Doctoral theses at NTNU, 2023:321

Kinga Wasilkiewicz Edwin

Advancing safety management in construction

Additional inputs through information sharing and an integrated safety approach

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Science and Technology

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Doctoral thesis

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To A and A

PREFACE

This thesis is submitted in partial fulfilment of the requirements for the degree of Philosophiae Doctor (PhD) in Industrial Economics and Technology Management at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. The main supervisor was Professor Eirik Albrechtsen, and the co-supervisor was Professor Trond Kongsvik. The following coursework of 30 ECTS has been undertaken as the compulsory part of the PhD education: Risk Perception and Risk Communication (PSY8002), Philosophy of Science for the Social Sciences (SFEL8000), and the Understanding and Management of Risk and Vulnerability Problems (IØ8502). The course Communicating Science in Journals and to the General Public (HFEL8000) was also completed as a supplementary course (3 ECTS).

The PhD was funded by the Department of Industrial Economics and Technology Management (IØT) at the Faculty of Economics and Management at NTNU. The work was performed between September 2016 and April 2023. The thesis is a collection of three scientific articles (two published and one manuscript submitted to a journal) related through this thesis.

Before starting the PhD, I did a master's degree at IØT, NTNU, specialising in Safety Management, followed by a stint at SINTEF Technology and Society. These experiences motivated me to pursue a PhD education in the field of Safety Research.

'Done is better than perfect,
because perfect never gets done'.
- Unknown

A PhD is the highest formal education in Norway, with the research results being one part of the outcome and the other being the schooling of the candidate. It is a journey that makes its way through acquiring new skills and gaining experiences. This includes learning new topics and research methods, applying those in research and scientific writing, and trying, failing and succeeding. Although the main requirements of a PhD degree are structured, the content and execution are flexible and original and require an ability to carry out the work independently with support through supervision. The challenge has been to sharpen and delimit the topic, as my interest in the field kept wanting me to divert and include many other aspects, which is not feasible even in a four-year period.

For sure many things could have been done differently; however, I am happy with the experience and the in-depth insight I have gained into the safety field, affiliated topics and the construction industry. I am proud to finally see the end results of my work, handing in a thesis consisting of all required parts and, most importantly, having developed myself as a researcher and person.

'If you do what you have always done,
you will get what you have always gotten'.

- Jessie Potter

The construction industry continues to report reoccurring injuries and fatalities, indicating that current strategies are insufficient and that there is potential for improvement regarding occupational safety. This thesis explores information sharing and an integrated safety approach as means for developing safety management and improving occupational safety. The work is of value to actors across the industry who wish to gain knowledge and improve safety.

'For the world you are someone,
for someone you are the world'.
- Erich Fried

I hope the thesis will be of value to both researchers and practitioners and contribute to a safer working life in the construction industry, so everyone can come back home safe and sound to those that matter to one.

Sandefjord, April 2023

Kinga Wasilkiewicz Edwin

ABSTRACT

Managing safety is an essential function in construction projects, yet unwanted incidents continue to occur. Though injury and fatality rates in the Norwegian construction industry have decreased over the decades, the improvement has somewhat stagnated, making it challenging to lower them further. Developing safety management through innovative solutions can be a key contributor to reducing unwanted incidents.

The main objective of this thesis is to explore how safety management in the construction industry can be developed by expanding the information base and applying a more integrated safety approach. The overall question of the thesis, '*How can incorporating additional inputs develop safety management in the construction industry?*' is addressed through the following three research questions:

1. What opportunities for safety management exist in broader information sharing across the construction industry?
2. How can the construction industry improve safety management by looking at practices from the Norwegian petroleum industry?
3. How is project management related to safety management in construction projects?

These research questions are answered based on three articles. The first article investigates post-incident sharing practices and information sharing arenas across companies in the Norwegian construction industry through interviews of safety personnel across actors in the industry. The second article explores characteristics of occupational safety in the Norwegian petroleum and construction industries and investigates the potential of sharing safety-related information between the two. Interviews were conducted with actors from safety authorities, top management, employer and employee organisations, and HSE personnel across both industries. The third article explores the relationship between project management factors, safety management factors and safety performance in a sample of Norwegian construction projects through a statistical analysis based on performance measurement data and incident data. The three articles lead to discussions on information sharing as a catalyser for safety management development and advancing safety management through an integrated safety approach.

The advantages of a broader information base across actors, phases and industries are identified. These include feeding input to risk and safety management across project phases and actors in future projects and serving in developing safety management mechanisms, such as indicators. Information sharing depends on several factors related

to the organisation, type of data and technology. It is found that willingness to share and intention to use can limit information sharing. Furthermore, a common taxonomy for safety-related data and standardisation of classifications (e.g., activities, incident type) to structure information was found important for sharing and utilising information. Digitalisation, new technological solutions, and the possibility to integrate an expanded information base into organisational systems allow broader use and utilisation of shared information.

Advancing safety management through an integrated safety approach is discussed in two parts, firstly looking at safety management as an aspect system and then looking into two safety perspectives (Safety-I and Safety-II). It is important to look at different project processes together, as many common factors contribute to value creation and hazard control. Further, this provides an opportunity to relate and monitor safety management by using data from processes of a system or parts of it. Existing safety performance indicators can be complemented with leading safety management indicators that measure the expected control of hazards by assessing project management elements related to safety management. This relates to the second part of the discussion about a better combination of the traditional Safety-I approach in formal safety management with the more adaptive and proactive Safety-II approach. Such a combined approach can enhance the value of shared information across the construction industry and contribute to a more holistic safety approach, developing safety management and improving safety performance.

