidents were identified including injuries to pedestrians in highway work zones and in back overs on construction sites, and injuries to drivers caused by shifting loads while transporting construction materials.

In a study of 153 construction fatalities in Kocaeli, Turkey (1990-2001), Colak, Etiler and Bicer (2004) found that the 'cause of death' was fall from height (45%), vehicle accidents (14%), and electrocution (14%). In a study of 235 construction fatalities in a 'new development area in east China' (1991-1997), Xia et al. (2000) found that falls were the leading cause of death (46%) followed by collisions, struck by/against something, electrocutions, and excavation cave-ins. These accident types represented 94% of all fatalities. In a Dutch study of 'accident types' in the construction industry, Ale et al. (2008) used a more detailed accident type variable. The most frequent accident types were contact with falling/collapsing object, followed by fall from height-roof/floor/platform, struck by moving vehicle, and fall from moveable platform. They also found differences in the distribution of accident types between fatal and non-fatal accidents. In a study of work-related fatal and nonfatal injuries among US construction workers (1992-2008), Dong, Wang, Herleikson, and Center (2010) found that falls (from roofs, ladders and scaffolds) was the leading cause of death in construction (32%), followed by transportation accidents, contact with objects, and exposure to harmful substances or environments. They also found that patterns of leading causes for nonfatal injuries differ from those for fatal injuries. They underline that the numbers should be interpreted and used with caution, because some construction workers are 'misclassified' in non-construction industries. For instance, workers from temporary work agencies are classified in 'services'.

In the Eurostat statistics (EU28) of fatal construction accidents 597 fatal were registered in 2016 (Eurostat, 2019). The most frequent 'deviations' were; fall of persons (29%); breakage/fall/collapse etc. of material agent (19%); and loss of control of machines, equipment, tools etc. (17%). The distribution of 'deviations' for non-fatal accidents was somewhat different. Kjellén (2018) analysed some of the same accidents (N=60) as in this study to develop a safety performance indicator suitable for real-time management of major accident hazards in construction. He found that about 70% of the accidents belonged to three main categories: fall from height, driver or person outside the cabin killed by moving construction machine/vehicle, and person killed by load or equipment during material handling. The three main categories were divided into subcategories and analysed to identify barriers to prevent adverse consequences.

It is demanding to compare the different studies and statistics since there are different variables and categories used for describing accidents, e.g. 'deviations', 'cause', 'accident/injury types' and 'central events'. Based on a review of construction safety literature using mortality data, Swuste, Frijters, and Guldenmund (2012) concluded that the most frequent 'central events' were: falling from height; contact with falling or collapsing objects; contact with electricity; contact with moving machinery parts; falling from a moving platform; contact with hoisted, hanging, swinging objects; hit by vehicle; squeezed between or against something; and contact with objects thrown from machine. Swuste, Frijters, and

Guldenmund (2012) also concluded that '… between countries there is consensus on this list' (ibid. p. 1341).

2 Material and methods

2.1 Sample

One limitation with the official construction accident statistics in Norway, and many other countries, is that it includes only workers employed by construction companies. It does not include hired workers employed by temporary employment agencies or workers from other industries doing work at construction projects. This means that construction accident rates can be underestimated in many countries. Dong et al. (2010) also reported that some construction workers are 'misclassified' in non-construction industries.

To capture all construction fatalities, sampling was undertaken in three steps. First, all the 57 construction fatalities from the official statistics were registered. Norwegian companies are classified after economic activities according to NACE Rev 2 (Eurostat, 2008). Second, three of the 57 were removed from the sample because the work carried out had nothing to do with construction. Fatalities in traffic accidents between different work operations were included. Third, to capture workers killed in construction accidents, not employed by construction companies, we analysed all fatal occupational accidents in the period to capture construction fatalities registered in other industries. We registered 18 workers killed in construction accidents not employed by construction companies, that was included in the sample. So, the study sample consists of 72 fatal injuries (57-3+18) killed in 69 accidents. The workers not employed by construction companies represent 25% of the sample. It is assumed by the NLIA that almost all occupational fatal accidents are captured in NLIAs database. The main study sample of fatal injuries is compared to a sample of 180 non-fatal injuries investigated by the NLIA in 2015. These are mostly relatively severe injuries, because it is fatal injuries and severe injuries that must be reported to the police and the NLIA, according to the Norwegian Work Environment Act (Winge and Albrechtsen, 2018).

2.2 Incident concentration analysis

The study sample of 69 fatal accidents (72 injuries) was analysed using 'Incident concentration-analysis', which is an approach to identify clusters of incidents with common characteristics, e.g. hazards, deviations, barrier failures, time and place (Kjellén and Albrechtsen, 2017). The concentrations indicate where to prioritise safety measures and types of measures to prioritise. Incident-concentration analysis in industrial settings is carried out in several 'dimensions'. The basic assumption is that each industrial system has its own clusters of accidents, mainly decided by the types of energies involved in the production. The steps in the incident concentration analysis used in this research were to:

(1) Establish uni- and bi-variate distributions for different dimensions

(2) Select concentrations making up a significant portion of the total number of records (e.g. 5-10 out of 50 records) with similar characteristics

(3) Analyse these concentrations in more detail

(4) Look for similarities in activities, sequence of events and energy involved.

2.3 Accident types

There are several variables for categorising 'accident types' (e.g. Eurostat and ILO), and each 'accident type' is linked to a specific hazard which is a source of energy. An accident type variable helps to identify how a hazard affects a worker. To identify relatively detailed accident types, a variable developed for occupational accidents by the WORM project (Workgroup Occupational Risk Model) in the Netherlands (Hale et al., 2007) was applied. This variable is based on the bowtie and the aim behind the variable is to '… describe all types of occupational accidents in a set of generic descriptions, or scenarios, linking the development of each type of accident to the possible barriers …' (ibid. p. 1701). The variable has 36 different 'scenarios' and was also used in the 'Storybuilder' tool (Hale et al., 2007; Bellamy et al., 2007) and in a study of construction accidents in the Netherlands (Ale et al., 2008).

2.4 Barrier failures

There is no generally accepted definition of barriers (Sklet, 2006). In this paper, we apply Kjellén and Albrechtsen's (2017, p. 130) definition of a barrier as '… a set of system elements (human, technical, organisational) that as a whole provide a barrier function with the ability to intervene into the energy flow to change the intensity or direction of it'. A *barrier function* is 'the ability of a barrier to intervene into an accident sequence to eliminate or reduce loss', and the *barrier system* is '… a set of interacting, human, technical and organisational elements that make up the barrier function'. The categories of barrier element failures in this research are developed inductively based on the qualitative descriptions of the accident sequence in the material.

2.5 Barrier limitations

To identify types of barrier limitations, we used Trost and Nertney's (1995) three types of limitations. The first limitation is that barriers were *not practical* (NP). Barriers was impossible to be placed in such a way as to protect the persons and objects due to the nature of the energy source, cost of the barrier, etc. The second limitation is that *barriers fail* (BF). Barriers could be in place and built as designed, correctly, but still fail. For example, a roof, scaffold floor, building structure, brakes on a vehicle or guardrail, can fail. This can be caused by energy levels that build up gradually. No barrier is 100% effective. Physical barriers can erode, and procedural barriers can deteriorate through weak change control. The third limitation is when *barriers are not used* (NU). Sometimes barriers could/should have been provided but were not (NP). Or, barriers were provided but were not correctly used by persons (Worker actions, WA).

2.6 Unsafe acts

Based on the development and employment of the ConAC framework (Haslam et al., 2003; 2005) we defined worker actions and behaviours ('unsafe acts') to be all acts by frontline workers that have an impact on the accident, such as mistakes, unsafe acts, violations of procedures, taking shortcuts, etc. (Winge, Albrechtsen and Mostue, 2019). Included in the definitions was both 'unsafe acts' by the injured workers themselves and other worker actions that contributed to the accidents. There was not sufficient information in most of the accident cases to assess categories of 'human error' by Reason (1990).

2.7 Deviation analysis

In addition to barrier limitations, deviations (i.e. an event or a condition that depart from the norm for the faultless or planned process) in the work system and production processes explain direct causes for accidents (Kjellén and Albrechtsen, 2017). There are many different schemes for classification of deviations available (e.g. Kjellén and Larsson, 1981; Bird and Germain, 1985). In the present study we apply a checklist provided by Kjellén and Albrechtsen (2017) that includes deviations related to the work situation, the surroundings, the incident and the development of injury/damage (Table 1). Deviations represent a state of lack of control of energy, that might transgress into loss of control of the energy source in which damage is likely to happen. In the analysis of the accidents type, loss of control of the energy source was also included (table 1).

2.8 Theoretical framework for analysis

Table 1 summarize that classification schemes used to analyse the set of fatal accidents. The study sample of the fatal accidents were classified according to this framework. The accident type variable used includes 36 categories and is not included in the table (Hale et al., 2007).

Table 1. Framework for the analysis of accidents

Construction type (Haslam et al., 2003)	**Type of barrier involved (Haddon, 1980)**	**Barrier limitation (Trost and Nertney,1995)**	**Deviations (Kjellén and Albrechtsen, 2017)**	**Type of loss of control (Kjellén and Albrechtsen, 2017)**
1. Building: residential (houses/apartments) and non-residential (commercial/industrial buildings) 2. Civil Engineering: Building of infrastructure such as roads, railways, bridges. 3. Engineering Construction: Construction of petro-chemical systems, power generation systems, and other heavy industrial systems 4. Refurbishment: Refurbishment and renovation.	1.Prevent the creation of the hazard 2.Modify relevant basic qualities of the hazard 3.Reduce the amount of the hazard 4.Prevent the release of the hazard 5.Modify the rate or spatial distribution of release of the hazard from its source 5.Modify the rate or spatial distribution of release of the hazard from its source 6.Separate, in time or space, the hazard and the vulnerable target 7.Separate the hazard and object by physical barriers 8.Make the object more resistant 9.Limit the development of loss 10. Stabilise, repair and rehabilitate	1. Barriers were not practical (NP) 2. Barriers fail (BF). 3. Barriers are not used (NU). 4. Barriers could/should have been provided but were not (NP) 5. Worker actions, (WA).	1. Unsafe acts, e.g. wrong action, wrong sequence, omission 2. Technical failure, e.g. machine break down, missing equipment or tools 3. Disturbance in material flow, e.g. bad raw materials, delays 4. Personnel deviations, e.g. absence, temporary personnel, indisposed 5. Inadequate information, e.g. instructions, work permits, risk assessment 6. Progress delay 7. Intersecting or parallel activities, e.g. other work team 8. Poor house keeping 9. Poor physical environment, e.g. excessive noise, high temperature 10. Substandard buildings or infrastructure, e.g. roads 11. Loss-of-control 12. Failure of active safety systems 13. Failure of fixed barriers 14. Failure in personal protective equipment or cloths 15. Person(s) in danger zone 16. Failure in alarm and mobilisation of emergency response team 17. Failure in limiting injury/damage 18. Failure in management of emergency information	1. A person is exposed to an uncontrolled energy flow from the environment 2. A person loses control of an external energy source. 3. A person loses control of a hand tool that is powered by his muscular energy. 4. A person loses control of own body movements. 5. A person loses control of his body due to loss of control of external energy source 6. A person is exposed to energy from activities in the environment (not uncontrolled)

3 Results

3.1 Background data

Table 2 shows the background data for the 72 injured workers. All injured persons were men.

Table 2. Background data for the 72 injured workers (%).

Age		Employers' registered economic activity (NACE rev. 2)		Workers' Citizenship	
15-19	3	Construction of buildings	14	Norway	69
20-24	10	Civil Engineering	12	Eastern Eur.	26
25-39	38	Specialised construction activities	49	Other	4
40-54	32	Other	25	Tot.	100.0
55-67	17	Tot.	100.0		
67<	1				
Tot.	100.0				

3.2 Accident types

Figure 1 shows accident types using the accident type variable developed by the WORM project (Hale et al., 2007). There are more fatal than non-fatal injuries among the vehicle accidents, working at height unprotected, and explosions. And there are more non-fatal than fatal injuries among fall from roof/platform/floor/ladder/scaffold, contact with moving parts of machine and contact with flying/ejected objects. The differences can be explained by differences in the types and amounts of energy involved as described by the energy model (Gibson, 1961; Haddon, 1973). There were too few cases in each cell to carry out a chi square test.

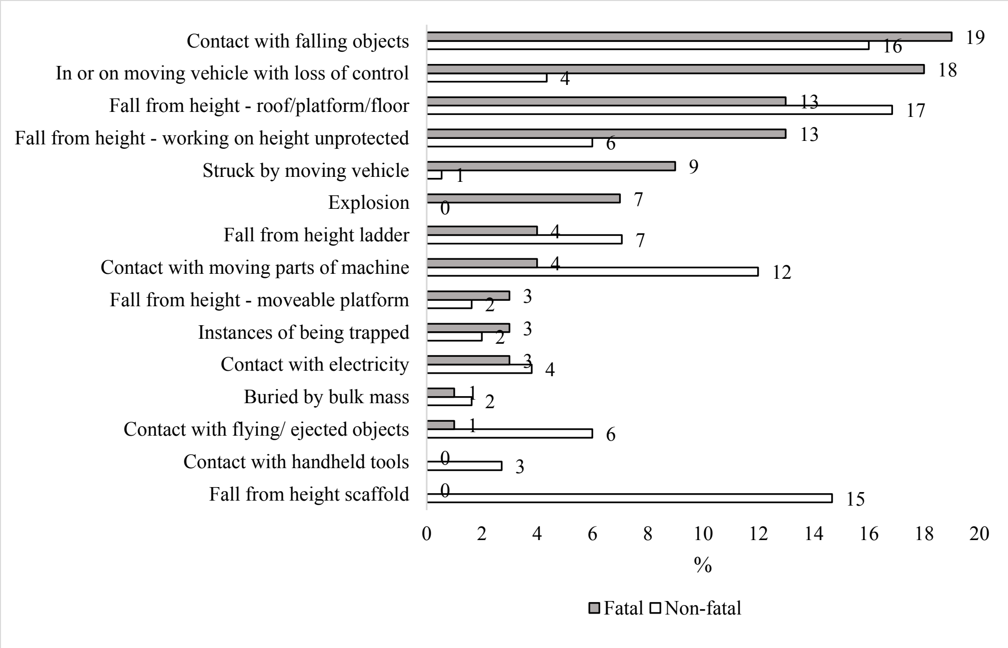

Figure 1. Most frequent accident types (%) for fatal injuries (N=68*) compared to non-fatal injuries (N=179*). (*Accidents categorised as 'other' was removed from the calculations).

3.3 'Unsafe acts'

'Unsafe acts' by frontline workers were identified in 58 of the 69 accidents, latent failures without unsafe acts by frontline workers in four accidents, while in seven accidents there was not sufficient information to assess unsafe acts. This means that unsafe acts were involved in 94% of the accidents where we had sufficient information to assess unsafe acts (58/69-7=94%). Most of the unsafe acts were about deciding to carry out dangerous jobs without adequate safety barriers. The unsafe acts are analysed in more detail in the analysis of the most frequent accident types (section 3.4) and in the deviation analysis (section 3.5).

3.4 Analysis of prioritised accident types and barrier failures

Table 3 shows the results of an analysis of the six most frequent fatal accident types, the number of accidents where unsafe acts were present, and its central barrier element failures. When it was obvious at the time that the risk was high (not just in retrospect), it was judged that the job should never have been undertaken in that circumstances or the hazard should have been eliminated in other ways, the accident is coded 1 (elimination). Sudden loss of control is coded 4. Safety equipment on persons (e.g. fall arrest equipment) are defined as Haddon number 5. There are often multiple barrier element failures in each accident. The table shows that unsafe acts was involved in almost all of the accident types, that each accident type has its specific barrier element failures, and that the most frequent barrier failures are Haddon's number 4 (prevent sudden release of the hazard), 5 (modify the energy when it has been released) 6 (separate hazard and victim in time/space) and 7 (separate hazard and victim by physical means).

Table 3. Analysis of the six most frequent accident types (n=50 accidents/53 injuries) unsafe acts, barrier element failures (Haddon, 1980), and barrier limitations (Trost and Nertney, 1995). (NU=Not used. BF=Partial or total failure. NP=Not practical).

Accident type	**Accidents and number of fatalities in parenthesis (n)**	**Accidents with unsafe acts (n)**	**Central barrier element failures**	**n.**	**Haddon**	**Barrier limitation**
Contact with falling objects	13 (13)	11	Workers in danger zone	12	6	NU
			Collapse of structure	4	4	BF
			Technical failures	2	4	BF
In or on a moving vehicle with loss of control	12 (12)	10	No physical barriers preventing the vehicle from driving out	6	7	NU/NP
			Driver losing control of vehicle	5	4	BF
			Surface (unstable, slippery)	4	4	BF
			Seat belt not used	3	5	NU
Fall from height – roof/platform/floor	9 (9)	9	Fall protective equipment not used	4	5	NU
			Edge protection	3	7	NU
			Collapse of structure	2	4	BF
Fall from height – unprotected	8 (9)	7	No physical barrier preventing fall	6	7	NU
			Fall protective equipment not used	5	5	NU
			Collapse of structure	2	4	BF
Struck by moving vehicle	6 (6)	6	Workers in danger zone	6	6	NU
			Technical failures	2	4	BF
Explosion	3 (5)	2	Elimination of hazard	3	1	BF
Total	51 (53)	45	-	69	-	-

3.4.1 Contact with falling objects

In 13 accidents, workers were hit by falling objects. The falling objects were different types of materials and equipment (6), building elements/structures (5) and rocks (2). In seven accidents there were no barriers to prevent the release of the hazard (Haddon 4) while the worker was in the danger zone (Haddon 6). In four accidents, elements/structures collapsed during construction (bridge, concrete elements, other structures). In two accidents, there were technical failures on vehicles. In 12 of the accidents, the danger zones had not been defined. The 11 unsafe acts were mainly about decisions to carry out dangerous operations with workers in danger zones. The two accidents judged not to be unsafe acts, were the result of latent design failures.