Based on the discussed points, steps towards expanding information sharing across the construction industry are suggested. These include a practical approach to obtain an expanded information base for safety-related information, with elements such as standardisation, a shared understanding of taxonomy in the industry, the creation of a digital platform and data processing, and obtaining a more holistic and integrated approach for improved safety driven by its management.

The novelty of the research comes from the work wielding information from across the construction industry, including several project phases and actor types and looking across industries. Furthermore, the thesis advocates treating safety management as an integral aspect of production through the relationship with project management. Finally, it illuminates the opportunities to combine more perspectives, particularly Safety-I and Safety-II, for the construction industry's formal aspects of safety management.

SAMMENDRAG

Håndtering av sikkerhet er en grunnleggende funksjon i bygge- og anleggsprosjekter, likevel fortsetter uønskede hendelser å skje. De siste tiårene har skade- og dødstallene i den norske bygge- og anleggsnæringen sunket, men forbedringsnivået har stagnert, noe som gjør det vanskelig å redusere tallene ytterligere. En videreutvikling av sikkerhetsledelse gjennom innovative løsninger kan bidra til å redusere uønskede hendelser.

Hovedmålet med avhandlingen er å utforske hvordan sikkerhetsledelse kan utvikles ved å utvide informasjonsgrunnlaget og ved å anvende en mer integrert sikkerhetstilnærming. Det overordnede spørsmålet i oppgaven 'Hvordan kan innlemming av ytterligere input utvikle sikkerhetsledelse i bygge- og anleggsnæringen?' besvares med tre forskningsspørsmål:

1. Hvilke muligheter for sikkerhetsledelse finnes i bredere informasjonsdeling på tvers av bygge- og anleggsnæringen?
2. Hvordan kan bygge- og anleggsnæringen forbedre sikkerhetsledelse ved å se på praksis fra norsk petroleumsnæring?
3. Hvordan er prosjektledelse relatert til sikkerhetsledelse i bygge- og anleggsprosjekter?

Disse forskningsspørsmålene besvares på bakgrunn av tre artikler. Første artikkel undersøker delingspraksis etter hendelser og informasjonsdelingsarenaer på tvers av bedrifter i norsk bygge- og anleggsnæring gjennom intervjuer med sikkerhetspersonell fra aktører i næringen. Den andre artikkelen utforsker kjennetegn ved sikkerhet i norsk petroleumsindustri og bygge- og anleggsnæring, og ser på potensialet av å dele sikkerhetsrelevant informasjon mellom disse. Det ble gjennomført intervjuer med aktører fra tilsynsmyndigheter, toppledelse, arbeidsgiver- og arbeidstakerorganisasjoner og HMS-personell i begge næringer. Den tredje artikkelen utforsker sammenhengen mellom prosjektledelsesfaktorer, sikkerhetsledelsesfaktorer og sikkerhetsytelse i et utvalg norske bygge- og anleggsprosjekter gjennom en statistisk analyse basert på data fra prestasjonsmåling og hendelsesdata. De tre artiklene leder til diskusjoner om bredere informasjonsdeling som en katalysator for utvikling av sikkerhetsledelse, og om utvikling gjennom en integrert tilnærming til sikkerhet.

Fordelene med et bredere informasjonsgrunnlag på tvers av aktører, faser og næringer er identifisert. Dette kan for eksempel brukes som input til risiko- og sikkerhetsstyring på tvers av prosjektfaser og aktører i kommende prosjekter og i utvikling av sikkerhetsstyringsmekanismer, som eksempelvis indikatorer. Informasjonsdeling er

funnet å være avhengig av flere faktorer knyttet til organisasjon, data og teknologi. Vilje til deling og intensjon knyttet til bruk kan hindre informasjonsdeling. Videre ble en felles taksonomi med hensyn til sikkerhetsrelatert informasjon, og standardisering av klassifiseringer (f.eks. aktiviteter, hendelsestype) for å strukturere informasjon, funnet viktig for deling og utnyttelse av informasjon. Digitalisering, nye teknologiske løsninger, og mulighet til å innlemme et bredere informasjonsgrunnlag i organisatoriske systemer gir anledning til bredere bruk og utnyttelse av delt informasjon.

Å fremme sikkerhetsledelse gjennom en integrert sikkerhetstilnærming diskuteres i to deler, der sikkerhetsledelse sees på som et aspektsystem, og ved å se på to sikkerhetsperspektiver (Safety-I og Safety-II). Det er viktig å se på ulike prosjektprosesser sammen, da mange av de samme faktorene bidrar til verdiskaping i et prosjekt og til farekontroll. Videre gir dette også en mulighet til å relatere og overvåke sikkerhetsledelse ved å bruke data fra prosesser i et system eller deler av det. Eksisterende sikkerhetsytelsesindikatorer kan berikes med ledende sikkerhetsstyrings-indikatorer som måler forventet kontroll av farer ved å vurdere elementer av prosjektledelse som er relatert til sikkerhetsledelse. Dette bygger opp om den andre delen av diskusjonen som omhandler å kombinere den tradisjonelle Safety-I-tilnærmingen i formell sikkerhetsledelse bedre med den mer adaptive og proaktive Safety-II-tilnærmingen. En kombinert tilnærming kan øke nytten av delt informasjon på tvers av bygge- og anleggsnæringen og bidra til en mer helhetlig sikkerhetstilnærming, utvikling av sikkerhetsledelse og forbedring av sikkerhetsytelse.