3.4.2 In or on a moving vehicle with loss of control

12 accidents occurred in or on moving vehicles with loss of control. 11 of the accidents occurred in Civil Engineering. Involved vehicles were dumper trucks (5), lorry/truck (3) and excavators (2). In five accidents, the driver lost control of the vehicle. Two accidents were traffic accidents driving off public road. Frequent barrier failures were lack of physical barriers preventing the vehicle from driving out, driver losing control of vehicle, collapse of surface or slippery surface, and seatbelt not used. The unsafe acts in 10 accidents were mainly about decisions to drive vehicles at dangerous places with edges without physical barriers, not being competent to drive the vehicle, poor assessments of surfaces/ground conditions, and not using seatbelts.

3.4.3 Fall from height – roof/platform/floor

Nine accidents were fall from roof, platform and floor. Six occurred in Building, two in Refurbishment, and one in Engineering construction. Four workers fell from roofs/platforms, three fell through openings/holes in building structures, and two fell through roofs while replacing roof/tiles. All accidents were judged to involve unsafe acts. All unsafe acts were about decisions to carry out dangerous work without adequate barriers.

3.4.4 Fall from height – unprotected

In eight accidents, workers fell from height being unprotected. Four occurred in Engineering construction, two in Civil engineering and two in Building. The workers fell from different places, e.g. container, basket, electricity pole, and racking. What is characteristic about this accident type is that the workers are falling from height without any physical barriers (Haddon 7). Two workers fell when the structure they stayed on collapsed. In six accidents it would have been possible to implement physical barriers. Five of the accidents could have been prevented using fall protective equipment. The unsafe acts were mainly about decisions to carry out dangerous work without adequate barriers.

3.4.5 Struck by moving vehicle

Six accidents were struck by moving vehicle. Five accidents occurred in Civil Engineering. The vehicles involved were trucks (3), excavators (2), and dumper truck (1). Three accidents involved vehicles and workers on the ground, where the worker on the ground was run over by the vehicle. In two accidents, the vehicles started to move while parked and ran over the drivers. In one accident, the driver lost control of the vehicle, jumped out, and was run over by the vehicle. Unsafe acts were about poor planning of the work operations, poor communication between workers, and work in danger zones.

3.4.6 Explosion

There were 5 fatalities in three explosion accidents. One occurred at a manufacturing site and is considered irrelevant for assessing barrier failures and unsafe acts. The two others occurred in Civil Engineering. The unsafe acts and main barrier failures was that remains of explosives were not removed (eliminated) after blasting (Haddon 1) and ignited by later operations. The injured workers did not know they were in danger zones.

3.5 Deviation analysis

SMORT level 1 (Kjellén and Albrechtsen, 2017) was applied to analyse deviations (i.e. an event or a condition that depart from the norm for the faultless or planned process) as a direct cause to the fatal accidents, see table 4. The most dominant deviation was 'unsafe act', which is already identified as a main barrier element failure in the barrier analysis above. The second most dominant deviation was loss of control of energy or loss of control of person relative to the energy. About half of these deviations were that a person was exposed to an uncontrolled energy flow from the environment, e.g. an explosion. The other half was that a person either lost control of an external energy source, lost control of own body movements or lost control of body movement due to loss of control of external energy source. Then lack of fixed barriers was the most frequent deviation.

These four frequent deviations indicate that the accidents have happened in a vulnerable system, where only a single failure by humans or technology can lead to severe consequences. Many fatal accidents happen due to humans losing control of either an energy source or his/her body movement. In such a case there is no robust barrier system to prevent the accident from happening. Similarly, many of the human errors are intentional decisions to e.g. carry out operations in danger zones, avoid using safety belts in vehicles, climbing over scaffolds into danger areas. In such situations the only action that can prevent an accident is the action of the victim.

Table 4. Deviation analysis for the six most frequent fatal accidents (n=51)

Deviation	**Accidents on/in moving vehicles**	**Contact with falling objects**	**Fall from height – roof, floor, etc.**	**Fall from height – unprotected, other**	**Struck by moving vehicle**	**Explosion**	**Total**
1.1 'Unsafe acts', e.g. wrong action, wrong sequence, omission,	10	10	9	7	6	2	44
1.2 Technical failure, e.g. machine break down, missing equipment or tools	2	7	3	4	2	1	19
1.3 Disturbance in material flow, e.g. bad raw materials, delays		3	2			2	7
1.4 Personnel deviations, e.g. absence, temporary personnel, indisposed	1	1	1	1	1		5
1.5 Inadequate information, e.g. instructions, work permits, risk assessment	2	5	2	3	2		14
1.6 Progress delay		1					1
2.1 Intersecting or parallel activities, e.g. other work team							
2.2 Poor housekeeping			2				2
2.3 Poor physical environment, e.g. excessive noise, high temperature	4	2		1	2		9
2.4 Substandard buildings or infrastructure, e.g. roads	3	1	2	2	2	1	11
3.1 Loss-of-control	10	10	8	6	1	1	36
3.2 Failure of active safety systems	3	1					4
3.3 Failure of fixed barriers.	6	1	8	4	2		21
3.4 Failure in personal protective equipment or cloths							
3.5 Person(s) in danger zone	1	6			5	2	14
4.1 Failure in alarm and mobilisation of emergency response team							
4.2 Failure in limiting injury/damage	1						1
4.3 Failure in management of information							

3.6 Construction types

Figure 2 compares construction types for fatal injuries and non-fatal injuries. The coding of the injuries was based on an assessment by the researchers of the type of work taking place (see Table 1). There exist no exposure data, e.g. man-years or number of employees for these categories, and it is therefore impossible to compare risk exposure for the construction types.

A chi square test was undertaken, showing that the distribution of fatal- and non-fatal injuries was significantly different across the four construction types (x2(4)=43.126, p≤.000). The Phi coefficient was .415 (p≤.000), showing a moderate strong connection between construction type and injury consequence. The results show for example that more than half of the fatal injuries occurred in Civil Engineering, while almost half of the non-fatal injuries occurred in Building.

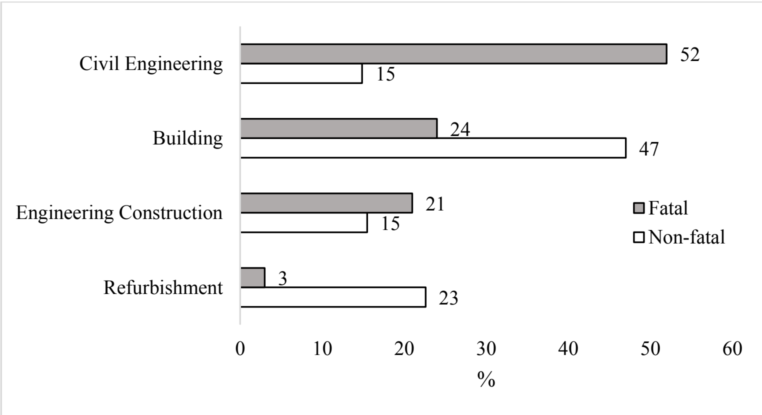

Figure 2. Per cent of fatal injuries (N=66*) and non-fatal injuries (N=168*) across construction types (Typology based on Haslam et al. 2003). (*6 fatalities and 16 non-fatal injuries was categorised as 'other' construction types and excluded).

Figure 3 shows large differences in accident types across construction types. For example, fall dominates in Building and Engineering Construction, while bumping, crash, collision dominates in Civil Engineering.

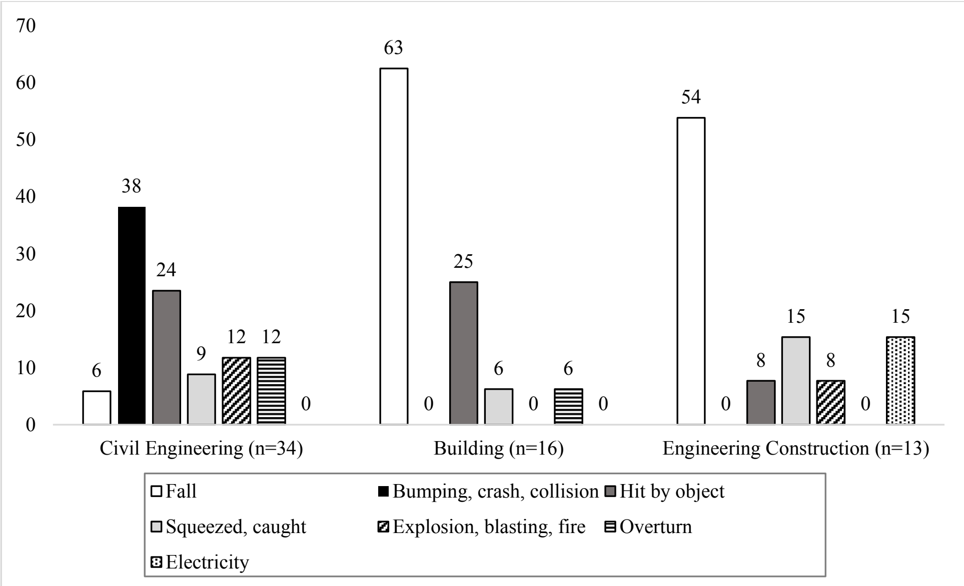

Figure 3 Accident types (%) for the three construction types with most injuries.

4 Discussion and conclusions

The purpose of this research was to identify (1) detailed accident types for fatal injuries, and (2) barrier failures, unsafe acts and other deviations related to the most frequent fatal accident types

4.1 Fatal accident types

Lists of frequent accident types are important for prioritisation and for checklists for safety inspections at construction sites. We found that the most frequent fatal accident types in rank order were (1) contact with falling objects, (2) in or on a moving vehicle with loss of control, (3) fall from roof/platform/floor, (4) fall from height – unprotected, (5) struck by moving vehicle, and (6) explosion.

It is problematic to compare these results to other studies since there are different variables used for describing accidents. There is however obvious that there are both similarities and dissimilarities with the list produced in this research and the list presented by Swuste, Frijters, and Guldenmund (2012) based on a review of construction safety literature using mortality data. In both lists, fall from height and falling objects are dominant. Vehicle accidents are more frequent in this research, while contact with electricity is less dominant compared to Swuste, Frijters, and Guldenmund (2012). One limitation with this type of research is that we lack exposure data for the types of work represented by the accident type categories. The frequencies do not indicate risk, only frequencies.

The results also showed that there were differences in accident types between the fatal injuries and non-fatal injuries, which is consistent with previous statistics and studies (Salminen, Saari, Saarela, & Räsänen, 1992; Jeong, 1998; Ale et al., 2008; Dong et al., 2010; Winge & Albrechtsen, 2018; Eurostat, 2019). There were more vehicle accidents, working at height unprotected, and explosions among the fatal injuries than among the non-fatal injuries. The differences can be explained by differences in work types, hazards, energy types and energy amounts. The results show that hazards of minor and major accidents are different and that we can not necessarily prevent major accidents by studying and tackling the minor accidents (Hale, 2002), or the other way around.

Practical implications are that the list of frequent fatal accident types produced in this research can be used on a national level for prioritising fatal accident types. To reduce the number of fatal accidents significantly, it is necessary to develop countermeasure strategies directed at each of these detailed accident types. At the same time, we found that the accident types were different across different construction types, suggesting a need for specific lists for each construction type. It also shows the importance of having safety management systems anchored to the specific hazards involved for each specific project (see Hale, 2003).

4.2 Barrier failures

Frequent barrier element failures were identified for the six most frequent accident types. Many of Haddon's (1980) strategies could have interrupted the accident process. Elimination (Haddon 1) is often impractical/impossible, but many barrier strategies could have prevented accidents, most notably prevent the release of the hazard (Haddon 4), modifying the energy when it has been released (Haddon 5), separate, in time or space, the hazard and the vulnerable target (Haddon 6), separate the hazard and the vulnerable target by physical devices (Haddon 7).

There were relatively few barrier elements present in most accidents. When one barrier element failed or was not used, there was no other barrier present to interrupt the accident sequence, so called defence in depth. In the offshore oil and gas industry, the philosophy is that there should be at least two physical barriers in place at all times to prevent a blowout (Hopkins, 2012). This material indicates that few barriers are usually utilised in occupational accidents. Systematic barrier management based on Haddon's (1980) strategies and the defence in depth principle are important strategies for preventing accidents similar to those in this this study. Many of the accidents occurred in work situations where the barrier system was totally dependent on the human barrier element. An analysis of the unsafe acts involved in the accidents was therefore carried out.

4.3 Unsafe acts

It is generally accepted that 80-90% of accidents are due to human error (Hale & Glendon, 1987; Reason, 1997). In this research we found that 'unsafe acts' by frontline worker were involved in 94% of the accidents where we had sufficient information to assess unsafe acts. A Finnish study of occupational accidents (Salminen & Tallberg, 1996) found that 'human errors' were involved in 84% of serious accidents and 94% of fatal accidents. Most of the unsafe acts in this study were about decisions to carry out dangerous jobs without adequate safety barriers. It is important to underline that it is easier in hindsight to say that the task should not have been carried out or should have been carried out in another way knowing the hazards involved and the lack of, or limitations of the barrier(s). The results, however, show how important front-line construction workers are in preventing and causing accidents. When frontline workers are part of the barrier system, we must expect accidents to happen '… due to inherent variability in human performance' (Kjellén & Albrechtsen, 2017, p. 142). It is important to underline that identifying 'unsafe acts' is not about blaming frontline workers. Blaming workers does nothing to reduce the inherent risks within the workplace (Reason, 2000). Today, it is widely acknowledged that worker behaviour is largely a result of the system workers are part of (Reason, 1997) and symptomatic of trouble deeper within a system (Dekker, 2014), as demonstrated by e.g. Winge, Albrechtsen and Mostue (2019).

The results suggest that prevention of unsafe acts is a necessary strategy for preventing fatal construction accidents. Lingard and Rowlinson (2005) argue that the human element is particularly important in a labour-intensive industry as the construction industry. Runyan and Baker (2009) argue that 'behaviour-change strategies' are often less effective than passive approaches like Haddon's (1980) strategies. However, it is also important to make frontline workers more 'mindful', i.e., more error-wise and alert to hazards and risks. Reason (2016) argues that 'purely systematic counter-measures are not enough to prevent tragedies' (ibid., p. 87). Mindful safety practices (Skjerve, 2008) implies that workers are encouraged to review situations from different perspectives: to be open to the possible relevance of new information and/or to be open to the need for reinterpretation of old information, and colleagues that watch after each other and correct each other. This is in accordance with a Danish study that emphasise the importance of network and friendship between workers (Baarts, 2004). 'Unsafe acts' must therefore be prevented by multiple measures directed at worker behaviour as well as the systems, for example modifications of working conditions, skills and knowledge, attitudes, and selection of personnel (Dyreborg et al., 2013).

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PAPER III

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Causal factors and connections in construction accidents

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ABSTRACT

The aim of this study was to add to the relatively sparse literature on accident causality in the construction industry by identifying frequent causal factors and connections between causal factors. Using the Construction Accident Causation (ConAC) framework, 176 relatively severe construction accidents investigated by the Labour Inspection Authority in 2015 were analysed. The seven factors most identified were (in rank order): (1) worker actions, (2) risk management, (3) immediate supervision, (4) usability of materials or equipment, (5) local hazards, (6) worker capabilities, and (7) project management. A set theoretic approach was used to identify causal connections between causal factors. Risk management, immediate supervision and worker actions were found to be key causal factors and strongly connected. The analyses identified seven causal factors consistently connected to worker actions, for example immediate supervision and local hazards. Immediate supervision was found to be strongly connected to both worker actions and risk management, underlining the importance of the supervisor controlling unsafe conditions/acts and planning the work to reduce risk. Strong connections were also found between risk management and immediate supervision, and between risk management and worker actions. Risk management and immediate supervision is to a large degree about planning and risk control at different levels, underlining the importance of risk being addressed at different levels and by different actors in construction projects.

1. Introduction

The construction industry is among the industries with the highest share of fatal occupational accidents. In Europe (EU-28), construction had the highest share of fatal occupational accidents in 2014 with one in five accidents (Eurostat, 2016). In Norway, the construction industry had the second highest share of fatal occupational accidents in 2016, also with one in five accidents (Statistics Norway, 2017). An increase in the annual number of fatalities and some major dramatic accidents led to an initiative from stakeholders in the Norwegian construction industry to establish a tripartite cooperation with a vision-zero-approach. The cooperation expressed a need for further knowledge on proximal and distal causal factors in construction accidents for developing preventive strategies.

Accident prevention begins with having a clear understanding of factors that play key roles in causation (Hinze et al., 1998). In a review of construction site safety literature, Khosravi et al. (2014) concluded that there is little research on the key causes and contributory factors of unsafe behaviours and accidents at construction sites. The aim of this study was to add to this literature by studying causal factors in 176 severe construction accidents in depth. The specific purposes were to identify (1) frequent causal factors in construction accidents, and (2) important connections between the causal factors.

Information about accident mechanisms and injury agents can be extracted from national injury statistics. Acquiring knowledge about distal causal factors is more problematic since national statistics do not '… generally permit detailed analysis of causes beyond the identification of the mechanism and agency of injury' (Cooke and Lingard, 2011, p. 279). The sample analysed in this study consists of all construction accidents investigated by the Norwegian Labour Inspection Authority (LIA) for one year (2015). These accidents were relatively severe, and the qualitative documentation of the accidents was assessed to be sufficient to assess causal factors using a holistic system model.

2. Theoretical approach

Khanzode et al. (2012) divide accident causation theories into four generations as accident proneness theory, domino theories, injury epidemiology models, and system theories. Some accident causality research in construction have much in common with injury epidemiology models. The energy-barrier model (Gibson, 1961; Haddon, 1980) and the bowtie are important theoretical inspirations. Lipscomb et al. (2000) identified the 'external causes' of work related deaths (e.g. motor vehicle accidents) and 'major causes' of the frequent external causes (e.g. backovers). Papazoglou and Ale (2007) developed a logical model for quantification of occupational risk that allows the user to input relationships between events, corresponding probabilities for events and obtain at the end the quantified corresponding simplified event tree. In a Dutch study of construction accidents Ale et al. (2008) used the tool Storybuilder based on the bowtie to identify causes (e.g. barrier failures) and consequences of frequent accident types. A similar approach was used by Winge and Albrechtsen (2018) identifying frequent accident types and its barrier failures and consequences. The material used was the same as the 176 accidents analysed in this paper.

This study does not divide the accidents into accident types but study the sample of 176 accidents using a holistic system approach to identify relatively many causal factors and connections between factors at different organisational levels. We see this approach as

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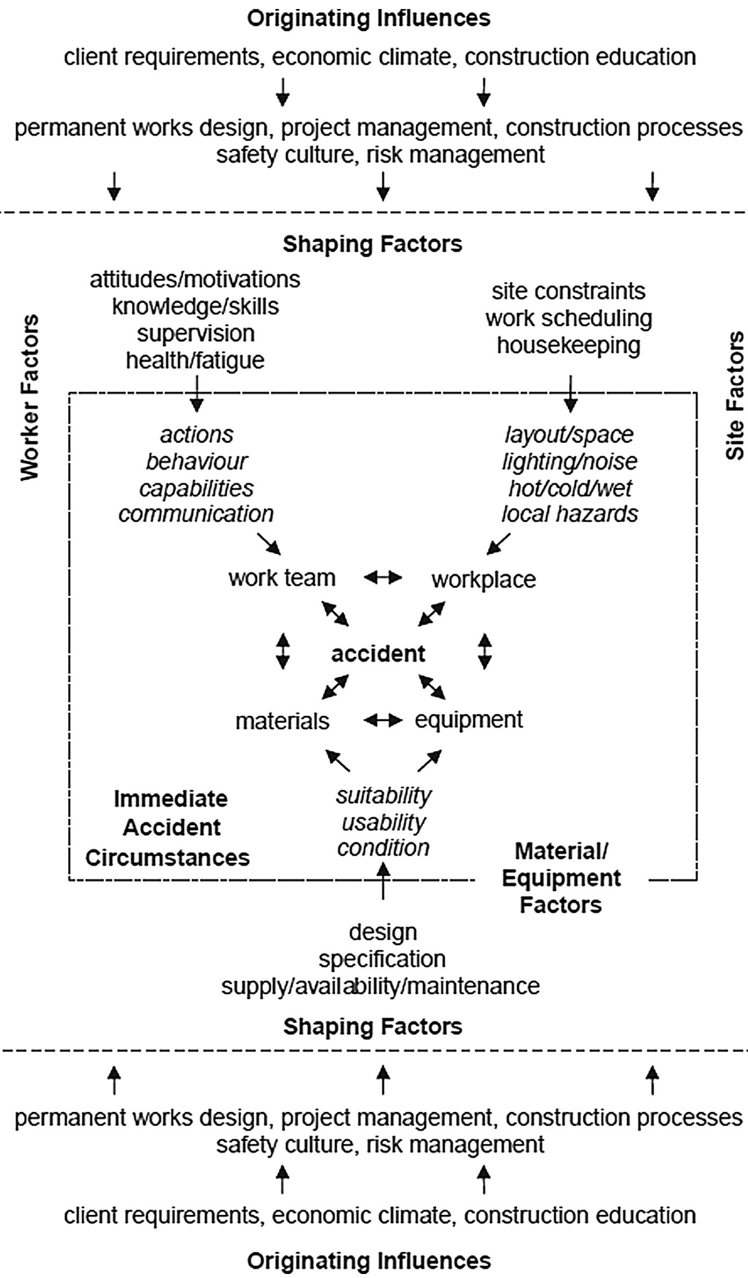

Fig. 1. The Construction Accident Causation Framework (Haslam et al., 2003, 2005).

complementary to the approach described above giving complementary advice for prevention. The causes found in accident analyses reflect the accident model used, the so called 'What-You-Look-For-Is-What-You-Find'-principle (Lundberg et al., 2009).

System models focus on both organisations, integrated safety systems, and interacting social and technical systems (Khanzode et al., 2012). Reason's Swiss cheese model (SCM) (e.g., Reason, 1997, 2016; Reason et al., 2006) has had a major impact on the understanding of accident causation and prevention. In the SCM, major accidents depend on defence in depth, where each slice of cheese represents a fallible barrier. Gaps in the defences arise for two reasons, unsafe acts by 'sharp-enders', and latent conditions, for example, poor supervision, maintenance or training.

Many studies and literature reviews on construction safety emphasise that construction sites are technologically and organisationally complex (e.g., Mitropoulos et al., 2005; Pinto et al., 2011; Swuste et al., 2012; Lingaard, 2013). Lingard (2013) argue that in construction there is a specific need to manage the interests and influences of stakeholders,

Table 1
Operational definitions of the 23 factors used in this study. Based on Haslam et al. (2003; 2005), Behm (2009), Behm and Schneller (2013), and this study.

	Factors	Description
Worker and work team	Worker actions and behaviours	Includes all acts at the 'sharp end' that have an impact on the accident, such as mistakes, unsafe acts, violations of procedures, taking shortcuts, etc. Included are unsafe acts by the injured workers themselves and other worker actions that contributed to the accidents.
	Worker capabilities	Did the worker/team have adequate *training* to know how to do the job, use the equipment, and identify hazards and risks associated with the work, etc.? Training is context-specific, dealing with procedures or rules for undertaking particular tasks or activities.
	Communication	Lack of, or poor, communication at work group level, supervisory level or the organizational level and between organisations. Includes poor command of the language and lack of safety communication from supervisors. Includes the written as well as the spoken word.
	Attitudes and motivations	Attitudes towards safety. Motivation: prizes for safety performance, disciplinary measures, financial incentives, priced work, payment methods, bonuses, etc.
	Knowledge and skills	Did the worker/team have the *education* to know how to do the job, use the equipment, and identify hazard and risks associated with the work, etc. Compared to 'worker capabilities', education imparts a higher level of knowledge and skills, which is transferable to different situations.
	Immediate supervision	The supervisor is a key individual in accident prevention, having daily contact with staff and the opportunity to control unsafe conditions and acts likely to cause accidents and plan the work in a manner to reduce risk and identifiable hazards. The assessment is based on (1) inadequacies in *controlling* unsafe conditions and acts likely to cause accidents, and (2) *plan* the work in a manner to reduce risk and identifiable hazards.
	Worker health/fatigue	Worker health/fatigue
Workplace	Local hazards	Hazards and risks that are specific to the site, which should have been identified or somehow managed or planned to avoid or minimize.
	Site layout and space	Includes the ground and area where the work is performed, and the immediate adjacent area if contributing to the accident, and the relationship to the hazards and risks of the tasks.
	Work environment	The work environment includes wet conditions, thermal stressors, lights, noise, and other physical, climatic factors involved in influencing the factors involved in the incident.
	Housekeeping	Disorderly condition of trucks, equipment, materials, waste, etc
	Work scheduling	Poor required pace of the work, work sequencing, scheduling pressures, and other factors affecting the safety and health of workers in relation to work preparation and arrangement.
	Site constraints	The space in which the work is performed. Includes the relationship of equipment and the work team to identifiable hazards.
Materials/equipment	Condition	Unsafe condition of materials/equipment
	Usability	Lack of/limited functionality of the materials/equipment or lack of materials/equipment themselves
	Suitability	Materials/equipment utilized not suitable for the job and task to be performed. Materials/ equipment used for other types of work than meant for.
	Design and specification	Poor designs and specifications of materials and equipment
	Supply and availability	Poor supply and availability of materials and equipment
Originating	Permanent works design	Permanent features of the equipment and buildings that influences the incident. It also includes temporary structures (temporary works) built for the tasks and projects. Includes information about underground and overhead utilities in the planning of projects/tasks.
	Project management	The safety oversight of the intricacies of the project and tasks. Includes contractor arrangements, subcontracting, labour supply, work scheduling, time management, time pressures and individuals taking it upon themselves to do jobs/tasks.
	Construction processes	Improper methods statements or absence of method statements if there should have been one developed and communicated. Inadequate or lack of verbal instructions when they should have been given or more thoroughly planned. Includes improper tools for the job or using tools not suitable for the job.
	Safety culture	Safety culture is the way things are done in and around the organisation and can be at different levels: organisational, divisional, and group (work team). This study assessed safety culture based on descriptions of five of the factors in the ConAC framework used as indicators: worker actions; communication; attitudes/motivations; supervision; and risk management.
	Risk management	Includes: Improper, or a lack of formal or informal, risk assessments, work method statements, job hazard analyses; improper incident investigation (which includes not learning from past mistakes and/or failures); poor identification of proper remedial actions in respect of identified risks; lack of, or poor employee consultation and participation in identification of hazards and risks; conditions where recognizable hazards were not identified; and situations where recognizable risks were not properly anticipated and identified.

ensure compatibility among the components that make up a facility, and manage and coordinate the activities of different work crews and trades to ensure that workers, materials and equipment are constantly moving. This technological and organisational complexity is the reason for developing systemic accident frameworks specifically for the construction setting and studying interactions of distal and proximal factors in construction accident causation (e.g., Abdelhamid and Everett, 2000; Suraji et al., 2001; Leveson, 2004; Mitropoulos et al., 2005; Haslam et al., 2005; Manu et al., 2010; Priemus and Ale, 2010; Hale et al.; 2012; Khosravi et al., 2014).

Hale et al. (2012) developed a framework for identifying underlying causes of fatal construction accidents. The results showed '… a concentration of underlying factors associated with inadequacies in planning and risk assessments, competence assurance, hardware design, purchase and installation, and contracting strategy' (p. 2020). Khosravi et al. (2014) included 56 studies in a literature review to determine variables that influence unsafe behaviours and accidents on construction sites. The studies showed high evidence of association for organisation (e.g., safety climate/culture, information management, and policy/plan) and project management (e.g., commitment/support, management style and review/feedback). The studies also showed moderate evidence for the connections between accidents and supervision (e.g., effective enforcement, supervision style and communication), site condition (e.g., unsafe condition and hazardous operation), individual characteristics (e.g., attitude/motivation, psychological distress and age/experience) and contractor (e.g., size and subcontractor rate).

The framework chosen for this study was the Construction Accident

Causation (ConAC) framework (Haslam et al., 2003, 2005). The ConAC framework was developed inductively through a combination of focus groups and a detailed study of 100 construction accidents. The framework was chosen for mainly three reasons. First, it builds on acknowledged accident theories and models, for example, an ergonomics systems approach (Haslam et al., 2003, 2005), and it '… adopts a similar framework to that presented by Reason (1997) but places it in the context of the construction industry' (Lingard and Rowlinson, 2005, p. 30). Second, the framework was used by other studies in different construction settings and countries (Cooke and Lingard, 2011; Lingard et al., 2013; Behm and Schneller, 2013), and the experiences were that the framework's terminology was 'sufficiently generalizable' and can be '… applied to a variety of construction accident consequences and yield numerous organizational learning opportunities at both the sharp end on site and the blunt end of project management or design' (Gibb et al., 2014, p. 457). Third, the methodology and operational definitions of the factors in the framework were documented by the original research and later studies and is hence easier to replicate.

3. Analysis framework

3.1. The ConAC framework and understanding of causality

The ConAC framework has previously had different names. We use the term ConAC as it is used in the paper by Gibb et al. (2014). The framework has three levels of factors (Fig. 1): *Immediate* factors (e.g., worker actions) are influenced by *shaping* factors (e.g., supervision), and the shaping factors are influenced by *originating* factors (e.g., risk management). The shaping and immediate factors are divided into worker/team factors, site factors and material and equipment factors. The double arrows at the centre of the model represent multiple two-way interactions.

The understanding of causality in the SCM, and implicitly in many other accident models, is that accidents in complex systems occur through the interaction of multiple factors, where each may be necessary but where they are only jointly sufficient to produce the accident (Reason et al., 2006; Hopkins, 2014). No failure, human or technical, is *sufficient* alone to cause an accident. According to Reason et al. (2006) the proximal factor (e.g., errors and violations) is the causal factor in an accident, while a latent condition is '… not necessarily a cause, but it is necessary for a causal factor to have an impact. Oxygen is a necessary condition for fire; but its cause is a source of ignition' (Reason et al., 2006, p. 7). This understanding of causality is also implicit in the ConAC model: 'All accidents are multi-causal, with a rare combination of factors needing to coincide to give rise to an incident. Underlying each of the causal factors are a range of influences determining the extent to which they undermine safety' (Haslam et al., 2003, p. 58).

3.2. Operational definitions of the ConAC factors

Like Cooke and Lingard (2011) and Behm and Schneller (2013), we also found it problematic that the classification of factors was open to interpretation. Behm (2009) and Behm and Schneller (2013) developed operational definitions guided by previous research by Haslam et al. (2003; 2005). This study has used these definitions and added some clarifications based on how the terms are operationalised in this study (Table 1). This study does not include the outer originating factors in the framework due to lack of information in the material. The factors included are the same 23 factors that Gibb et al. (2014) used when comparing the material from UK, Australia and USA.

3.3. Previous use of the ConAC framework

The ConAC framework was developed through a combination of focus groups and a detailed study of 100 construction accidents by Haslam et al. (2003, 2005). Worker actions/behaviours were identified in 49% of the accidents. Explanations for unsafe acts were: safety being overlooked in the context of heavy workloads and other priorities; taking shortcuts to save efforts and time; and inaccurate perception of risk. Underlying the worker actions/behaviours were inadequate safety knowledge. Risk management was identified in 84% of the accidents. Haslam et. al. (2005) concluded that '… there is a pervasive failure of the industry to engage in effective risk management' (p. 413). The failures of risk management typically were lack of, or inadequate, risk assessments.

Cooke and Lingard (2011) used the ConAC framework to analyse 258 fatal construction accidents in Australia based on coronial investigations. The preliminary analysis suggested that many investigations focussed on immediate factors and '… may not identify the extent to which these immediate factors arise as a result of shaping factors or originating influences' (p. 284). Frequent factors identified were mainly immediate factors, for example, worker actions/behaviour, site layout/space and suitability of materials and equipment.

In a study of 10 fatal accidents involving excavators, Lingard et al. (2013) found that it was possible to identify immediate factors in most cases, shaping factors in only a few cases and originating factors in none of the cases. The immediate factors included unsafe work methods/actions, aspects of the site layout and the condition of mobile plant. The shaping factors included on-site communication issues, design of work processes and the specification/suitability of plant for the site location and/or activity being performed.

Behm and Schneller (2013) used the ConAC model interviewing employees, witnesses, supervisors and safety engineers in 27 construction accidents. The most frequent factors found were (in rank order) (1) risk management, (2) worker actions and behaviour, (3) worker capabilities including knowledge and skills, (4) local hazards, (5) project management and (6) attitude and motivation. They also analysed if the factors were correlated to other factors in the framework and found that worker actions were negatively correlated with worker capabilities, indicating that these factors acted independently. Further, they found that worker actions were correlated with attitudes and motivations, attitudes and motivation were correlated with safety culture, worker actions were correlated with availability of equipment and materials, site conditions were correlated with work scheduling and work scheduling was correlated with construction processes.

Gibb et al. (2014) compared the results on 23 of the ConAC factors from research in the UK, Australia and USA, and found similarities and dissimilarities in the ranking of factors between the three studies. Differences were explained by differences in, for example, accident severity, researcher background, use of primary versus secondary data and types of hazards. The average percentage of each factor from the studies showed that the most frequent immediate factors were worker actions, suitability of materials/equipment and worker capabilities. The most frequent shaping factors were knowledge/skills and attitudes/motivations, and the most frequent originating factors were risk management, project management and permanent works design.

4. Material and methods

4.1. Study sample

The study sample consists of 176 construction accidents investigated by the Norwegian Labour Inspection (LIA) in 2015. The same sample is used and described in more detail in another paper identifying frequent accident types and barrier failures (Winge and Albrechtsen, 2018). This sample gives sufficient descriptions of the accident sequence as well as a sufficient number of recent accidents. The study sample is limited to accidents investigated by the LIA for one whole year, 2015. In 2015, LIA carried out investigations of 189 construction accidents, involving 210 companies. Seven of the 189 accidents were excluded from the sample since they did not take place during construction work or at constructions sites, and six accidents were excluded due to lack of sufficient information about the accident. Hence, the main study sample is 176 accidents involving 184 injured persons, of which four were fatalities.

According to the Norwegian Work Environment Act, occupational accidents that lead to fatal or severe injuries must be reported to the police and the LIA. Severe injury here means any harm (physical or mental) that results in permanent or prolonged incapacitation. There is guidance on LIA's website describing nine characteristics that indicate severe injury, including injuries to the head, skeleton, or internal organs; loss of a body part; poisoning; unconsciousness; metabolism/frost injury; hypothermia; and injuries that lead to hospitalisation (Labour Inspection Authority, 2018). When the LIA is notified of an accident, it decides whether to complete an investigation based on assessments of potential severity and available inspectors. The criteria for selecting accidents for the study sample included:

1. At least one construction company involved
2. Occurred during construction work
3. Inspected by the LIA in 2015

Construction accident statistics normally do not include workers employed by non-construction companies that are injured in construction accidents, for example, hired workers employed by temporary employment agencies. Criteria 1 and 2 above ensured that these workers were included in the sample.