Basert på de diskuterte temaene, foreslås steg mot utvidelse av informasjonsdeling på tvers av bygge- og anleggsnæringen. Disse inkluderer en praktisk tilnærming for å oppnå et felles informasjonsgrunnlag for sikkerhetsrelatert informasjon, med elementer som standardisering, felles forståelse av taksonomi i næringen, opprettelse av en digital plattform og databehandling, samt å oppnå en mer helhetlig og integrert tilnærming for forbedret sikkerhet gjennom ledelse.

Bidraget til forskningen kommer fra arbeidet med informasjonsdeling på tvers av bygge- og anleggsnæringen, inkludert prosjektfaser og aktørtyper, og på tvers av næringer. Videre taler avhandlingen for å håndtere sikkerhetsledelse som en integrert del av produksjon gjennom forholdet til prosjektledelse. Avhandlingen belyser også mulighetene for å kombinere flere perspektiver, spesielt Safety-I og Safety-II, for formelle aspekter ved sikkerhetsstyring i bygge- og anleggsnæringen.

'And, when you want something,
all the universe conspires
in helping you to achieve it'.

- Paulo Coelho, the Alchemist

ACKNOWLEDGEMENTS

The years since I started my PhD have been filled with much more than just the PhD work. Though it has taken a long time, I am happy that I have filled this journey also with other life achievements and milestones.

The first time my attention was drawn to a PhD was in 2012 when Amir was doing one. After completing my Master's in 2014, it felt like I wasn't finished studying, and I entertained the idea that one day I would continue my education through a PhD. Meantime, I was inspired by people and ideas and met several who have motivated me. All of these individuals and experiences helped me on my way, and finally, in 2016, I took the plunge. This led me to a challenging and rewarding experience, and it is with humble gratitude that I would like to recognise them here.

Firstly, I owe a debt of gratitude to my main supervisor, Professor Eirik Albrechtsen, for this opportunity and the wonderful journey. Thank you for your limitless patience and motivation and for guiding me through all these years in research, teaching duties, collaboration experiences and life. For always having an open door for professional discussions, mentoring, or just chatting. Thank you for making me comfortable to express my opinions freely, whatever they might have been. And most importantly, not giving up or letting me give up.

A big thank you to Jan Hovden, who got me into the safety field and followed me on this journey, to Urban Kjellén, who taught me incredibly much about safety management, to Trond Kongsvik, for being my co-supervisor and always prepared to help, comment and discuss, to my former colleagues at SINTEF and NTNU for inspiration and good talks, to the STERNA-project and all involved for collaboration opportunities, to all friends in Trondheim contributing to these years being so much more than PhD work, and to TIX, who´s songs were just what I needed in 2020. I also want to thank my fellow PhD-candidates and friends for bursts of motivation at the right times. A particularly big thank you to Marie Nilsen for always being there for me and spreading happiness and to Guillermina Peñaloza for coming in as a like-minded safety enthusiast. There is one thing that I value more than anything in working life, and that is the work environment. I am genuinely pleased and grateful that I had such great colleagues in the department during my time at NTNU. I have enjoyed all our gatherings, trips, everyday lunches, small talks in the corridor and at the coffee machine, and the weekly social online HSE games on Teams during Covid-19. I will miss all of this, but the memories will stay forever. Additionally, I would like to thank everyone who participated in the interviews for giving their time to make my data collection successful. I also wish to thank my current employer, particularly Tore Karlsen at PricewaterhouseCoopers (PwC), for encouraging me to finish my PhD and offering flexibility and time to finalise the work that was in its final stage and just needed another push.

I wish to thank my family, parents and parents-in-law for their support, patience, and love. Thank you, Uncle, for proofreading the manuscripts and the thesis. The greatest gratitude of all goes to my husband, Nathaniel, for the support, motivation, safety discussions, feedback on my work, informal supervision, proofreading and regular pushes to continue and complete the journey. Thank you for the late evening teas and for taking care of the home and family.

Finally, I have accomplished what I set out to do on this journey. So, at least for now, I feel finished with studying.

CONTENT

Part II: Collection of Articles

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AI	Artificial intelligence
BIM	Building information modelling
CAPES	Coordination for the Improvement of Higher Education Personnel (Brazil)
Diku	Norwegian Agency for International Cooperation and Quality Enhancement in Higher Education
GIS	Geographic information systems
HSE	Health, safety, and environment
IØT	Department of Industrial Economics and Technology Management
LTI	Lost time injuries
NLIA	Norwegian Labour Inspection Authority
NTNU	Norwegian University of Science and Technology
NSD	Norwegian Centre for Data Research
PhD	Philosophiae Doctor
PPE	Personal protective equipment
PSA	Petroleum Safety Authority Norway
RQ	Research question
SfS	Working Together for Safety [Samarbeid for sikkerhet]
SfS BA	Working Together for Safety in Construction [Samarbeid for sikkerhet i bygg og anlegg]
SMS	Safety management systems
SSB	Statistics Norway
TRI	Total recordable injuries
UFRGS	Federal University of Rio Grande do Sul
VR	Virtual reality

PUBLICATIONS

The following three journal articles are included in the second part of the thesis.