An investigated accident can involve many documents and normally consists of the notification of the accident, accident reports from the LIA and the company, and letters between the LIA and companies involved in the accident. When an accident is reported by mail or phone to the LIA, basic information about the accident is collected to decide whether an investigation is going to be carried out. During the investigation, the inspectors collect information to investigate if there have been any violations of the law and to describe the course of events. After the investigation, the inspectors produce an investigation report that in most cases includes a description of the accident sequence, causal factors and violations of the law when identified. In most cases, the investigated company is decreed to produce an accident investigation report and a plan including measures to prevent similar accidents.

The amount of information available on the accidents varies significantly. Some accidents in this sample consisted of only one document, others consisted of up to 50 documents. Some accidents were sparsely described, and six accidents were excluded due to lack of sufficient information. Other accidents had rich descriptions and were investigated by professional accident investigators.

This study includes all data collected from the reporting of the accident and the entire process related to the investigation. Four analysts were engaged in finding relevant documents and extracting relevant information from the accident documentation for entry into a text file, consisting of 84,000 words.

4.2. Identifying causal factors

The method for using the ConAC framework was inspired by the methods described by Behm and Schneller (2013), adapted to the secondary data used in this study:

1. Identify immediate circumstances (e.g., worker actions)
2. Identify the shaping factor(s) associated with the immediate factor (e.g., supervision)
3. Identify originating influence(s) influencing the shaping factor(s) (e.g., risk management)
4. Repeat the sequence for each immediate circumstance

A spreadsheet used by Behm and Schneller (2013) was used to describe how each factor was linked to the accident. Originating influences may appear more than once in a single incident if there are multiple deficiencies.

Like the other studies using the ConAC framework, the researchers coded the accidents and their related factors based on their judgement of 'reasonable confidence' that a factor was present in an accident (Haslam et al., 2005). The outer originating influences are rarely clearly identifiable in incident investigations (Haslam et al., 2005). Therefore, like Behm and Schneller (2013), this study did not attempt to trace incident influences to these outer originating influences in the framework. This study uses the same 23 factors Gibb et al. (2014) used when comparing the Australian, UK and US studies.

Four analysts studied the documents related to the accidents. To ensure internal validity, quality assurance measures were carried out in five steps:

1. The first author studied the previous studies in depth and gave training to the others.
2. A few accidents were analysed according to the method described above by the analysts jointly before the accidents were divided among the analysts for reading documents and coding.
3. There were regular meetings of the analysts where accidents and factors were discussed.
4. After all of the accidents had been assessed and coded, two analysts divided the accidents in two groups and carried out quality assurance of the coding of all of the accidents (not accidents they had originally coded).
5. During analysis of the accidents, the first author compared the coding and recoded where there were discrepancies in the coding.

4.3. Approach for identifying connections between causal factors

Reason et al. (2006) state that it '… is now broadly recognised that accidents in complex systems occur through the concatenation of multiple factors, where each may be necessary but where they are only jointly sufficient to produce the accident' (p. 2). This study uses a set theoretic approach that allows for assessing necessity and sufficiency of conditions in data sets (Ragin, 2006, 2008; Goertz and Mahoney, 2012; Schneider and Wagemann, 2012). The term 'causal condition' is used generically in this paper to refer to an aspect of a case that is relevant in some way to the explanation of the outcome (see Ragin, 2008).

It is not possible to assess necessary and sufficient conditions for accidents as such, since binary variables are necessary to do that, and there are no 'non-accidents' in this material. However, it is possible to assess necessary and sufficient conditions for causal factors in the ConAC framework, for instance, conditions that can explain worker actions and local hazards. In this approach the 'independent variable' is called *condition* (X), and the 'dependant variable' is called *outcome* (Y).

Set-theoretic connections are often illustrated by Venn-diagrams (Fig. 2) where each circle represents cases with a given characteristic. For instance, X can represent accidents with poor risk management, and Y can represent accidents with poor worker actions. Fig. 2 illustrates different combinations of sufficiency and necessity.

A condition (X) is *sufficient* if, whenever it is present across cases, the outcome (Y) is also present (If X, then Y). Sufficient conditions can produce the outcome alone, but there are also other conditions with this capability. For binary variables, the assessment of sufficiency and necessity of conditions are carried out in two-by-two tables. If a condition is sufficient, there are cases in cell B and no cases in cell D (Fig. 3).

The logic behind necessary conditions can be viewed as the mirror image of that for a sufficient condition (Schneider and Wagemann, 2012). A condition (X) is necessary if, whenever the outcome (Y) is present across cases, the condition (X) is also present. A necessary condition must be present for the outcome to occur. If a condition is necessary, there are cases in cell B, and no cases in cell A (Fig. 3). Table 2 summarises the strategies for assessing sufficiency and necessity.

In data sets, connections between factors are rarely perfectly

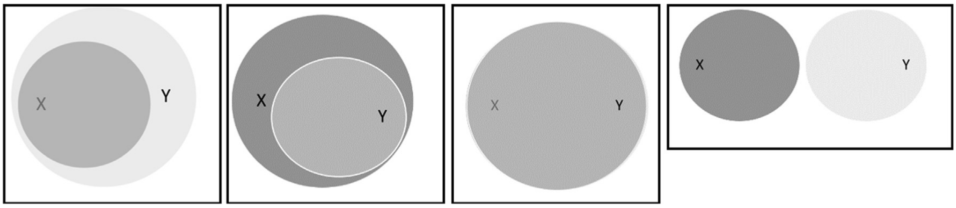

Fig. 2. Venn diagrams illustrating (from left to right) (1) X as a sufficient condition (if X, then Y), (2) X as a necessary condition (if Y, then X), (3) X as a sufficient and necessary condition, and (4) no connection.

	X=0	X=1
Y=1	A	B
Y=0	C	D

Fig. 3. Two-by-two table.

consistent. Some cases will usually deviate from the general patterns so that conditions can be quasi-necessary or quasi-sufficient (Legewie, 2013). Consistency and coverage are parameters used to assess how well the cases in a data set fit a relation.

The calculation of consistency is described in Table 3 and in an example in the results section. *Consistency* resembles significance in statistical approaches where 0 indicates no consistency and 1 indicates perfect consistency. The consistency value for conditions should be higher than 0.75 (Schneider and Wagemann, 2012). If a relation is established to be consistent, the coverage should be calculated. *Coverage* assesses the degree to which a condition accounts for instances of an outcome, or empirical relevance (Ragin, 2008). The analogous measure in statistical models would be R2, the explained variance contribution of a variable (Thiem, 2010), with values between 0 and 1.

Behm and Schneller (2013) analysed correlations (*phi*) for each pairing of all factors in the ConAC framework. Correlations and set theoretic connections indicate different types of connections. Therefore, correlations (*phi*) are included in the tables in the results section along with the assessment of consistent connections.

5. Results

5.1. Background data

Table 4 shows background data for injured persons and the accidents in the main study sample.

The average age of the injured person was 38 years; 64% of the injured were between 25 and 55 years of age, and 22% were younger than age 25. Only three injured workers were women. Thirty-eight percent of the injured persons had foreign citizenship, most of them from Eastern Europe. 'Building' was the most frequent construction type and nearly half of the accidents involved a fall from height. The material did not always provide information about the conditions of employment, but at least 18% were hired workers and 9% were apprentices or hired for a summer job.

A method used by Haslam et al. (2003) was also used in this study to indicate potential fatality. Information from the accidents was used to evaluate alternative outcomes and to assess the outcome if the injured person had been in a slightly different location or if a different part of the body had been involved. *Likely fatality* required only a minor change in circumstances and *possible fatality* required a number of circumstances to change. There were four fatalities in this material (2%); 47% were assessed to be *likely* fatalities, 26% *possible* fatalities, and 25% were *not possible* fatalities.

5.2. Causal factors

Fig. 4 summarises factors identified using the ConAC framework (Haslam et al., 2003, 2005). In total, 1.039 causal factors were identified in the 176 accidents, an average of 5.9 factors per accident. There were on average 2.7 immediate factors, 1.8 shaping factors and 1.5 originating factors per accident. The left side of the figure shows that worker and team factors were identified in 90% of the accidents, site factors in 55%, material and equipment factors in 56%, and originating influences in 66% of the accidents.

The right side of the figure shows the percentage of accidents where the detailed factors were identified. Seven of the factors were identified in more than 30% of the accidents: the immediate factors worker actions, worker capabilities, usability of materials or equipment and local hazards; the shaping factor immediate supervision; and the originating factors project management and risk management. These seven factors are important in the analysis of connections between factors in Section 5.3 and is therefore described in more detail below.

5.2.1. Worker actions and behaviours

Worker actions includes all acts at the 'sharp end' that have an impact on the accident, such as mistakes, unsafe acts, violations of procedures, taking shortcuts, etc. Included are unsafe acts by the injured workers themselves and other worker actions at the 'sharp end' that contributed to the accidents. Worker actions was identified to be a factor in 145 accidents (82%). Subcategories of poor worker actions were identified inductively. Some accidents had more than one of these characteristics, others had none. The most frequent categories found were (in rank order) (1) using wrong type/use of equipment, (2) working at heights without adequate safeguarding, (3) staying in a danger zone, (4) choosing a wrong working method or skipping a phase in the sequence of the operation, (5) not securing scaffolding or working platforms correctly/sufficiently, (6) not communicating to other workers or companies about hazards and danger zones, and (7) not securing materials or structures properly. In 25 accidents (24% of the worker actions-accidents), other workers than the injured worker contributed to the accident. Often, combinations of actions by the injured worker and other workers contributed to the accident. In some accidents, many actions by several workers led to the accident.

5.2.2. Worker capabilities

Worker capabilities is about workers not knowing how to do the job, use the equipment and identify hazards and risks associated with the work. Worker capabilities was identified to be a factor in 56 accidents (32%). The most frequent categories found were (in rank order) (1) lack of competence related to the use of machinery or equipment, (2) young and/or inexperienced workers, and (3) workers lacking sufficient general safety competence.

5.2.3. Immediate supervision

Immediate supervision refers to the supervisor (1) having daily

Table 2
Description of sufficient and necessary conditions.

Type	Description	Logic	Capacity	Examine cases that share same	Attempt to identify their shared
Sufficient	Whenever the condition is present, the outcome is also present	If X, then Y	Can produce the outcome alone	Conditions (X)	Outcome (Y)
Necessary	Whenever the outcome is present, the condition is also present.	If Y, then X	Must be present for the outcome to occur	Outcome (Y)	Conditions (X)

contact with staff and the opportunity to *control* unsafe conditions and acts likely to cause accidents, and (2) *planning* the work in a manner to reduce risk and identifiable hazards. There was great variation in the size and type of the construction work and hence the role of the supervisors. Immediate supervision in total was identified to be a factor in 95 accidents (54%). Of these, inadequacies in controlling unsafe conditions and actions were judged to have been involved in 68 accidents (38%). Further, inadequacies in planning the work in a manner to reduce risk and identifiable hazards were judged to have been involved in 51 accidents (29%).

5.2.4. *Local hazards*

Local hazards are hazards that are specific to the site and that should have been identified and managed. Included are hazards related to more or less fixed installations like platforms and scaffolding. Local hazards were identified to be a factor in 71 accidents (40%). The most frequent categories found were: inadequate barriers on walkways, platforms, roofs and scaffoldings structures; holes and openings in building structures; and loose or rotten roofs and floors.

5.2.5. *Usability of materials or equipment*

Usability of materials and equipment refers to lack or limited functionality of materials/equipment. Usability of materials and equipment was identified to be a factor in 72 accidents (42%). The most frequent deficiencies were scaffolding and platforms lacking adequate barriers and poor condition of scaffolding floors. A factor in many of the fall accidents was that fall arrest equipment was not available or that opportunities for attaching the fall arrest equipment was lacking. In many accidents where saw was involved, the saw lacked a push stick and the worker used the hand instead.

5.2.6. *Project management*

Project management refers to the oversight of the intricacies of the project and tasks and contractor arrangements, subcontracting, labour supply, work scheduling, time management, time pressures, and individuals taking it upon themselves to do jobs/tasks. Project management was identified to be a factor in 57 accidents (32%). The most frequent problems were related to unclear organisational structures and responsibilities, cooperation and communication between workers and companies, lack of control on actors and worker behaviour in the project, time pressure and new types of jobs unfamiliar to the work team.

5.2.7. *Risk management*

Risk management refers to improper risk assessments, not learning from past failures, poor identification of remedial actions and poor employee consultation and participation in identification of hazards and risks. Risk management was identified to be a factor in 98 accidents (56%). The most frequent categories of deficiencies in risk management in this research were (1) poor systematic health and safety work/internal control, (2) poor routines for assessing risk in working operations, (3) not following the safety and health plan and (4) poor or lacking risk assessments. There were combinations of such deficiencies in most of the risk management accidents.

5.3. *Connections between factors*

In this section, conditions and outcomes of frequent causal factor are analysed. There is an abundance of possible connections between the 23 factors in this material but all are not theoretical plausible. Table 5 shows connections that are: theoretically plausible (cf. Fig. 1); consistent (> 0.75); empirically relevant (coverage > 0.30); involve the most frequent factors; and do not include factors that include same type of characteristics. The calculation of consistency and coverage is explained in Section 4.3 and in an example below.

Worker actions was identified in 145 accidents (82%). Table 5

Table 3
Assessing consistency and coverage for sufficient and necessary conditions. Based on Ragin (2008) and Schneider & Wagemann (2012).

Sufficiency				Necessity			
	X = 0	X = 1	Coverage		X = 0	X = 1	Consistency
Y = 1	A	B	B/(A + B)	Y = 1	A	B	B/(A + B)
Y = 0	C	D	–	Y = 0	C	D	–
Consistency	–	B/(B + D)	–	Coverage	–	B/(B + D)	–

shows that seven factors were identified as 'sufficient', but not 'necessary', conditions for worker actions. The connection between immediate supervision (X) and worker actions (Y) is used for illustration. Table 6 and Fig. 5 shows that most (91%) of the immediate supervision-accidents (X) are also worker actions-accidents (Y). This gives support to the logical argument 'if X, then Y', or if poor immediate supervision, then poor worker actions. X covers most (59%) of Y, indicating that the empirical relevance (coverage) is strong. The 59 accidents (41%) that are not X, indicate that X is not *necessary* for Y and that there must be other conditions that can also explain Y, which is confirmed in Table 5. Four of the factors also show a positive correlation, indicating a symmetric relationship between the factors.

Local hazards were identified in 71 accidents (40%). Table 5 shows that worker actions was identified as a 'necessary', but not 'sufficient', condition for producing local hazards. This supports the argument that poor worker actions must be present for local hazards to occur, but only together with other conditions. The results also show that 'site constraints' is 'sufficient', but not 'necessary', for producing local hazards, but the empirical relevance (coverage) is relatively low.

Usability of materials or equipment was identified in 74 accidents (42%). Worker actions was identified as a 'necessary' condition for producing usability of materials/equipment.

Immediate supervision was identified to be a factor in 95 accidents (54%). Immediate supervision is a shaping (intermediate) factor in the ConAC framework and can be a condition as well as an outcome. Table 5 shows that risk management is both a 'sufficient' and 'necessary' condition for immediate supervision. This indicates that poor risk management is almost always present when poor immediate supervision is present, *and* that when poor immediate supervision is present, poor risk management is also present. The results also show that project management is 'sufficient' for poor immediate supervision. Immediate supervision can also be a condition, and the results indicate that immediate supervision is a 'sufficient' condition for 'worker actions' and 'necessary' for work scheduling.

Risk management was the originating factor identified most frequently. Table 5 shows that risk management is both 'sufficient' and 'necessary' condition for poor immediate supervision, 'sufficient' for poor worker actions, and 'necessary' for seven factors. Project management was the second most originating factor identified. The results show that poor project management is a 'sufficient' condition for poor immediate supervision and poor worker actions.

6. Discussion

6.1. Frequent causal factors and connections

By studying 176 construction accidents in depth, we aimed at contributing to the knowledge of causal factors in construction accidents and connections between causal factors. Fig. 6 simplifies and summarises the seven most frequent causal factors identified, and causal conditions that are consistent and empirically relevant. The term 'causal condition' is used generically to refer to an aspect of a case that is relevant in some way to the explanation of the outcome (Ragin, 2008). The discussion emphasises the three factors most identified in this study: worker actions, immediate supervision, and risk management.

6.2. Worker actions

Depending on operational definitions, it is often concluded that 'human error' is a determining factor in 70–80% (Rasmussen, 1997) or 80–90% (Phillips, 2005) of accidents. Worker actions was identified to be a factor involved in 82% of the accidents in this study. This is more than that reported in other studies using the ConAC framework in the UK (49%), Australia (53%) and USA (63%) (Gibb et al., 2014).

Today, it is widely acknowledged that 'human error' is largely a result of the system humans are part of (Reason, 1997) and symptomatic of trouble deeper within a system (Dekker, 2017). Implicit in the works of Rasmussen (1997), Reason (1990) and in the ConAC framework (Haslam et al., 2005), is the involvement of human factors and ergonomic factors. The results in this study suggest that worker actions were influenced by many conditions, most notably immediate supervision, risk management, usability of materials or equipment, local hazards, worker capabilities and project management. The result is broadly consistent with many other studies. In the inductive process of developing the ConAC framework it was found that worker actions were shaped by attitudes/motivations, knowledge/skills, supervision and health/fatigue (Haslam et al., 2005). Behm and Schneller (2013) found that worker actions were positively correlated with attitudes/motivations and availability of equipment/materials, and negatively correlated with worker capabilities, indicating that these factors acted independently. Interviewing victims of construction accidents in Hong Kong, Choudry and Fang (2008) identified 11 factors influencing worker's safety behaviour at construction sites, for example management, experience, performance pressure, working environment and

Table 4
Background data for the 176 accidents/184 injuries in the main study sample in percentages.