Article 1: Edwin, K. W. (2022). Sharing Incident Experiences: A Roadmap towards Collective Safety Information in the Norwegian Construction Industry. *International Journal of Occupational Safety and Ergonomics*. DOI:10.1080/10803548.2022.2118983

Article 2: Edwin, K. W., Nilsen, M. & Albrechtsen, E. (2021). Why Is the Construction Industry Killing More Workers Than the Offshore Petroleum Industry in Occupational Accidents? *Sustainability, 13*(14). 10.3390/su13147592

Manuscript for Article 3: Edwin, K. W., Albrechtsen, E. & Kongsvik, T. An analysis of the relationship between project management and safety management in the Norwegian construction. industry *Submitted to the Journal of Safety Research (2023)*

Declaration of authorship

The contributions of each author in the included articles are presented in Table 1. The PhD candidate has been the main author and contributor to all the three articles.

Contributions:
A Initial research idea and concept
B Data collection
C Data analysis and interpretation of results
D Writing - original manuscript draft preparation
E Critical review of the article
Bold First author

Table 1: Author contribution to included articles

Author	Article		
	1	2	3
Kinga Wasilkiewicz Edwin	**A-E**	**A-E**	**A, C-E**
Eirik Albrechtsen		A, D, E	A, C-E
Marie Nilsen		A-E	
Trond Kongsvik			A, C-E

Publications not included in the thesis

Two conference papers were written during the PhD work, however, not included as a part of this thesis.

Article 4: Wasilkiewicz, K. (2018). Information flow and knowledge transfer of accident investigation results in the Norwegian construction industry in *Safety and Reliability – Safe Societies in a Changing World, Haugen et al. (eds.),* pp. 2855-2862, ISBN 978-0-853-8682-7. CRC Press: London, UK. Taylor & Francis Group. 10.1201/9781351174664-358

Article 5: Peñaloza, G.A., Wasilkiewicz, K., Saurin, T.A., Herrera, I. & Formoso, C.T. (2019). Safety-I and Safety-II: Opportunities for an integrated approach in the construction industry in *Proceedings from the 8th REA Symposium on Resilience Engineering: Scaling up and Speeding up*, 24. June 2019 -27. June 2019, Kalmar, Sweden. 10.15626/rea8.18

PART I: MAIN REPORT

1 INTRODUCTION

This section introduces this PhD thesis, the reasoning for its importance by presenting the background talking about accidents in the construction industry, and the need for broader information sharing. This leads up to the research objective and questions, as well as the limitations of the work. At the end of the section, the outline of the thesis is presented.

1.1 Background

1.1.1 Fatalities in the construction industry

Every year the construction industry in Norway experiences fatalities related to work activities. Both the injury and fatality numbers and rates in the construction industry are among the highest in the labour market in Norway (SSB, 2022b;2022d). Nevertheless, the rates have stabilised in recent years (Mostue et al., 2022), indicating a somewhat stagnating improvement.

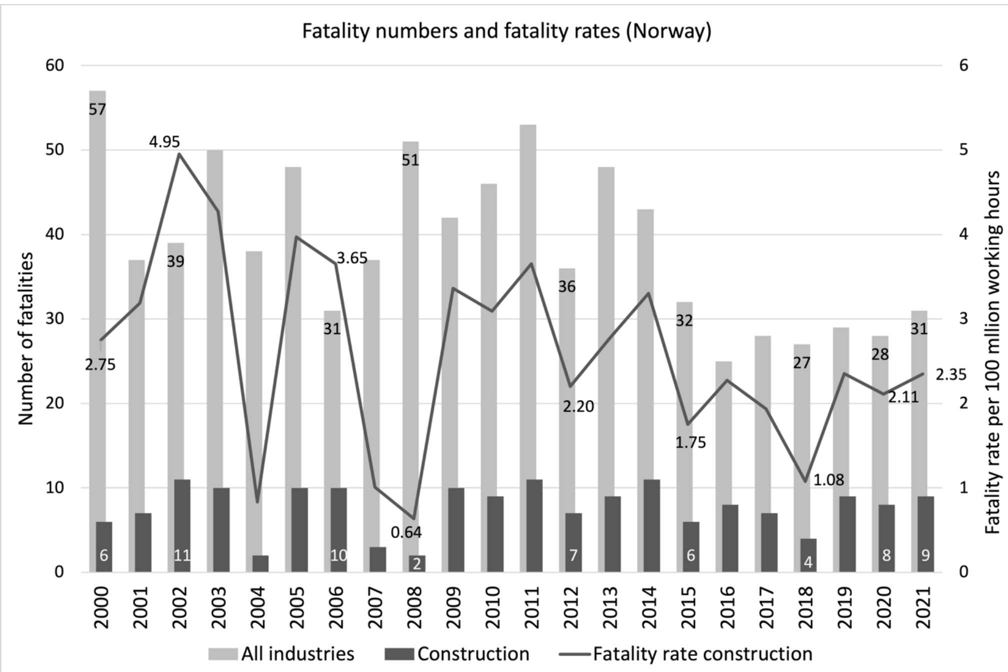

Figure 1: Number of fatalities in the Norwegian construction industry and all industries in Norway, and the fatality rate per 100 million working hours based on numbers from NLIA (2022); SSB (2022a;2023)

Figure 1 shows the fatality rate in the construction industry relative to those in all industrial sectors in Norway since 2000. Compared to other countries, the occupational fatality rates in Norway are relatively low (see Figure 2), however, the occupational safety performance is still not satisfactory. The 'Working Together for Safety in Construction' network (SfS BA), a non-profit organisation that facilitates collaboration between actors in the Norwegian construction industry, has also manifested the reduction of fatalities and injuries as an industry objective (Gravseth et al., 2019; SfSBA, 2019).

About every-fourth of all fatal accidents per year in ´Norwegian working life happened in the construction industry over the period 2017-2021 (NLIA, 2022). In 2015-2019, there were on average 3.1 fatalities per 100.000 workers in the construction industry compared to 1.1 fatalities per 100.000 workers for all land-based sectors (Mostue et al., 2020a). The fatality rate for 2020 in the construction industry was on the same level, with 3.2 fatalities per 100,000 workers (Mostue et al., 2021). The accident statistics for the Norwegian construction industry have been quite stable in the last decade (Mostue et al., 2020a; Mostue et al., 2022), exhibiting a pattern similar to non-fatal accidents. Also, the high injury rates compared to other industries are similar in other countries (Lingard and Wakefield, 2019, p. 3).

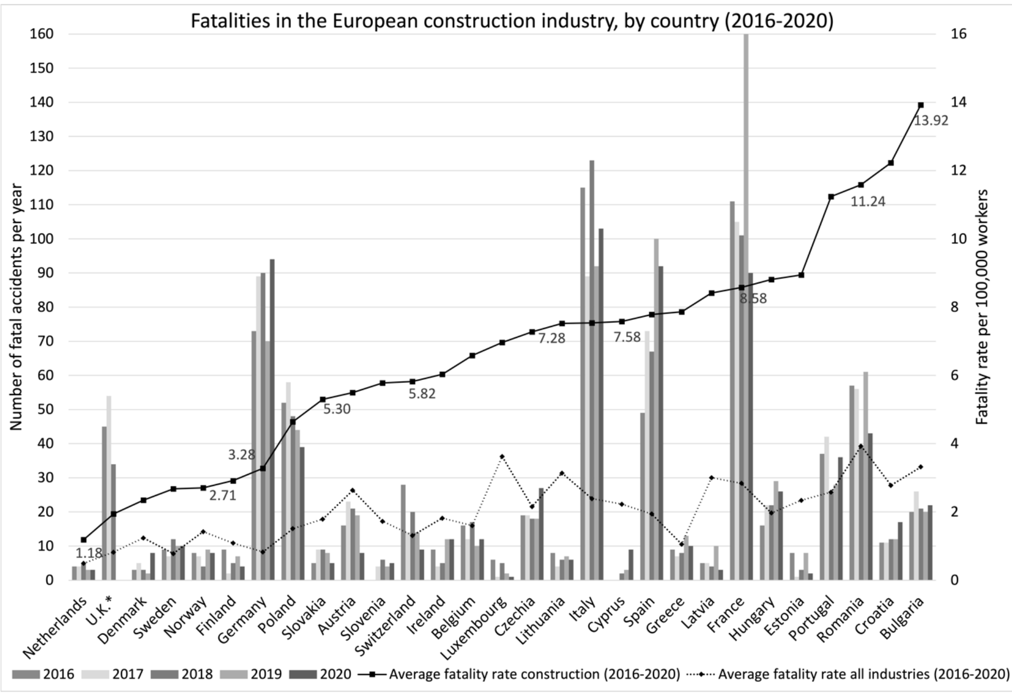

Figure 2: Fatal occupational accident in the construction industry in European countries, based on numbers from (Eurostat, 2023) * Numbers for U.K. for 2019 and 2020 are not available

Furthermore, occupational safety in the construction industry is relevant outside the Norwegian context. For example, in the years 2016-2020, for most European countries (the European Union (EU), Norway and Switzerland, excluding the U.K.), the average fatality rate for the construction industry was significantly higher than for all industries in the respective countries – being 6.3 per 100,000 workers (not considering the number of working hours) in the construction industry versus 1.8 for all industries (Eurostat, 2023). Figure 2 shows the number of fatal accidents in most European countries in 2016-2020 and the average fatality rate in the construction industry and for all industries in these countries. It shows a significant number of fatalities in the construction industry, with the fatality rate being much higher than in other industries combined for all the presented countries.

Additionally, many accident types are well-known and reoccurring (SSB, 2022b). Figure 3 shows the reoccurring accident types and frequencies per year in the Norwegian construction industry. Comparing the kinds of accidents leading to fatalities show that these are similar both over time and across different countries (Lingard and Wakefield, 2019, p. 3). The reoccurring accident types and previously mentioned fatality rates suggest that experiences and information from the past are not utilised optimally in preventing accidents and for better safety in subsequent projects. Therefore, more understanding and preventive approaches are necessary to sustain and surpass occupational safety performance in the industry.