Age of injured workers (%) (n = 184)		Nationality of injured workers (%) (n = 184)		Construction type (%) (n = 176)		Accident type (%) (n = 176)		Potential fatality of accident (%) (n = 176)	
15–19	8	Norway	62	Building	41	Fall	48	Fatality	2
20–24	14	Other Nordic countries	6	Refurbishment	20	Hit by object	24	Likely	47
25–39	30	Eastern Europe	26	Civil Engineering	15	Cut by sharp object	13	Possible	26
40–54	34	Other European countries	6	Engineering Construction	14	Squeezed, caught	6	Not possible	25
55–67	13	Non-European countries	1	Other	9	Electricity	4	Total	100
67 <	1	Total	101	Total	100	Other	5		
Total	100					Total	100		

Fig. 4. Percent of causal factors identified in 176 accidents (several factors possible for each accident). (White = immediate factors. Black = Shaping factors. Stripes = Originating influences).

training. In a literature review on construction safety, Khosravi et al. (2014) concluded that the causes of unsafe behaviours and accidents appear to be multifactorial, and generally related to society, organization, project management, supervision, contractor, site condition, work group, and individual characteristics.

One contribution of this study is the use of a set theoretic approach which makes it possible to assess sufficiency and necessity of conditions (Ragin, 2008). The understanding of causality in the SCM, and implicitly in many other accident models, is that accidents in complex systems occur through the interaction of multiple factors, where each may be necessary but where they are only jointly sufficient to produce the accident (Reason et al., 2006; Hopkins, 2014). When studying sets of accidents, it is possible to assess sufficiency and necessity of connections between factors. The results in this study indicate that 'poor worker actions' was the outcome of many 'sufficient' conditions. 'Sufficient' conditions can produce the outcome alone, at the same time as there are other conditions that have this capability, so-called multiple causation or equifinality (Goertz and Mahoney, 2012). This have practical implications for prevention. The results suggest that to reduce the number of construction accidents, it is necessary to ensure the quality of each of these 'sufficient' conditions.

Ideally, hazards should be eliminated before they are present (Haddon, 1980). However, the situation at many construction sites today is that construction workers must tackle several hazards daily. The human is usually considered a hazard, but humans can be heroes as well, whose behaviours can avoid hazards leading to accidents (Reason, 2008). Most hazards will not lead to injuries because they are observed and addressed by people's behaviours (Jørgensen, 2016). Lingard and Rowlinson (2005) state that the human element is particularly important in a labour-intensive industry, such as the construction industry. Strategies for reducing unsafe acts should therefore include multiple measures including eliminating and interrupting the injury process, manpower recruitment and planning, education and training, an ergonomics/human factors approach, as well as behavioural measures.

Table 5
Connections between factors in rank order by coverage (empirical strength) (N = 176). n = cases where both factors are present. Consistency > 0.75. Coverage > 0.30. S/N = Sufficient/Necessary. Correlations (*phi*).

Condition (X)	Outcome (Y)	n.	Consistency	Coverage	S/N	R.*	Sig.
Risk management	Immediate supervision	77	0.79	0.81	S&N	0.553	0.000
Immediate supervision	Worker actions	86	0.91	0.59	S	0.231	0.002
Risk management	Worker actions	86	0.88	0.59	S	0.158	0.036
Project management	Immediate supervision	49	0.86	0.52	S	0.444	0.000
Usability of materials or equipment	Worker actions	66	0.89	0.46	S	0.152	0.044
Local hazards	Worker actions	59	0.83	0.41	S	n.s.	n.s.
Immediate supervision	Work scheduling	38	0.90	0.40	N	0.410	0.000
Risk management	Construction processes	37	0.84	0.38	N	0.330	0.000
Worker capabilities	Worker actions	51	0.91	0.35	S	0.156	0.039
Project management	Worker actions	50	0.88	0.34	S	n.s.	n.s.
Risk management	Work scheduling	33	0.79	0.34	N	0.258	0.001
Knowledge/skills	Worker actions	46	0.90	0.32	S	n.s.	n.s.

* Correlations (phi): $p < .05$. Strength R: weak (0–0.3), moderate (0.3–0.6), and strong (0.6–1.0). n.s. = Not significant.

Table 6
Connection between 'poor immediate supervision' (condition) (n = 95) and 'poor worker actions' (outcome).

	Not poor immediate supervision (X = 0)	Poor immediate supervision (X = 1)	Tot.	Coverage
Poor worker actions (Y = 1)	A: 59	B 86	145	0.59
Not poor worker actions (Y = 0)	C: 22	D: 9	31	–
Tot.	81	95	176	–
Consistency	–	0.91	–	–

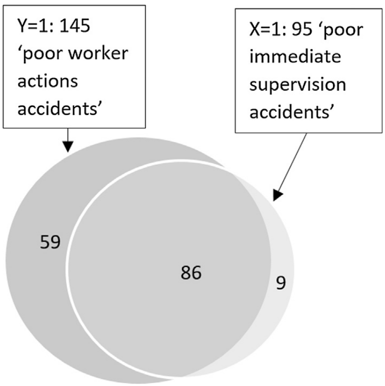

Fig. 5. Venn diagram illustrating the connection between 'poor immediate supervision' (X) (n = 95) and 'poor worker actions' (Y) (n = 145).

6.3. Immediate supervision

Immediate supervision was the factor thirdly most identified in this study, and one of the factors strongly connected to worker actions (Fig. 6). Immediate supervision was identified more often in this study (54%) compared to the studies in UK (13%), Australia (16%), and USA (30%) (Gibb et al., 2014). The results showed inadequate immediate supervision in *controlling* unsafe conditions and actions on site and in *planning* the work in a manner to reduce risk and identifiable hazards.

Immediate supervision is a shaping (intermediate) factor in the ConAC framework, and Fig. 6 illustrates that immediate supervision is an outcome of the originating factors risk management ('sufficient' and 'necessary') and project management ('sufficient'), and a condition for the immediate factor worker actions ('sufficient'). The results are broadly consistent with other studies. Rowlinson et al. (2003) concluded that the foreman is the key interface between worker and management and plays a key role in ensuring that safety management systems operate effectively. Mohamed (2002) concluded that the more aware of occupational health and safety (OHS) supervisors are, the more positive is the OHS climate. Choudry and Fang (2008) found that management involvement and toolbox talks were found to be the most effective factors for site safety, and that workers feel more comfortable with supervisors who care for their safety. Kines et al. (2010) found that coaching construction site foremen to include safety in their daily verbal exchanges with workers had a significantly positive and lasting effect on the level of safety. In a literature review, Khosravi et al. (2014) found that effective enforcement, worker-supervision communication, and good supervision style had moderate evidence of negative association with unsafe behaviours and accidents. This study and the studies described above show the importance of the supervisor/foreman being the connection between workers and management, and in controlling and planning the work to prevent unsafe conditions and acts.

6.4. Risk management

Risk management was the originating factor most identified in this study (56%), and in the studies in the UK (84%), Australia (21%), and USA (67%) (Gibb et al., 2014). The most frequent categories of deficiencies in risk management in this research were poor or lacking risk assessments, poor routines for assessing risk in working operations,

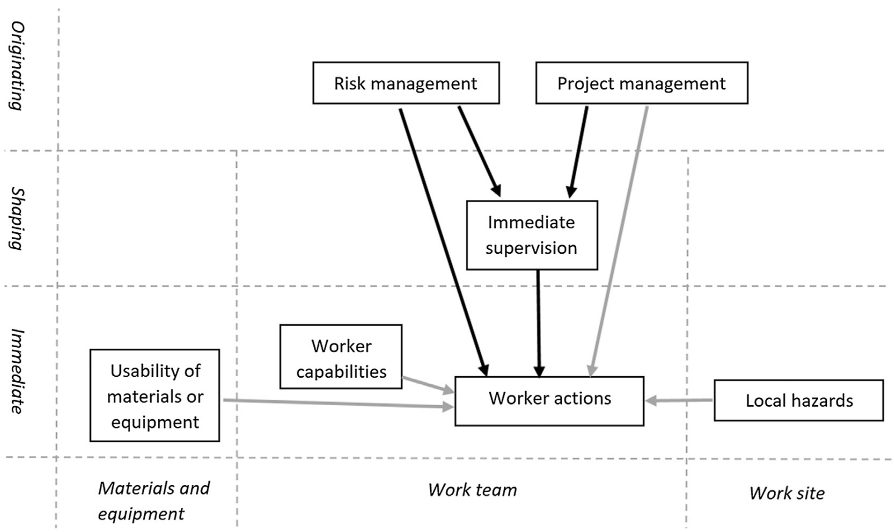

Fig. 6. Factors consistently connected to poor worker actions (coverage > 0.3) and poor immediate supervision, and connections between these factors. Black arrows indicate strong connections (coverage > 0.5).

inadequate systematic health and safety work/internal control, and not following the safety and health plan. There were combinations of such deficiencies in most of the risk management accidents. The results are similar to those of Haslam et al. (2005) who found that the failures of risk management typically were lack of, or inadequate, risk assessments. Hale et al. (2012) also found failures in planned risk control at the workplace level and planning and risk management at the 'delivery systems' level. These inadequacies are largely about inadequacies in risk management at different levels and underline the importance of risk being addressed at different levels by different actors (Hale et al., 2012; Rasmussen and Svedung, 2000).

Risk management was found to be both a 'sufficient' and 'necessary' condition for poor immediate supervision in this study, suggesting that it can produce poor immediate supervision alone, and that it 'almost always' produces poor immediate supervision. This is not surprising, since the supervisor plays a key role in risk management in many construction projects as described above. Risk management was also found to be a 'necessary' condition for construction processes and work scheduling indicating causal connections to the planning and scheduling of the work operations. The results are not surprising, since accidents '… invariably involve an inadequately controlled risk, indicative of a management failing' (Haslam et al, 2005, p. 413). Risk management in this study is an example of what Reason (1997) call a latent condition that '… can increase the likelihood of active failures through the creation of local factors promoting errors and violations' (p. 11). Latent conditions like poor risk management can contribute to a number of different other causal factors and accidents.

6.5. Limitations

There are some limitations in using this framework and material. First, the framework used and the factors included will influence the outcome. Lundberg et al. (2009) has expressed this as 'What-you-look-for-is-what-you-find'. Second, like Cooke and Lingard (2011) and Behm and Schneller (2013) we found that the classification of the factors was open to interpretation. Differences in results from different studies using the ConAC framework can be explained by, for example, differences in accident severity, researcher background, use of primary versus secondary data and types of hazards (Gibb et al., 2014). The operational definitions created by Behm and Schneller (2013) were used and described in more detail and with examples from this study to increase internal validity. Third, the data used in this study, like in the Australian study (Cooke and Lingard, 2011), are secondary and some factors were difficult to assess due to little information. The outer originating factors in the framework were excluded and there was little information about some factors, for example, permanent works design and worker health/fatigue and housekeeping, which are clearly underreported in this material. Moreover, it was easier to identify factors at the sharp end on site than at the blunt end of, for example, project management or design. Fourth, the methods used for assessing connections between factors do not necessarily confirm causation. In the analysis, connections were established from an immediate factor to a shaping factor, and from the shaping factors to originating factors, as described in Section 4.1. However, there are many connections in the data set that are not validated in this way. To establish likely causal connections, it is necessary to study each connection in depth using other methods like for example process tracing (e.g., Goertz and Mahoney, 2012; George and Bennett, 2005). A suggestion for future research is to study in depth the causal processes between factors that are strongly connected, such as risk management, immediate supervision and worker actions.

7. Conclusion

The purpose of this study was to add to the relative sparse literature on accident causality in the construction industry. The ConAC framework and its terminology were found to be good tools for identifying and assessing causal factors in construction accidents. Despite some limitations concerning methods and material, the study revealed some strong and repeated patterns of frequent factors and connections between factors that provide valuable insight into construction accident causality. The results can be used for prioritising and developing preventive measures at different levels in the construction industry. This study and previous studies show that many construction accidents are multi-causal, and that different combinations of factors are present in different accidents. Strategies for reducing unsafe acts and accidents must also be multifactorial. All factors are, however, not equally important, and this study suggest that worker actions, immediate supervision and risk management are key causal factors in construction accidents and accident prevention.

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PAPER IV

A comparative analysis of safety management and safety performance in twelve construction projects

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Abstract

Introduction: Safety management in construction is complicated due to the complex "nature" of the construction industry. The aim of this research was to identify safety management factors (e.g. risk management and site management), contextual factors (e.g. organisational complexity) and combinations of such factors connected to safety performance.

Method: 12 construction projects were selected to compare their safety management and safety performance. An analytical framework was developed based on previous research, regulations and standards where each management factor was defined. We employed qualitative comparative analysis (QCA) to produce case knowledge, compare the cases, and identify connections between the factors and safety performance. The material collected and analysed included e.g. construction planning documents, reports from OHS-inspections, safety indicators, and interviews with project leaders and OHS experts.

Results and conclusions: The research showed that: (1) the average score on 12 safety management factors was higher among projects with high safety performance compared to projects with low safety performance; (2) high safety performance can be achieved with both high and low construction complexity and organisational complexity, but these factors complicate coordination of actors and operations; (3) it is possible to achieve high safety performance despite relatively poor performance on many safety management factors; (4) eight safety management factors were found to be "necessary" for high safety performance, namely roles and responsibilities, project management, OHS management and integration, safety climate, learning, site management, staff management, and operative risk management. Site management, operative risk management, and staff management were the three factors most strongly connected to safety performance.

Practical implications: Construction stakeholders should understand that the ability to achieve high safety performance in construction projects is connected to key safety management factors, contextual factors and combinations of such factors.

Keywords:

- Occupational health and safety management
- Safety performance
- Construction safety
- Construction project
- Comparative methods
- Qualitative comparative analysis
- Causal complexity

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1 Introduction

The construction industry in Europe (EU-28) had the highest share of fatal occupational accidents in 2015, with more than one in five accidents (Eurostat, 2018). Safety management in construction is demanding, since construction projects are technologically and organizationally complex (Lingard, 2013).

Previous research on the effectiveness of occupational health and safety management (OHSM) on safety performance is ambiguous, and the importance of different factors are debated (Zwetsloot, 2013). There is little research on the effect of safety management systems and programs on safety performance in construction. There is however some research that have identified factors potentially connected to safety performance in construction, for example management commitment (Loushine, Hoonakker, Carayon and Smith, 2006), subcontractor selection and management (Hallowell and Gambatese, 2009), worker involvement (Chen and Yin, 2013), interrelations between various project partners (Terwel and Jansen, 2014), site-specific safety plans (Hallowell and Calhoun, 2011), and safety culture (Choudhry, Fang and Mohamed, 2007).

The aim of this research is to identify how safety management factors, contextual factors and combinations of such factors influence safety performance. To do that, we (1) developed an analytical framework iteratively based on relevant literature and empirical results, (2) analysed documents (e.g. health and safety plans, inspection reports), safety indicators, and interviewed project leaders and OHS inspectors from 12 construction projects, and (3) assessed factors and combinations of factors connected to safety performance employing Qualitative comparative analysis (QCA) (Ragin, 1987; 2008). The study was performed in cooperation with Statsbygg, a Norwegian government client organisation who build and rehabilitate public buildings.

Construction contractors have traditionally been held responsible for OHS on construction sites (Lingard and Rowlinson, 2005). In 1992, the EU Construction Sites Directive (92/57/EEC) (European Commission, 1992, 2011) put heavy responsibility for OHS on the client. The motivation for the directive was the recognition that many occupational accidents had been attributed to unsatisfactory architectural and/or organisational options, poor planning and inadequate co-ordination (Berger, 2000). Clients can play a positive role in safety management during construction projects (Huang and Hinze, 2006; Spangenberg, 2010; Lingard, Oswald and Le, 2018). This paper focuses on safety management in construction projects primarily from a client's perspective.

2 Literature on safety management

Safety management can be defined as "the *process* to realise certain safety functions", and a safety management system (SMS) is commonly defined as "… the management procedures, elements and activities that aim to improve the safety performance of and within an organisation" (Li and Guldenmund, 2018, p. 96). An occupational health and safety management system (OHSMS) is defined as "A set of interrelated or interacting elements to establish OSH policy and objectives, and to achieve those objectives" (ILO, 2001, p. 19). The purpose of an OHSMS is to "provide a framework for managing OH&S risks and opportunities" (ISO, 2018, p. vi). In this research we use the term *safety management* to include both specific safety management factors as well as general management factors that can influence safety performance.

Tinmannsvik and Hovden (2003) distinguish between safety specific factors (management factors mainly to promote safety) and general management factors (management factors to improve the production system and organisation in general). In this research we include both safety specific factors as well as other management factors with a potential of influencing safety performance, like e.g. staff management and project management. This is in line with Hale (2003b), who argues that safety management should be seen as an aspect system, not a subsystem, of the organisation.

The literature reviewed use different terms – safety management (SM), occupational health and safety management (OHSM), and safety programs. In this research we use the term *safety management* to include all these terms. Risk control and safety management is often seen in terms of a hierarchy of system levels (Rasmussen, 1997; Reason; 1997; Hale, 2003a). The operational work is at the lowest level, where the accidents happen, being controlled by technology and human behaviour, which is in turn controlled by management provision of resources, information and instruction. These in turn are influenced by policy, regulation, market and other societal forces (Hale, Guldenmund, Van Loenhout and Oh, 2010).

Hale (2003a; 2005) argues that we know "quite securely" the structure of a good safety management system, including, (1) an anchorage to the specific hazards of the production, (2) a life cycle approach, (3) problem-solving at three levels (operational, tactical, strategic), (4) systems at the tactical level delivering the crucial resources and controls for safety-critical tasks at the operational level, and, (5) feedback and monitoring loops ensuring assessment against performance indicators at each of the three levels.