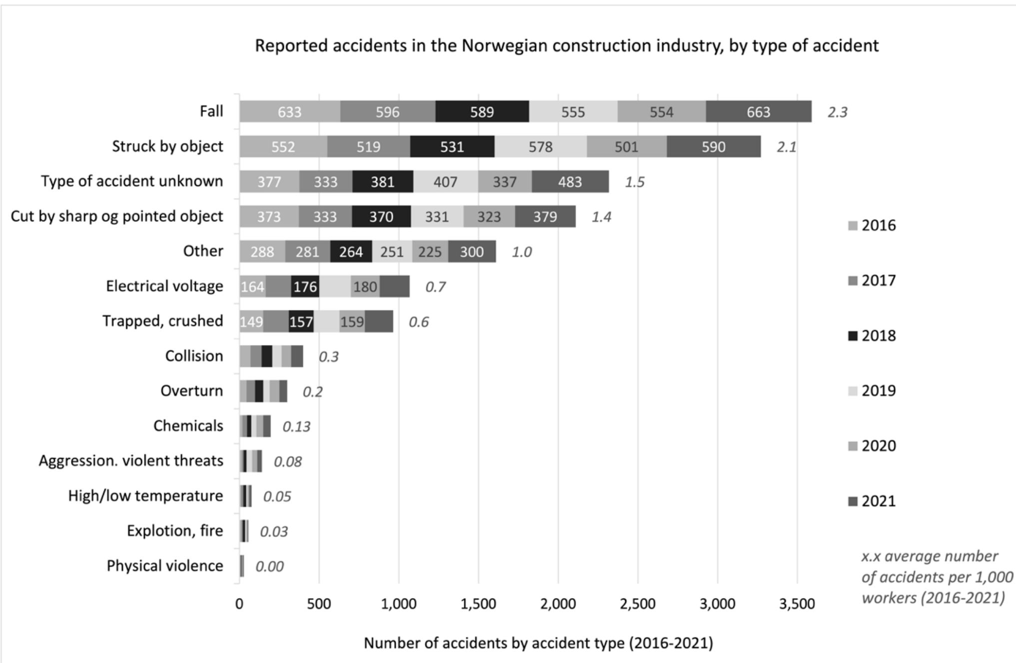

Figure 3: Reported accidents in the Norwegian construction industry by type and average per 1,000 employees based on numbers from SSB (2022b)

1.1.2 Broader information sharing for a reduced number of accidents

The fatality numbers and reoccurring accident types show that there is still an urgent need to reduce the accident numbers in the Norwegian construction industry. A greater focus on information sharing is one of the necessary directions towards improvement. This highlights the broader potential towards driving improvement for safety management through an expanded information base, using the Norwegian construction industry as a case.

An essential foundation for safety management is experience feedback, which is the process by which information on the results of an activity is fed back to decision-makers as new input to modify and improve subsequent activities (Kjellén and Albrechtsen, 2017, pp. 91-93). Similarly, information can be generated by anticipating expected results from activities, referred to as feedforward (Kjellén and Albrechtsen, 2017, p. 91). Experiences are input to the feedback process because they generate the information required for decision-making and actions. Safety management tools and approaches such as reporting systems, audits, inspections, risk analyses and accident investigations contribute to input data. Most of these identify what went wrong and make up an important information foundation which can be shared. Sharing safety-related information is key for expanding the information base and establishing a foundation for learning and improvements. In a feedforward process, control measures are used to react to and alter a possible disturbance before any reactions. One example is when using risk analysis results in a control measure (Kjellén and Albrechtsen, 2017, p. 91).

The need to broaden the base of information can be explained by Ashby's law of requisite variety, which refers to the need for a variety of measures to cope with the complexity of problems faced in a system (Ashby, 1956, p. 207; Kjellén and Albrechtsen, 2017, p. 99). Simply stated, to control a system, one must generate information that fits the complexity and dynamics of the system, as variety absorbs variety. Translated to the construction industry and safety management, it implies that different aspects influencing risks at work require at least as many control mechanisms or measures, as there are possible influencing factors that can cause disturbance in the system. Examples of such factors can be simultaneous work affecting risks of other activities, unfamiliar working methods, new technological solutions for work, such as digital instruments or software, or hired labour unfamiliar to co-workers. By expanding the available information, better control of the system can be obtained.

Sharing information is important across an organisation, as relevant experiences and information might reside in other parts of it (Nesheim and Gressgård, 2014). In the same way, safety-related information can be useful across an industry, particularly regarding accidents, as the number of experiences in one organisation is limited while possible hazards are plenty. To improve occupational safety in the construction industry and be prepared for possible new and changed risk influencing factors, current hazards must be better understood and handled, and future risks and influencing factors need to be anticipated. Furthermore, constant developments in working life (e.g., technology) and goals of sustainable, decent and safe work (Ministry of Labour and Social Affairs, 2011; United Nations, 2015), mean that approaches towards safety must be driven forward to keep up with changes and given ambitions on safety performance. The social aspect of sustainability includes good health and well-being, which for construction involves the absence of accidents and good working conditions. From a social perspective, sustainable safety management and performance are thus parts of moving toward a sustainable construction industry.

To develop improvements in the field of incident prevention, interdisciplinary, system-oriented and cross-sectoral approaches are needed (Stanton et al., 2017). The thesis discusses two areas for this: 1) information sharing across organisations in the construction industry, as well as from other industries, 2) perceiving safety management holistically – as an integrated part of overall management and by using more perspectives for safety. Expanding the information sources and thus increasing the information base across the industry, is an innovation of current formal safety management. This can contribute to reducing accidents if the available safety-related information is used as input to safety management, for example, towards decision-making and for taking improved measures. In this way, the experience feedback loop can be closed, as the information is utilised for safety improvements.

1.2 Objective and research questions

The main objective of this thesis is to explore how safety management in the construction industry can be advanced. Based on this, an overall research question is formulated:

> *How can incorporating additional inputs develop safety management in the construction industry?*

The overall research question is explored through three sub-questions. With the described research problem from section 1.1 in mind, the following research questions (RQ) are addressed:

> **RQ1** – *What opportunities for safety management exist in broader information sharing across the construction industry?*
>
> **RQ2** – *How can the construction industry improve safety management by looking at practices from the Norwegian petroleum industry?*
>
> **RQ3** – *How is project management related to safety management in construction projects?*

Information sharing within safety management is traditionally linked to supporting learning from incidents within an organisation (Drupsteen and Guldenmund, 2014; Kjellén and Albrechtsen, 2017, pp. 107-108). The research questions are novel in the sense that they explore other types of inputs and approaches than what is predominantly found in the industry. RQ1 broadens information sharing from within organisations to information sharing across organisational boundaries. RQ2 addresses information sharing between different industry sectors – in particular, safety-related information and practices that the Norwegian construction industry can adopt from the Norwegian petroleum industry. RQ3 explores how good project management can contribute to achieving good safety management in construction projects.