The research on the effectiveness of OHSMSs on safety performance is however ambiguous. In a literature review, Gallagher, Rimmer and Underhill (2001) concluded that OHSMSs can deliver more healthy and safe workplaces under the right circumstances. In another review, Robson et al. (2007) concluded that the body of evidence was insufficient to make recommendations either in favour of or against OHSMSs. In a review of the effectiveness of safety management systems (SMS), Thomas (2011) concluded that organisations with a certified SMS had significantly lower accident rates. There was however a lack of agreement about which components of a safety management system contributed the most to safety performance. Zwetsloot (2013) argue that the difficulties in demonstrating the effects of OHSMS on safety performance can be explained that many do not consider "contextual factors" like the ambitions and commitment of management, the participation of workers, and the continual adaptation to changing circumstances. Zwetsloot (2013) also argues that the system is more than the sum of its parts and the interactions between the elements are just as important as the elements.

A literature review of 49 studies of safety management and quality management in construction projects supported the use of integrated safety and quality management (Loushine, Hoonakker, Carayon and Smith, 2006). The characteristics found to contribute to improved construction safety were management commitment, employee involvement, a formal safety management program, training, audits and observations, continuous improvement, and communication.

Hallowell and Gambatese (2009) identified from previous research 13 critical elements of an effective construction safety program: a written and comprehensive safety and health plan, upper management support, job hazard analyses and hazard communication, safety and health orientation and training, frequent worksite inspections, emergency response planning, record keeping and accident analyses, project-specific training and regular safety meetings, safety and health committees, substance abuse programs, safety manager on site, subcontractor selection and management, and employee involvement safety and evaluation. Hallowell and Calhoun (2011) quantified the interrelationships between these 13 elements and concluded that the most central elements in an effective program were the site safety manager, worker participation and involvement, a site-specific safety plan, and upper management support and commitment. Another important conclusion was that many of the strategies found to be effective in isolation also provided a high level of synergistic effects that enhance the effectiveness of other elements.

In a review of 90 papers, Mohammadi, Tavakolan, and Khosravi (2018) identified 13 factors influencing safety performance in construction: motivation, rules and regulation, competency, safety investment and costs, financial aspects and productivity, resource and equipment, work pressure, work condition, culture and climate, attitude and behaviour, lesson learned from accidents, organization, and safety programs and management systems. They also concluded that safety performance is not only determined by management activities within project levels, but also by the interactions among factors at different hierarchical levels.

The ISO 45001 (Occupational health and safety management systems, ISO, 2018) also states that effectiveness and the ability to achieve the outcomes of an OHS system are dependent on a number of key factors, for example top management leadership and commitment, communication, consultation and participation of workers, allocation of necessary resources, risk management, continual performance evaluation and monitoring, integration of the OHSM system into the organisation's business processes (ISO, 2018).

Summarised, the research on safety management in construction shows several factors connected to safety performance. Some studies also show that certain combinations of factors increase the effect on safety performance. Based on a literature review, Mohammadi et al. (2018) suggested that more research is needed to investigate the interaction between the identified factors and determine how they are able to affect safety performance, which is one of the aims of this research.

3 Material and methods

3.1 Analytical framework

In qualitative comparative analysis (QCA), explanatory models are developed in an *iterative* manner to facilitate a dialogue between theory and evidence as described by Ragin (2014). The analytical framework (Table 1) was therefore developed in an iterative manner and employed for measuring and comparing safety performance and safety management in 12 construction projects.

A preliminary framework was developed based on previous research, regulations and standards. Important sources were: (1) The ConAC framework (Haslam et al., 2005), which we had used to identify deficiencies in management factors (and other factors) in construction accidents (Winge and Albrechtsen, 2018); (2) Hale et al. (2012), who developed an analytical framework for understanding underlying causes of construction fatal accidents; (3) Törner and Pousette (2009) who carried out an inductive, qualitative interview study of experienced workers (worker safety representatives) and first-line supervisors in construction to identify "preconditions and components of high safety standards" in the construction industry; (4) The Directive 92/57/EEC (European Commission, 1992) and the Norwegian version, the Construction Client Regulations (Directorate of Labour Inspection, 2009), which specify key elements for OHS management systems in construction; (5) The OHSM system standards by ILO (2001) and ISO (2018). Many of the detailed analytical questions underlying the relatively broadly defined factors in the framework were adapted from the safety management and organisation review technique (SMORT) which was originally based on the management oversight and risk tree MORT (Johnson, 1980). SMORT was originally published by Kjellén, Tinmannsvik, Ulleberg, Olsen, and Saxvik (1987) and is later revised based on more recent experiences and standards (Kjellén and Albrechtsen, 2017).

The preliminary analytical framework consisted of 18 main categories and 83 subcategories. The framework was then tested on the documentation collected (see section 3.4 and 3.5) from eight projects and revised. Then the framework was tested as an interview guide for semi structured "pilot interviews" with three projects leaders (for client) and revised to the final version with the 16 categories displayed in Table 1.

The factors in the framework can be divided into different categories. Since we focus primarily on the execution stage of construction projects, factors 1-4 are treated as "contextual factors". They are to some extent "contextual" factors and/or decisions made at an early stage. Factor 5 (contract management) can be seen as both as a contextual factor and a safety management factor. Factors 6-16 represent the safety management process of the project. Factors 13-16 to large extent manage the workplace – the "sharp end".

Table 1. Operational definitions of outcome and factors

Name	Description
OUTCOME:	
Safety performance (SP)	Assessment of the overall safety at site based on: (1) interviews with OHS-inspectors about their assessments of the relative extent of hazards and dangerous situations; (2) interviews with the client project leaders about their assessments of the relative extent of hazards and dangerous situations; (3) reports from audits/inspections; (4) analysis of all registered dangerous situations (RUOs and SDs); and (5) the total recordable injury rate (TRI-rate).
CONDITIONS /FACTORS:	
1. Construction complexity (CC)	The characteristics and inherent complexity of the project, the structure being constructed (buildability), location, and physical restrictions of the site.
2. Organisational complexity (OC)	The extent of use of subcontractors, other companies and hired workers relative to project size.
3. Time (TI)	Progress plans, time pressure and delays.
4. Economy (EC)	Whether the project was on budget, and whether contractors made money.
5. Contract management (CO)	Contracting strategy, contract type, cooperation between client and contractors, and the contractor's commitment to OHS.
6. OHS-planning (PL)	Whether OHS was part of project planning and activities: Adequate SH-plan communicated to all actors and regularly updated; assessment of risks in advance with specific measures; and progress plans.
7. Roles & responsibilities (RO)	The presence, clarity and performance of roles central to OHS (client, principal enterprise, coordinators for the planning stage and execution stage, HS staff).
8. Project management (PM)	Coordination, cooperation, communication and follow-up of actors on OHS.
9. Management commitment to OHS (MC)	Commitment to OHS by managers (client and contractors) and emphasis on and integration of safety management with project management.
10. Safety climate (SC)	Attitudes, communication, openness and trust regarding OHS.
11. Learning (LE)	Learning from incidents, accidents and deviations through reporting, safety walks and inspections.
12. Performance evaluation (PE)	Ability to evaluate OHS performance and implement measures.
13. Operative risk management (RM)	Operative risk management by people in direct control of the risk at the operational level (planning of operations to reduce risk).
14. Site management (SI)	Site organisation, storage, logistics, housekeeping and provision of physical barriers.
15. Staff management (SM)	Planning to ensure the availability of sufficient workers with adequate capacity that is competent and suitable. Supervision and follow up of safety behaviour (short-cuts and compliance) on site.
16. Hardware management (HA)	Availability, condition, usability and suitability of materials and equipment.

3.2 Qualitative comparative analysis (QCA)

Hale (2003a) argued that we need to do comparative studies of good and bad companies to see "… what features are crucial" (ibid. p. 192). We employed Qualitative comparative analysis (QCA) (Ragin, 1987; Ragin, 2008) to identify conditions and combinations of conditions connected to safety performance. QCA uses the terms "condition" (causal factor), outcome, and connections (associations). In this research we use the term condition when using QCA, and otherwise use the term factor since that is the term used in most of the safety literature studied.

QCA is a methodological approach for comparing cases, producing case knowledge and identifying associations between conditions and the outcome. QCA strives to meet two apparently contradictory goals of in-depth insight into cases and complexity, and the production of generalisations (Ragin, 1987). Comparative studies of "good" and "bad" construction projects is also an opportunity to study both what goes right (safety I) and what goes wrong (safety II) in safety management in construction projects (Hollnagel, 2014).

QCA is a set-theoretic approach where concepts are understood as sets in which cases have membership. There are two types of sets. Crisp sets allow only full membership (1) and full non-membership (0). Fuzzy sets allow for partial membership in addition to full membership and non-membership where the point of maximum ambiguity (fuzziness) is .5. A fuzzy set can be seen as a continuous variable that has been calibrated to indicate degree of membership. Researchers must use substantive and theoretical knowledge to calibrate membership.

The approach is based on a notion of causal complexity, where outcomes are produced by combinations of conditions (configurations), and that different configurations can produce a similar outcome (equifinality). QCA is very well suited to researching complexity (Gerrits and Verveij, 2018). When QCAs are undertaken, we look for conditions that are *necessary* parts of a combination of conditions (configurations). A condition (X) is necessary if, whenever the outcome (Y) is present across cases, the condition (X) is also present. We also look for configurations that are *sufficient* to explain the outcome. A condition or configuration is *sufficient* if, whenever it is present across cases, the outcome is also present (If X, then Y). There can, however, be several configurations that are sufficient for the outcome (equifinality). Sufficient conditions or configurations can produce the outcome alone, but there can also be other conditions/configurations with this ability.

QCA has gained increased in popularity in recent decades, especially in the disciplines of comparative politics, business and economy, sociology, and management and organisation (Roig-Tierno, Gonzalez-Cruz and Llopis-Martinez, 2017). As QCA is a relatively new technique, we explain its basic logic and steps (for a detailed treatment, see Ragin, 2008, and Schneider and Wagemann, 2012). Data analysis was performed using the fsQCA 3.0 for Windows software (Ragin and Davey, 2017) and its software manual (Ragin, 2017).

3.3 Case selection

The study was performed in cooperation with Statsbygg, a government client organisation responsible to the Norwegian Ministry of Local Government and Modernisation (KMD). Statsbygg build and rehabilitate state public buildings, such as court buildings, prisons, museums and university buildings. Statsbygg is actively involved in safety management in projects with project staff present at the site and following up production and OHS regularly.

The sampling was carried out in dialogue with OHS experts in Statsbygg based on their familiarity with projects. The cases were selected based on three criteria: 1) Projects initially assessed to have relatively high or low safety performance were selected, because it is advantageous to include cases with a "positive" or a "negative" outcome in comparative methods (Berg-Schlosser, De Meur, Ragin and Rihoux, 2009). 2) Projects relatively similar in size (working hours), building type, and contractual arrangements were selected to keep these conditions as constant as possible; 3) Projects that were finished or more than halfway finished were selected making it possible to compare safety performance.

Materials from eleven different projects were collected. One project was much larger than the others. This project experienced many problems in the first part of the executions stage regarding project management and safety management. It was paused for some weeks and several measures were implemented. Since the two parts of the execution stage were very different as regards safety management, it was decided to analyse it as two cases. The number of cases analysed is therefore 12.

Statsbygg is one of Norway’s largest clients, with a top management strongly committed to OHS. The client and projects are therefore not "representative" for construction projects, and the projects are not representative of Statsbygg’s projects, since most Statsbygg projects have a high safety performance.

3.4 Measuring safety performance

Oswald, Zhang, and Lingard (2018) argue that great care needs to be taken when using safety indicators to evaluate organisational safety policy and practices. Common health and safety indicators can for example be subject to manipulation and misinterpretation. In this research we found indications that some injuries that should have been registered as lost time injuries (LTIs), were registered as medical treatment injuries (MTIs). LTI-rate was therefore assessed to be a relatively unreliable indicator since systems of registration were different across the projects studied, in addition to the other weaknesses of the LTI-rate (see Kjellén and Albrechtsen, 2017). The total recordable injury rate (TRI-rate) was assessed to be the only reliable quantitative injury indicator with which to indicate safety performance. TRI-rate is more robust than LTI-rate since the number of injuries is higher. TRI-rate includes mostly less severe injuries and is therefore primarily an indicator of the presence of less severe hazards and occurrences.

The data collection took place after the projects were finished, or in some cases, more than halfway, making it possible to assess results from most of the construction period. It was therefore not practicable to use safety climate surveys or other leading indicators. Because of limitations in the safety indicators, and difficulties using more leading indicators, we chose to do a researcher-based assessment of safety performance based on five sources (triangulation):

1. The total recordable injury rate (TRI-rate).
2. Analysis of all registered dangerous situations (RUOs and SDs).
3. Reports from OHS audits/inspections (see section 3.5.2).
4. Interviews with client project leaders about their assessments of the extent of hazards and dangerous situations relative to the project size.
5. Interviews with OHS-inspectors about their assessments of the extent of hazards and dangerous situations relative to the project size.

Table 2 describes the indicators used. We interpret the number of "registered dangerous situations" (RUO & SD) primarily as an indicator of willingness to report and tackle safety issues, not as an indicator of high levels of danger (Hale et al., 2010).

Table 2. Materials, numbers and indicators used to assess safety performance and willingness to report.

Abbreviations	Description
WH	Working hours registered by main contractor, subcontractors and hired workers. Working hours by designers not included.
LTI-rate	Lost time injuries (LTI) per 1 million working hours. LTIs are injuries resulting in more sick leave than just the day of injury as reported by the contractors to the client.
MTI-rate	Medical treatment injuries (MTI) per 1 million working hours. MTIs are reported from the contractors to the client.
TRI-rate	Total recordable injuries (TRI=LTI+MTI) per 1 million working hours. Reported from the contractors to the client.
RUOs & SDs	Registered unwanted occurrences (RUO) include accidents and near accidents. Site deviations (SD) include deviations from regulations registered by contractors and client on mostly safe job analysis (SJAs), working instructions, lack of personal protective equipment, failure of scaffolding, and danger zones not defined.
WTR	Willingness to report: RUO&SD per 1 000 working hours.

3.5 Measuring safety management factors and contextual factors

Different materials were used and triangulated to assess the factors in Table 1: safety and health plans, inspection and audit reports, logs of OHS-related information, and interviews with OHS coordinators and project managers.

3.5.1 The client's safety and health plan (SH plan)

Directive 92/57/EEC (European Commission, 1992) and the Norwegian version, the Construction Client Regulations (Directorate of Labour Inspection, 2009), require the client to produce a plan for safety and health plan (SH plan), which must be communicated to all actors in the construction project. The SH plan is the client's documentation that the work is planned and that risks are assessed in advance, and a *tool* for the client ensuring that the work is carried out without health and safety risks. The SH plan must describe (1): the organisation of the project, including roles and responsibilities for OHS; (2) a progress plan describing when and where the various work operations are to be carried out, for example, coordinating various work operations; (3) specific measures connected to activities that may involve risks to life and health with specific measures for work involving risk; and (4) procedures for handling deviations. During the execution phase the SH plan must be updated after any changes that may affect health and safety. There can thus be many versions of the SH plan during a project. Between two and four SH plans from different phases for each project were analysed.

3.5.2 Reports from OHS audits/inspections

OHS audits/inspections of projects are regularly conducted and led by OHS experts from the OHS department at Statsbygg. Other participants include representatives of project management in Statsbygg and representatives from the main contractor (e.g. project leader, supervisor, OHS expert). The OHS inspection reports consist of: (1) document reviews (SH plan, progress plans, SJAs, list of workers, companies, RUOs, etc.); (2) interviews with central persons (e.g. managers, coordinators, safety representatives); (3) description of site inspection focusing on deviations; and (4) requirements for following up deviations. The reports also include descriptions and pictures from the sites.

3.5.3 Log on OHS related information

OHS related occurrences and activities were registered continually during the projects, including results from safety rounds, SJAs, deviations, RUOs, dangerous operations, accidents, near accidents, OHS inspections and updates of the SH plan. More information was registered in the "poor" projects than the "good" projects. The descriptions gave a good overview of the projects and their development.

3.5.4 Interviews

After analysing indicators, SH plans, OHS inspection reports and OHS logs, interviews with client project leaders (PL) were undertaken. The interviews lasted between 60 and 90 minutes using videoconferencing or telephone. Interviews with OHS inspectors/experts were undertaken after all the documents and PL interviews were analysed. Four OHS experts who had each been inspecting several of the projects were interviewed about each of the projects. OHS experts who had inspected a project at least twice were selected for interview for that particular project. Before the interviews, the OHS experts read summaries of the preliminary analysis. All interviews were undertaken to supplement the documented information and to triangulate (verify or contradict) information from documents. The interviews were recorded and transcribed by the first author. One of the OHS experts and co-author of this article (Arnesen), had participated at inspections of all the projects and knew all projects well. He also participated in the analysis, which was a crucial advantage for data collection and analysis.

All in all, 22 interviews were carried out. Eleven interviews with client project leaders (one assistant project leader) and eleven interviews with OHS inspectors for each project were carried out. The interviews were semi-structured, using the analytical framework as an interview guide with both project leaders and OHS inspectors. The interviews were conducted as a dialogue, exploring how different factors affected the situations on site, and safety performance. The dialogue enabled the quality of different aspects of project performance to be compared.

4 Results

4.1 General characteristics of the projects

We do not present detailed information about the cases, and the projects are anonymised for reasons of sensitivity regarding the companies and persons involved. The buildings were museums and university buildings, mostly new buildings and rehabilitations of old buildings. Some projects also included groundworks and demolition. The number of working hours varied from some 17,000 to 1,150,000, with an average of 305,000.

4.2 Employing qualitative comparative analysis (QCA)

The results of the calibration of the outcome and the conditions (factors) are presented in Table 3. Recall that the calibration of the outcome and the condition scores are based on assessments of different types of data (triangulation) (see Section 3). The choice of the number of values for the outcome and each condition was based on the characteristics of each condition. For the outcome (safety performance) we used the six-value set with the values *very good* (1.0), *relatively good* (.8), *adequately* (.6) etc. We used the crisp set (0 or 1) for five conditions and the four-value set (0, .33, .67, 1) for eleven conditions.