Each article addresses the overall research question and focuses on one research question. Table 2 summarises the contributions of the articles, the relationship between them, and their input towards the discussion of this dissertation.

Table 2: Contribution of articles to the research questions and the consistency between the articles

Part	Contribution	Article		
		1	2	3
Research questions	Overall RQ	x	x	x
	RQ1	x		
	RQ2		x	
	RQ3			x
Discussion	Expanded information sharing as input for safety management development	x	x	x
	Adopting an integrated safety approach	x	x	x

The presented articles lead to a discussion about 1) expanded information sharing as input for safety management development and 2) an integrated approach for safety. By addressing the three research questions, different mechanisms are identified and discussed as input towards development of safety management in the construction industry. The approach is holistic in the sense that it refers to various information types, different safety practices, and improvement possibilities. This includes looking at past events across construction industry actors, practices from other industries, as well as improvement of safety based on aspects of project management functioning. Furthermore, the research questions contribute to empirical research by suggesting and giving arguments for an integrated safety approach through safety as an aspect of the overall system and through a joint safety perspective. Two safety perspectives are used for this discussion, namely Safety-I, representing the traditional and more common formally used safety approach, including looking to past events, and Safety-II, including identification of successes which can further contribute to expanding the information base. Figure 4 gives an overview of the thesis work and illustrates the relation between the different parts.

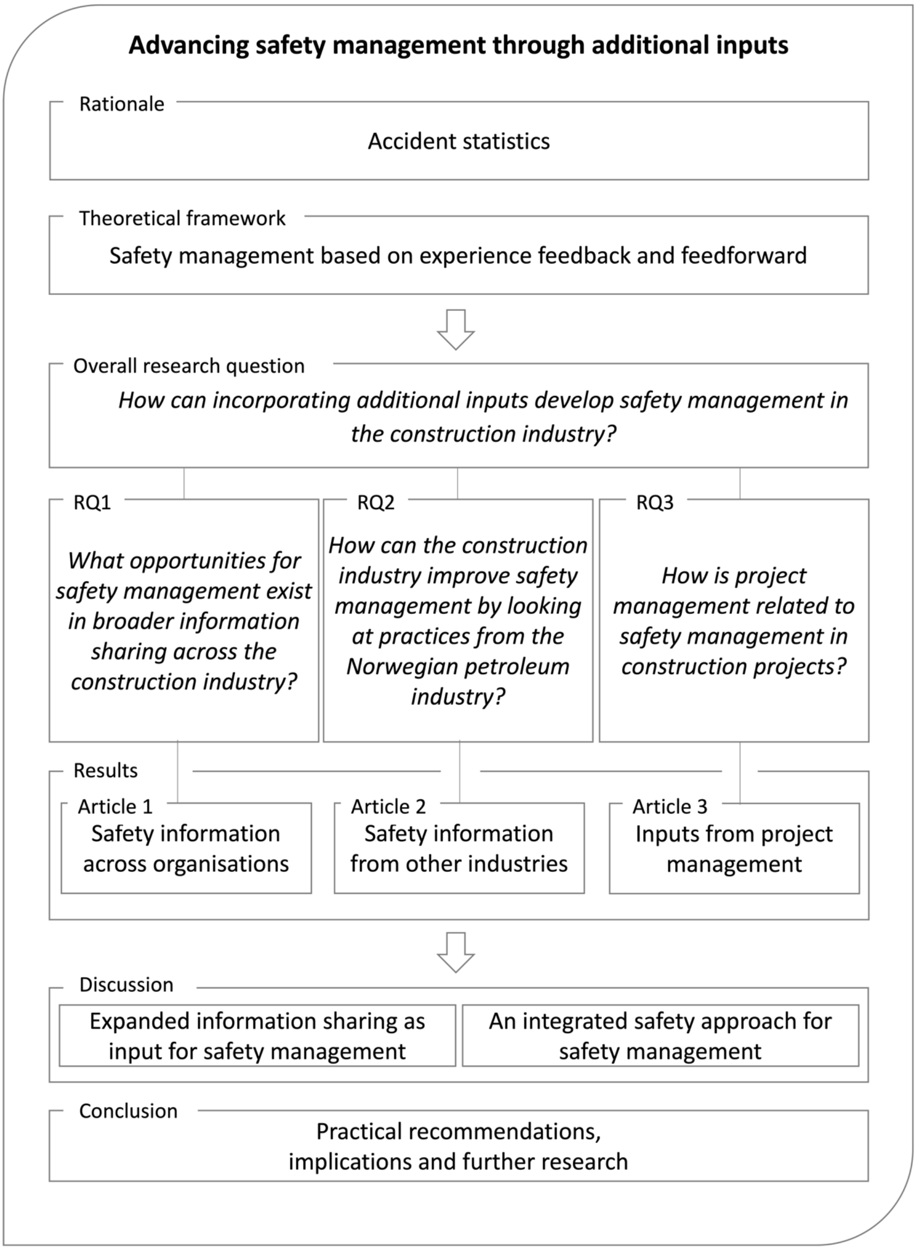

Figure 4: Outline of the research showing relations between the parts in the thesis

1.3 Limitations

Safety is an interdisciplinary science that uses theories from different fields for accident understanding and prevention, such as management, engineering, psychology and sociology (Rae and Dekker, 2019, p. 1). However, this thesis is limited to looking at safety management aspects for occupational safety, which focus on individuals at work and how the systems around them influence these individuals.