The second column in Table 3 shows the assessment of the outcome safety performance (SP). Half of the projects were considered to have relatively *high* safety performance (HSP) (.5<) and the other half relatively *low* safety performance (LSP) (.5>). This was not a coincidence since we selected projects that were initially assessed to have relatively high or low safety performance (see Section 3.3). The average score for the safety management factors (factors 5-16 in Table 1) was .53., for all projects, .77 for the HSPs, and .30 for the LSPs. Hardware management (HA) was assessed as good in all projects. The opinion of the client project leaders and OHS inspectors was that poor material and equipment is not tolerated, and when identified, measures are taken immediately. This means that hardware management cannot be included in QCA because it is a constant, and not a variable.

Table 3. Raw data for 12 construction projects

Case	SP	CC	OC	TI	EC	CO	PL	RO	PM	MC	SC	LE	PE	RM	SI	SM	HA
A	1	1	1	1	1	1	.67	1	1	1	1	1	1	1	.67	1	1
B	.8	.33	0	1	1	1	.67	1	1	1	.67	.67	1	1	.67	.67	1
C	.8	.33	.67	1	1	1	.33	.67	1	1	.67	.33	1	.67	.67	.67	1
D	.8	1	.67	0	0	0	.33	.33	.33	.33	.33	.33	1	.67	.67	.33	1
E	.6	.33	1	1	1	1	.33	.67	1	1	1	1	1	.67	.67	1	1
F	.6	0	0	1	1	1	.33	1	.67	.67	.67	1	1	.67	.67	.33	1
G	.4	.33	.33	1	1	0	.33	.33	.33	.33	.33	.67	0	.33	.33	.33	1
H	.4	.33	0	0	0	0	0	.33	.33	.33	0	.33	0	.33	.33	.33	1
I	.4	0	0	0	0	0	0	.33	.33	0	.33	.33	0	.33	.33	.33	1
J	.2	.33	.33	1	0	1	.33	.67	.33	.33	.33	.33	0	.33	.33	.33	1
K	.2	.67	.67	0	0	0	.33	.33	.33	.33	.33	.33	0	.33	.33	.33	1
L	0	0	.67	1	0	0	0	0	0	0	0	0	0	0	0	0	1

Note: Safety Performance (SP), Construction Complexity (CC), Organisational Complexity (OC), Time (TI), Economy (EC), Contract Management (CO), OHS-Planning (PL), Roles and responsibilities (RO), Project Management (PM), Management Commitment (MC), Safety Climate (SC), Learning (LE), Performance Evaluation (PE), Operative Risk Management (RM), Site (SI), Staff management (SM), Hardware management (HA).

4.3 Set coincidence

Set coincidence is the degree to which two or more sets overlap, or, in other words, the extent to which they constitute one and the same set (Borgna, 2013). Fuzzy-set coincidence is "… a special case of correlation" (Ragin, 2008, p. 59). A set coincidence score close to 1 indicates that most of the cases share exactly the same degree of membership in two sets. If two conditions have the same values in all projects, they can be merged into one, if it is theoretically advisable. The procedure was used to assess which conditions strongly coincide (.75≤), and whether they should be included in further analysis. Table 4 shows that staff management, operative risk management, roles and responsibilities, site management, project management, and safety climate strongly coincide with several conditions.

Table 4. Set coincidence matrix for 16 conditions in 12 construction projects.

Conditions	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Construction complexity															
2. Organisational complexity	.58														
3. Time	.27	.43													
4. Economy	.28	.36	**.75**												
5. Contract management	.28	.36	.48	.71											
6. OHS-planning	.56	.42	.35	.38	.38										
7. Roles and responsibilities	.47	.44	.57	.58	.65	.55									
8. Project management	.48	.50	.57	.65	.65	.55	**.82**								
9. Management commitment	.50	.52	.59	.68	.68	.58	**.77**	**.95**							
10. Safety climate	.47	.57	.52	.59	.59	.64	**.76**	**.85**	**.80**						
11. Learning	.50	.46	.53	.61	.54	.58	**.77**	**.77**	.73	**.80**					
12. Performance evaluation	.40	.42	.56	.71	.71	.38	.58	.65	.68	.59	.54				
13. Operative risk management	.57	.52	.48	.54	.54	.58	**.86**	**.86**	**.81**	**.80**	.73	.61			
14. Site management	.55	.50	.42	.46	.46	.64	**.76**	**.76**	.72	**.79**	.71	.53	**.90**		
15. Staff management	.55	.57	.46	.52	.52	.65	**.76**	**.85**	**.80**	**.89**	**.80**	.52	**.80**	**.79**	
16. Hardware management	.39	.45	.67	.50	.50	.30	.56	.55	.53	.47	.53	.50	.53	.47	.47

4.4 Necessary conditions

Consistency and coverage are parameters used to assess how well the cases in a data set fit a relation. *Consistency* resembles significance in statistical approaches where 0 indicates no consistency and 1 indicates perfect consistency. The consistency value for conditions should be higher than 0.75 (Schneider and Wagemann, 2012). If a relationship is established to be consistent, the coverage should be calculated. *Coverage* assesses the degree to which a condition accounts for instances of an outcome, or empirical relevance (Ragin, 2008). With a consistency threshold of 0.80, the results indicate that eight of the OHSM conditions are "necessary" for high safety performance, indicating that high safety performance cannot be achieved without high performance on that specific condition (e.g. operative risk management) (if Y, then X). The coverage (empirical relevance) is also high for these eight conditions. Hardware was previously identified as a constant and therefore cannot be included in the analysis.

Table 5. Necessary conditions for the outcome safety performance. N=12. Consistency and coverage.

Condition	Consistency	Coverage
1. Construction complexity	.62	-
2. Organisational complexity	.59	-
3. Time	.71	-
4. Economy	.68	-
5. Contract management	.64	-
6. OHS planning	.55	-
7. Roles and responsibilities	.87	.81
8. Project management	.89	.83
9. Management commitment	.84	.82
10. Safety climate	.80	.87
11. Learning	.80	.79
12. Performance evaluation	.74	-
13. Operative risk management	.92	.91
14. Site management	.85	.93
15. Staff management	.81	.89
16. Hardware management	-	-

4.5 Conditions and models for QCA analysis

The aim of QCA analysis is to identify combinations of conditions that are *sufficient* for the outcome (if X, then Y). This process requires four steps: (1) presenting the data in a truth table; (2) minimising the truth table; (3); reporting the parameters of fit for the solution formula, and (4) interpreting the results.

The number of conditions in QCA must be kept quiet low; three to eight conditions are recommended (Ragin, 2008). The problem is that as the number of binary conditions increases, the number of possible combinations of these variables increases exponentially, so-called limited diversity (Ragin, 1987). One strategy for including more conditions is to conduct separate QCAs for different sets of conditions (Gerrits and Verweij, 2018). We decided to conduct two QCAs, one including "contextual conditions" and one for "OHSM conditions".

4.6 QCA for contextual factors combined with operative risk management

The aim of this first QCA was to detect combinations of "contextual conditions" (project complexity, organisational complexity and contract management) combined with OHSM. Operative risk management is included in the analysis to represent OHSM. Operative risk management was selected because it coincides (overlaps) strongly with many of the other OHSM conditions (see Table 4).

4.6.1 Truth table

A truth table lists all possible logically possible configurations. Each row in the truth table represents one logically possible configuration (Ragin, 1987). Each case in the raw data matrix (Table 3) is assigned to the respective truth table row which it belongs. The fuzzy conditions need to be dichotomised to match calibrated fuzzy cases into a truth table. A fuzzy set score below 0.5 is dichotomised to 0, and a fuzzy set score above 0.5 is dichotomised to 1. The truth table shows the configurations as dichotomies, but the calibrated cases remain fuzzy. Since we include four conditions that can score either 0 or 1, there are 16 logically possible combinations of the four conditions. The truth table for the outcome *high* safety performance (Table 6) shows that there are cases in eight out of the 16 possible configurations. Column number 2-5 indicate the qualitative status of the four conditions (present 1 vs. not present 0). Column "SP" indicates whether the given row is sufficient for the outcome "high safety performance" (score of 1) or not sufficient (0). The decision about sufficiency is based on each row's consistency score ("Cons."). Consistency expresses the degree to which empirical evidence supports the claim that a set-theoretic relation exists. Values below 0.80 indicate substantial inconsistency. PRI is a consistency score that is more sensitive to the possibility that one row can be a subset of the outcome as well as its negation. This yields four rows which include six cases that are considered *sufficient* for high safety performance, and four rows including six cases that are considered *not sufficient* for high safety performance. The "Cases" column shows the labels of cases that are members of a given row.

Table 6. Truth table for contextual conditions with high safety performance.

Row	CC	OC	CO	RM	SP	Cons.	PRI.	Cases
1	1	1	1	1	1	0.93	0.90	A
2	1	1	0	1	1	0.90	0.78	D
3	0	0	1	1	1	0.90	0.80	B, F
4	0	1	1	1	1	0.88	0.77	C, E
5	1	1	0	0	0	0.65	0.22	K
6	0	0	1	0	0	0.65	0.22	J
7	0	0	0	0	0	0.52	0	G, H, I
8	0	1	0	0	0	0.40	0	L

Note: Construction Complexity (CC), Organisational Complexity (OC), Contract Management (CO), Operative Risk Management (RM), and Safety Performance (SP).

The occurrence and non-occurrence of the outcome require separate analysis because the concepts often contain various qualitatively different notions, so-called causal asymmetry (Ragin, 2008).

Table 7 shows the truth table for the outcome *low* safety performance. It shows four rows which include six cases that are considered *sufficient* for *low* safety performance, and four rows which include six cases that are considered *not sufficient* for low safety performance.

Table 7. Truth table for contextual conditions with low safety performance.

Row	CC	OC	CO	RM	SP	Cons.	PRI.	Cases
1	0	1	0	0	1	1	1	L
2	0	0	0	0	1	0.92	0.83	G, H, I
3	1	1	0	0	1	0.90	0.78	K
4	0	0	1	0	1	0.90	0.78	J
5	1	1	0	1	0	0.65	0.22	D
6	0	0	1	1	0	0.57	0.13	B, F
7	0	1	1	1	0	0.56	0.15	C, E
8	1	1	1	1	0	0.43	0.10	A

4.6.2 Minimising the truth table into a solution formula

Each of the four first rows in Table 6 has been identified as sufficient for *high* safety performance, and each of the four first rows in has been identified as sufficient for *low* safety performance. The rows of each truth table can be made simpler using logical minimisation (Quine-McCluskey Algorithm): "If two Boolean expressions differ in only one causal condition yet produce the same outcome, then the causal condition that distinguishes the two expressions can be considered irrelevant and can be removed to create a simpler, combined expression" (Ragin, 1987, p. 93).

Table 8 shows the results of the minimisation process. The table shows two configurations sufficient for *high* safety performance covering 80% of the outcome, and two configurations sufficient for *low* safety performance covering 78% of the outcome. Results using QCA are often presented using circles. Black circles (●) represent present conditions, white circles (○) represent absent conditions, and empty cells represent redundant conditions, that is, conditions that have been minimised away through pairwise comparison. *Consistency* measures the degree to which solution terms and the solution as a whole are sufficient for the outcome (sufficiency). *Raw coverage* calculates how much of the outcome is explained by each solution separately. *Unique coverage* measures the proportion of memberships in the outcome explained solely by each individual solution term and indicates the unique contributions to covering the outcome.

Table 8. Consistent configurations for high and low safety performance (Complex solution). (Algorithm: Quine-McCluskey)

	High safety performance configurations (frequency cut-off; 1, consistency cut-off; .90)		*Low* safety performance configurations (frequency cut-off; 1, consistency cut-off; .87)	
Conditions	**HP1**	**HP2**	**LP1**	**LP2**
Construction complexity	○	●	○	○
Organisational complexity		●	○	●
Contract management	●			○
Operative risk analysis	●	●	○	○
Consistency	.91	.92	.92	.94
Raw coverage	.44	.49	.63	.32
Unique coverage	.30	.35	.46	.15
Cases	B, C, E, F	A, D	G, H, I, J	K, L
Overall solution consistency	.93		.91	
Overall solution coverage	.80		.78	

●, core condition (present); ○, core condition (negated); empty cells, redundant conditions.

4.6.3 Interpretation

The part of QCA using the software is only one step in the QCA process. Interpreting means returning to the cases and asking more focused causal questions about the mechanisms producing the outcome (Rihoux and Lobe, 2009). There are two "paths" that produce high safety performance. Configuration HP1 combines high safety performance with high project complexity, good contract management, and good operative risk management. Since the projects differ in organisational complexity yet produce high safety performance, organisational complexity is considered redundant (irrelevant) for this configuration according to the logical minimisation process. Configuration HP2 includes two projects with low construction complexity and organisational complexity, and with good operative risk analysis. Contract management is considered redundant since one project has good contract management and the other projects poor contract management. Configuration LP1 has high project complexity and organisational complexity, combined with poor operative risk management. Contract management is considered redundant since one project has poor contract management while the others have good contract management. Configuration LP2 has low project complexity, high organisational complexity, poor contract management and poor operative risk analysis.

The results indicate that high safety performance can be achieved with both high and low construction complexity and organisational complexity, showing that the conditions are not "necessary" for high safety performance. What seems to be important is how project complexity and organisational complexity are handled by OHSM, here represented by operative risk management. The results also indicate that high safety performance can be achieved with both good and poor contract management, showing that contract management is not "necessary" for high safety performance. What seems to be more important than contract management is operative risk management. Operative risk management is good in all high safety performance projects and poor in all low safety performance projects, suggesting that it is "necessary" for high safety performance.

Similar explanations are also found for the time and economy conditions. Poor economy and time makes it more challenging to achieve high safety performance but can be handled by good OHSM. The results are interpreted in more depth in the next section, jointly with the QCA of OHSM conditions.

4.7 QCA for safety management factors

The aim of the second QCA was to detect combinations of safety management factors connected to safety performance.

4.7.1 Truth tables

Table 9 shows the truth table for OHMS configurations connected to *high* safety performance. There are four rows which include six cases that are considered *sufficient* for high safety performance, and two rows including six cases that are considered *not sufficient* for high safety performance.

Table 9. Truth table for OHSM conditions with high safety performance.

Row	RM	PL	RO	MC	SM	SP	Cons.	PRI	Cases
1	1	1	1	1	1	1	0,93	0,84	A, B
2	1	0	1	1	1	1	0,92	0,79	C, E
3	1	0	1	1	0	1	0,89	0,64	F
4	1	0	0	0	0	1	0,89	0,64	D
5	0	0	1	0	0	0	0,77	0,18	J
6	0	0	0	0	0	0	0,44	0,05	G, H, I, K, L

Note: Operative Risk Management (RM), OHS planning (PL), Roles and Responsibilities (RO), Management Commitment (MC), Staff management (SM) and Safety Performance (SP).

Table 10 shows the truth table for OHMS configurations connected to *low* safety performance. There are two rows which include six cases that are considered *sufficient* for *low* safety performance, and four rows including six cases that are considered *not sufficient* for high safety performance.

Table 10. Truth table for OHSM conditions with low safety performance.

Row	RM	PL	RO	MC	SM	SP	Cons.	PRI	Cases
1	0	0	1	0	0	1	0.95	0.82	J
2	0	0	0	0	0	1	0.92	0.87	G, H, I, K, L
3	1	0	0	0	0	0	0.80	0.36	D
4	1	0	1	1	0	0	0.78	0.28	F
5	1	0	1	1	1	0	0.67	0.16	C, E
6	1	1	1	1	1	0	0.61	0.16	A, B

4.7.2 Minimising the truth table into a solution formula

The next step is to minimise the configurations from the truth tables into a solution formula. The four configurations producing high safety performance in Table 9 are reduced to three configurations in Table 11. The three configurations are *sufficient* for high safety performance covering 90% of the outcome. The two configurations producing *low* safety performance in Table 10 are reduced to one configuration in Table 11. The configuration is *sufficient* for low safety performance covering 93% of the outcome.

Table 11. Consistent configurations for high and low safety performance (Complex solution). (Algorithm: Quine-McCluskey)

	High safety performance configurations (frequency cut-off; 1, consistency cut-off; .89)			Low safety performance configuration (frequency cut-off; 1, consistency cut-off; .92)
Conditions	**HP1**	**HP2**	**HP3**	**LP1**
Staff management	●		○	○
Operative risk management	●	●	●	○
OHS planning		○	○	○
Roles and responsibilities	●	●	○	
Management commitment	●	●	○	○
Consistency	.93	.91	.89	.94
Raw coverage	.75	.63	.33	.70
Unique coverage	.16	.04	.11	.06
Cases	A, B, C, E	C, E, F	D	G, H, I, J, K, L
Overall solution consistency	.93			.93
Overall solution coverage	.90			.93

4.7.3 Interpretation

4.7.3.1 High safety performance configuration 1 (HP1)

HP1 in Table 11 includes four cases with high safety performance. Project C and E are also part of HP2 and interpreted with HP2. Projects A and B performed relatively well on all OHSM conditions. One difference between project A and B was that A had low project complexity and organisational complexity, while B had relatively high project complexity and organisational complexity. This was analysed in the first QCA (Table 8). Project A had a main contractor directly employing many workers themselves, using few subcontractors and hired workers. Project B had many subcontractors and had to coordinate and follow all subcontractors and work operations closely (project management). Project B was good at following up the contractors to ensure that each contractor was responsible for the risks they brought into the project. The good project management had an impact on operative risk management and safety performance. OHS planning was relatively good for project A and B, compared to the other 10 projects.

4.7.3.2 High safety performance configuration 2 (HP2)

The three cases in HP2 performed relatively well on most OHS conditions and achieved relatively high safety performance. One difference between HP2 and HP1 was that OHS planning was relatively poor in HP2, indicating that good OHS planning might be "necessary" for the highest safety performance.

4.7.3.3 High safety performance configuration 3 (HP3)

Configuration 3 includes one project (D) that is different from the other high safety performance projects. Despite many deficiencies regarding project management and OHS management (e.g. planning, organising, roles and staff management), the project managed to respond to some of the deficiencies relatively early and implement a few decisive measures. A new project leader and a coordinator for the execution stage established a strong control regime, following up contractors and workers, handling hazards and potentially dangerous operations on site. The measures were time-consuming and labour-intensive for the client, taking over many of the responsibilities from the contractors. However, the measures worked as an improvised solution in the most safety-critical phase of the project to achieve high safety performance, showing the importance of operative risk management. The case demonstrates that OHSM is not deterministic: It is possible to achieve high safety performance despite many problems and deficiencies in OHSM. Contributory conditions were that this project (D) (like project A) combined low construction complexity and low organisational complexity that reduced the difficulties of managing safety.

4.7.3.4 Low safety performance configuration (LP1)

The combination of conditions connected to *high* safety performance are not necessarily the same as those which produce *low* safety performance, so-called causal asymmetry. The same conditions can play different roles in different contexts. A separate truth table analysis and minimisation process was therefore performed for *poor* safety performance.

The projects with poor safety performance were more similar to each other than the high safety performance projects, and the minimisation process produced only one solution for low safety performance. The solution combines poor staff management, poor operative risk management, poor OHS planning, and poor safety management commitment, while "roles" is redundant.

Project J performed relatively well on many factors (roles and responsibilities, contract management, and parts of the project management), but still had low safety performance. The main deficiency was that the focus on, and commitment to, OHS as a process was low and poorly integrated into production management. This implied, for instance, that the involvement and supervision of workers (staff management) was poor, and that planning of operations to reduce risk (operative risk management) was poor. As a consequence, safety behaviour was poor and there was a high TRI-rate. The project indicates that it is not sufficient to have a relatively good production and project management, it is also necessary to emphasise the OHSM management process on its own in order to achieve high safety performance.

Project L stands out as a project where almost all OHSM conditions and safety performance were very poor and is the total opposite of Project A where all OHMS conditions were good.

Project L had many similarities with Project D, where most OHSM conditions were poor. Both projects experienced major problems during the execution stage, but Project D managed to implement measures to improve OHSM and achieve high safety performance while Project L did not. One reason that Project D managed to implement sufficient changes and Project L did not, was that Project L was more complex regarding both organisation and the building and site (see Table 8).

4.8 Analysis of the 16 factors

This section analyses and discuss the influence of each of the 16 factors. The operational definitions of the factors are described in Table 1.

4.8.1 Construction complexity

Construction complexity was not found to be "necessary" for high safety performance. The results indicate that high safety performance can be achieved with both high and low construction complexity. What seemed to be important is how project complexity and organisational complexity were handled by operative risk management, and probably other management factors. The result is consistent with Törner and Pousette (2009), who found that project characteristics and nature of the work are "… the limiting conditions to which safety management must be adjusted", are difficult to change, and "establish the outer limits of safety management" (ibid. p. 404).

4.8.2 Organisational complexity

Organisational complexity was treated as a "contextual" in this research, even though it is also the result of management decisions. The results indicate that low organisational complexity is not "necessary" for high safety performance. The results do not contradict that there is an association between increased on-site subcontracting and increased risks of injuries (Azari-Rad, Philips and Thompson-Dawson, 2003). The results do, however, indicate that high organisational complexity complicates the coordination of actors and operations and achieving high safety performance. What seems to be important is how the organisational complexity is handled by safety management, particularly operative risk management.

4.8.3 Time and economy

Time and economy are tightly connected and are therefore described jointly. The hypothesis was that "poor" time and economy can bring about reduced effort on safety which can lead to poor safety performance. Adequate time and economy were not found to be "necessary" for safety performance. In most projects, there was a connection between time/economy and safety performance, but there was also one project with poor "time/economy" with high safety performance, and one project with good "time/economy" and poor safety performance. The results indicate, like organisational complexity, that poor contextual factors can be handled by good safety management. Previous studies have found connections between time/economy and safety performance (Holmes, Lingard, Yesilyurt & De Munk, 1999; Mullen, 2004; Han, Saba, Lee, Mohamed & Peña-Mora, 2014). Mullen (2004) found that when resources (i.e., time and money) were inadequate, there was pressure from both managers and co-workers to prioritise performance over safety, and that such pressure swiftly socialised individuals to adapt and consider unsafe practices as normal.

4.8.4 Contract management

Except for two projects, the contracts were different variants of *design and build* (turn-key) contracts where a main contractor is given a performance specification by the client and must undertake the project from design to construction, and to a completed building. What seemed to be most important in achieving a high safety performance was how well the client and contractors were able to cooperate, communicate and avoid conflicts, not the formal contract management and contract. The result is broadly consistent with Bolt, Haslam, Gibb, and Waterson (2012) who found that a key factor was that systems (contracts, processes, systems and equipment etc.) and people work in tandem. The choice of main contractor was also important for safety performance. Limited availability of suitable contractors was a contributory factor to poor safety performance in some projects. Like Hinze and Gambatese (2003), we also found that subcontractor safety performance was affected to a large extent by the actions of the general contractor and construction management. Hale et al. (2012) also found that contracting strategy (competitive tendering and contractorization) was an important causal factor in fatal accidents.

4.8.5 OHS-planning

OHS-planning was not found to be "necessary" for high safety performance. Most projects did not have an adequate SH-plan including assessment of risks in advance with specific measures. The results indicate that much residual risk was left for the frontline workers to handle. Only two projects had an adequate OHS-planning including adequate risk assessments and specific measures. These two projects also had the highest safety performance, indicating that good OHS planning might be "necessary" for high safety performance. The research also showed that assessment of risks in advance with specific measures is very demanding because of the dynamic nature and new risks being produced consecutively. Conventional OHS risk management methods, assuming that that work can be decomposed into its parts, is of limited value in construction because system elements are in constant dynamic interaction with one another (Cooke-Davis et al., 2007). Hallowell and Gambatese (2009) found that a written and comprehensive safety and health plan was an essential safety program element, and Hallowell and Calhoun (2011) found that a site-specific safety plan is one of the most central elements in an effective safety program.

4.8.6 Roles and responsibilities

Roles and responsibilities was found to be "necessary" for high safety performance. The results indicated that two types of roles were important for high safety performance. First, that

OHS was to a large degree a management responsibility with active project leaders. Second, that at least one of the roles with specific responsibilities for OHS (coordinator for the execution stage, OHS-leader, OHS-coordinator etc.) was very active in the OHS activities and coordination. These results are consistent with results from literature reviews about the importance of top management generally (e.g. Hale and Hovden, 1998, and Shannon, Mayr and Haines, 1997) and in construction (Tam, Zeng and Deng, 2004; Hallowell, Hinze, Baud, and Wehle, 2013). The results are also similar to Hale et al. (2010) who found that the amount of energy and creativity injected by top managers and coordinator (safety professional) appeared to be a distinguishing factor.

4.8.7 Project management

Project management was found to be "necessary" for high safety performance. Projects with adequate project management managed to follow up OHS, coordinate the activities and ensure adequate communication between the actors. Project management is defined differently in different studies and it is hence problematic to compare to many studies. Our definition is similar to the ConAC model (Haslam et al., 2005; Winge, Albrechtsen and Mostue, 2019). In different accident studies using the ConAC framework, deficiencies in project management was found to one of the most frequent "originating" factors (Gibb, Lingard, Behm, & Cooke, 2014; Winge et al., 2019).

4.8.8 Management commitment to OHS

Management commitment to OHS was found to be necessary for high safety performance. In projects with high safety performance and adequate management commitment to OHS, the managers expressed clearly that safety was prioritised before production, and actively participated in OHS and other OHS-related management factors like project management, safety climate, planning and staff management. The results are consistent with literature reviews (Shannon et al., 1997; Mohammadi et. al., 2018). Hallowell et al. (2013) concluded that safety performance is exceptionally strong when top management is visibly involved in safety.

4.8.9 Safety climate

The aim of including safety climate as a factor, was to assess the "informal aspects" of safety management. Antonsen (2009, p. 17) describes a "good" safety climate as "… one where managers at all levels are highly committed to safety; where the workforce express satisfaction with and adherence to the organization's safety system; where everyone is risk adverse; where there is no pressure towards maximizing profits at the expense of safety and where operators as well as managers are highly qualified and competent". Safety climate was found to be "necessary" for safety performance. Table 4 shows that safety climate coincides with several other factors, and the analysis suggests that safety climate both influence, and is influenced by, several other factors. Safety climate coincide with staff management, which indicates that safety climate is connected to the selection of personnel, and the safety climate they bring with them. What characterise the projects with a high score on safety climate, was that the project management and OHS coordinators followed up the frontline workers closely regarding safety behaviours, and that they had several social arrangements focussing on OHS where both managers and frontline workers participated. The results are consistent with Törner and Pousette (2009) who found that "interaction and cooperation and conditions supporting cooperation through empowerment, mutual trust, and having a keen ear were important in relation to safety" (p. 405). Based on a literature review, Mohammadi et al. (2018) concluded that an adequate safety climate is a key aspect to prevent accidents and illnesses.

4.8.10 Learning

Learning was found to be "necessary" for high safety performance. Projects with high performance on learning had regular inspections and safety walks, and safety representatives that were active and participated on safety walks. These projects had a high willingness to report unwanted occurrences (see Table 2) and risks were mostly handled consecutively. Mohammadi et al. (2018) identified "lesson learned from accidents" as one of the factors influencing safety performance in construction. Hallowell and Gambatese (2009) found in their literature review that "recordkeeping and accident analyses" was a central program element, but one of the least effective.

4.8.11 Performance evaluation

Performance evaluation was not found to be "necessary" for high safety performance. All projects had some problems regarding OHS management early in the execution stage, all tried to solve them, but not all succeeded. What seems to be important was how early problems were identified, which types of measures were implemented, and how extensive the measures were. It is also clear that construction complexity and organisational complexity described above influenced the opportunities for implementing the measures successfully. The result is similar to a literature review by Loushine et al. (2006) who concluded that continuous improvement requires continuous monitoring of work or collection of data, analysis, and changes in the work processes to ensure that work is progressing towards goals. Performance evaluation (continual performance evaluation and monitoring of the OH&S management system) is also a key factor in ISO 45001 (ISO 2018) for continuous improvement.

4.8.12 Operative risk management

Operative risk management was found to be "necessary" for high safety performance. Operative risk management was good in all high safety performance projects and poor in all low safety performance projects. One project illustrates the importance of operative risk management. The project performed poorly on most safety management factors but had good operative risk management and high safety performance (.8). The results also indicate that projects with high project complexity and organisational complexity can achieve high safety performance, if the operative risk management is good. Operative risk management does not, however, operate in isolation. An analysis indicated that project management and roles and responsibilities were consistent "necessary" factors for operative risk management.

One central explanation why operative risk management is important, is probably that many risks were not handled in early stages, and that many residual risks had to be handled consecutively. The factor OHS-planning (section 4.8.5) showed that most projects did not have an adequate OHS-planning, including assessment of risks in advance with specific measures, and that many risks therefore were left for the frontline workers to handle. These residual risks hence had to be handled by operative risk management. Poor risk management was also found to be a dominant organisational factor in accident analyses in construction (Haslam, 2005: Behm and Schneller, 2013, Winge and Albrechtsen, 2019).

4.8.13 Site management

Site management was found to be "necessary" for high safety performance. Projects that had adequate site management were well organised, had clearly defined danger zones, pathways, areas for storage, good housekeeping, and few hazards. The importance of site condition is evident in falls from height. In a literature review of 75 studies about falls from height, Nadhim, Hon, Xia, Stewart and Fang (2016) found that site condition was one of the most common factors. Falls from height could occur when there were e.g. unprotected walkways, improper guardrails, slippery or sloped surfaces.

4.8.14 Staff management

Staff management was found "necessary" for high safety performance. In projects with adequate staff management, the share of skilled (trained) workers was high, the companies and workers had often worked together in previous projects, the safety climate was good, and supervision and safety behaviour were good. Staff management coincide strongly with safety climate and project management (Table 4). The results are consistent with Choudhry and Fang (2008), who concluded that management behaviour plays an important role in improving workers' behavioural safety performance. They also concluded that management can help workers to improve safety behaviours through the influence of rules and regulations, training and increased communication. Several studies also show the importance of the supervisors in enhancing good safety behaviour (Fang, Wu, and Wu, 2015; Mohamed, 2002; Rowlinson, Mohamed, and Lam, 2003; Kines, Andersen, Spangenberg, Mikkelsen, Dyreborg and Zohar, 2010; Winge and Albrechtsen, 2019).

5 Discussion and conclusion

The aim of this research was to identify how safety management factors, contextual factors and combinations of factors influence safety performance.

5.1 Combinations of factors

The results showed that the average score for the 12 safety management factors was far better among the high safety performance projects compared to the low safety management projects. The result is broadly consistent with literature reviews that safety management systems can deliver more healthy and safe workplaces (Gallagher et al., 2001) and lower accident rates (and Thomas, 2011). The results are also broadly consistent with Loushine, et al. (2006) who in a literature review on safety management and quality management found that construction projects with integrated safety and quality management systems/programs have better safety performance.

The results showed that high safety performance can be achieved with both high and low construction complexity and organisational complexity. The results indicated, however, that high construction complexity and organisational complexity complicate safety management. What seemed to be important was how project complexity and organisational complexity was handled by operative risk management. Regarding construction complexity, the results are broadly consistent with Törner and Pousette (2009) who concluded that the inherent complexity of construction work restricts and complicates safety management and demands comprehensive safety management. Regarding organisational complexity, the results do not contradict that there is a statistical association between increased on-site subcontracting and increased risks of injuries (Azari-Rad, Philips and Thompson-Dawson, 2003). The results do, however, indicate that high organisational complexity complicates the coordination of actors and operations and the production of a high safety performance. In projects with high organisational complexity and high safety performance, the organisational complexity was adequately planned for, and extensively managed by, for example, involvement, cooperation and follow-up of the contractors. The results are consistent with Hallowell and Gambatese (2009) who found that strategic subcontractor selection and management is among the most effective elements in safety programs.

The results also showed that it is possible to achieve high safety performance despite many relatively poor safety management factors, and that it is possible to produce low safety performance despite many relatively good safety management factors. The results indicate that it is not sufficient to have a relatively good production and project management, it is also necessary to emphasise the safety management process on its own to achieve high safety performance. The result showing that single *necessary* factors can be jointly *sufficient* to produce high and low safety performance is broadly consistent with the understanding of causality in many accident models. (Reason, Hollnagel and Paries 2006; Hopkins, 2014, Winge et al., 2019). This research also showed that there can be different combinations of factors producing high and low safety performance, so-called equifinality. The results support that the combination of many factors play a key role in safety management (e.g. Shannon et al., 2001; Hale et al, 2005; Hallowell and Calhoun, 2011; Dyreborg et al. 2013). Similarly, ISO 45001 (ISO, 2018) states that the effectiveness and ability to achieve outcomes of an OHS system are dependent on several key elements.

5.2 Single factors

Safety performance is the result of a complex interplay between different factors as demonstrated by the QCA analysis. At the same time, single factors have special characteristics and can have a specific causal influence. All factors are analysed and discussed in the results section. The analysis showed how each factor influenced safety performance. Eight safety management factors were found to be "necessary" for high safety performance: (1) roles and responsibilities, (2) project management, (3) OHS management and integration, (4) safety climate, (5) learning, (6) site management, (7) staff management, and (8) operative risk management. Site management, operative risk management, and staff management were the three factors most strongly connected to safety performance. This is probably because the factors are the most proximal, with most direct influence on what is going on at the sharp end, and essential in the daily control of the safety at site.

5.3 Limitations, contributions and future research

One contribution of this research is the comparative approach studying "good" and "bad" construction projects employing QCA and the QCA software, which gives an opportunity to study what goes right and what goes wrong (Hollnagel, 2014). Our experience was that the approach and software helped to identify the patterns of causal complexity producing high and low safety performance. Employing QCA helped us identify complexity in combinations of factors (configurations) and different paths producing high and low safety performance (equifinality). There are however some methodological and empirical limitations in this research that we recommend is followed up by future research.

First, the results are not based on hard facts but on the researchers' assessment of each causal factor and safety performance. Regarding measurement of safety performance, there is much evidence of under-reporting of workplace injuries (Shannon et al., 2001) and safety indicators can be subject to manipulation and misinterpretation (Oswald et al., 2018). Several data sources and methods were therefore combined by triangulation (Denzin, 1970) and mixed methods (Tashakkori and Teddlie, 2010) to increase internal validity. Second, the assessment of safety performance and safety management performance was problematic in some of the construction projects since performance often varies during a project. Third the study focuses on safety management in construction projects primarily from a client's perspective, and the cases could have been studied more in depth from other actors' perspective, for example from contractor's perspective or frontline workers' perspective. It would have been preferable to study more documents and interview more managers and safety representatives at the sharp end. There is, however, always a trade-off between depth and width. Forth, it was challenging to compare the results to previous research due to different definitions and poorly described definitions of factors in many studies. It is important for the accumulation of knowledge that key factors are clearly described. Fifth, the number of factors using QCA must be kept relatively low. The problem is that as the number of binary factors increases, the number of possible combinations of these variables increases exponentially – so-called limited diversity (Ragin, 1987). Therefore, two different QCAs involving different combinations of factors were employed. Sixth, aiming for both in-depth insight into cases and complexity, and to produce generalisations, might seem to be contradictory goals (see Ragin, 1987). Twelve cases are relatively few to produce generic results, and the results must therefore be treated with caution. The research is therefore seen as a building-block type of research (George and Bennett, 2005), and we encourage researchers to undertake similar studies with larger N which makes it easier to include more factors and study how they operate together. We also encourage more case studies and intermediate-N studies to increase our knowledge of associations between safety management factors, combinations of factors, and safety performance in construction projects.

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