The thesis focuses on information sharing as a means towards the improvement of safety management. It does not look into the learning process as a whole, which refers to changes based on information and experiences, such as the application of those. Instead, the focus is on sharing information as a premise for learning. Experiences, both positive and negative, are a subset of learning and can be an input contributing to change. The information sharing process is important within learning processes, for example, in learning from incidents, but is paid little attention to in the safety literature (Drupsteen and Guldenmund, 2014).

The model in Figure 5 illustrates the focus area of the thesis related to information sharing, emphasising sharing from different sources, leading to a broad information base, which can be used as input to other systems and processes, such as safety management. The boundary is on the information sources and gathering them into an information base. The process is dynamic, where information is continuously collected and providing input to, for instance, safety management, and again collecting new information based on what is experienced. Furthermore, information sharing on an organisational level is looked at rather than information sharing features between individual employees or teams.

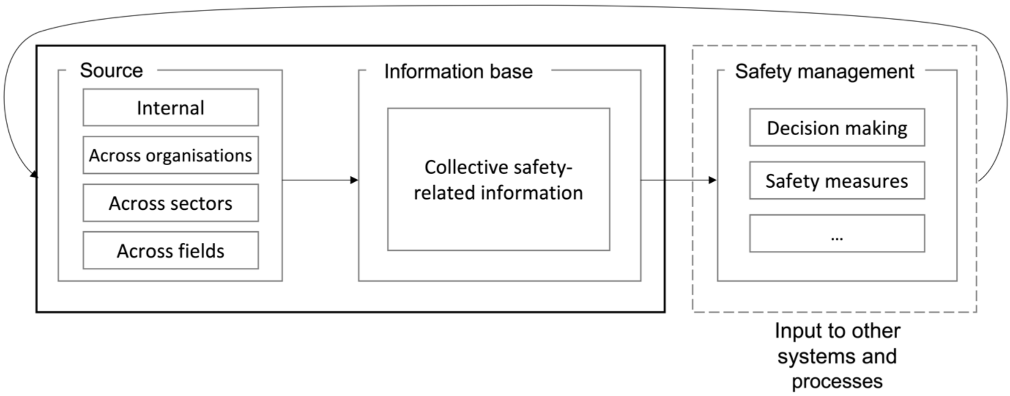

Figure 5: The boundaries of information sharing in the thesis

Construction is a diverse industry with many factors potentially influencing project execution and therein safety. Therefore, the thesis looks at safety-related information broadly, not addressing specific project considerations, such as contracting. However, such aspects can be relevant when information is to be used as input to other systems and processes for improvement. For project management only selected features are looked at, limited to the analysis performed in Article 3.

Throughout the thesis, the Norwegian work-life context is in focus. For example, accident numbers, regulations, and organisation of working life (e.g., the Nordic Model with tripartite collaboration) are among the factors that distinguish working conditions in one country from another. The context is, therefore, an important condition for the results and their further application. Nevertheless, the results and conclusions should also be relevant outside the Norwegian construction industry, especially the importance of information sharing and development opportunities for safety management, as well as providing a widened safety perspective.

1.4 Outline of this thesis

The thesis is divided into two main parts, 1) the introductory section, with eight chapters and references at the end, and part 2) the collection of three articles. The chapters in the introductory section introduce the research, relate the articles together, synthesise the significance of the results, and point to further research needs and opportunities. The content of each chapter is briefly described below.

Chapter 1 introduces the PhD thesis by presenting a rationale for the work, giving a problem statement, clarifying the research aim through research questions and giving an overview of the research contributions.

Chapter 2 explains the research context by introducing the construction industry.

Chapter 3 frames the theoretical background for the work, introducing information sharing and presenting safety management theory.

Chapter 4 describes how the research was conducted and its limitations.

Chapter 5 summarises the results from the articles and creates a basis for the discussion.

Chapter 6 discusses the findings in light of the research questions and points to development potential with regard to safety management.

Chapter 7 summarises the practical advice for practitioners and researchers.

Chapter 8 concludes the performed research, highlights the contributions and implications of the research, and makes suggestions for further research areas.

References provide the sources cited and referred to in the thesis.

2 CHARACTERISTICS OF THE CONSTRUCTION INDUSTRY

The term construction industry incorporates building and infrastructure projects in private and public sectors. Construction is, in many ways, a diverse industry with different lengths of projects, contract types, several project phases, many vocations, and actors of various sizes, to mention a few. These and other factors make each project unique and lead to structural and organisational complexity. Furthermore, there are factors influencing a project that are common across the industry, such as regulations and market mechanisms. This section describes the characteristics of the industry to form a background for the thesis.

2.1 Actors

The construction industry's actors are diverse and, to a large degree, operate across projects. Authorities, such as regulators, and associations, such as industry federations, labour unions and employer organisations, influence the industry overall. Furthermore, the labour inspection authority is directly involved during the project duration.

The builder is the project owner, supported by the architect and consulting engineers who design the project. A main contractor is responsible for the execution of the project along with their sub-contractors. Suppliers deliver materials, equipment, and other services to the project. The exact relationship between the actors depends on the contracting model of the project. Figure 6 illustrates a generic simplified organisation in the construction industry, showing how actors can be related across projects.

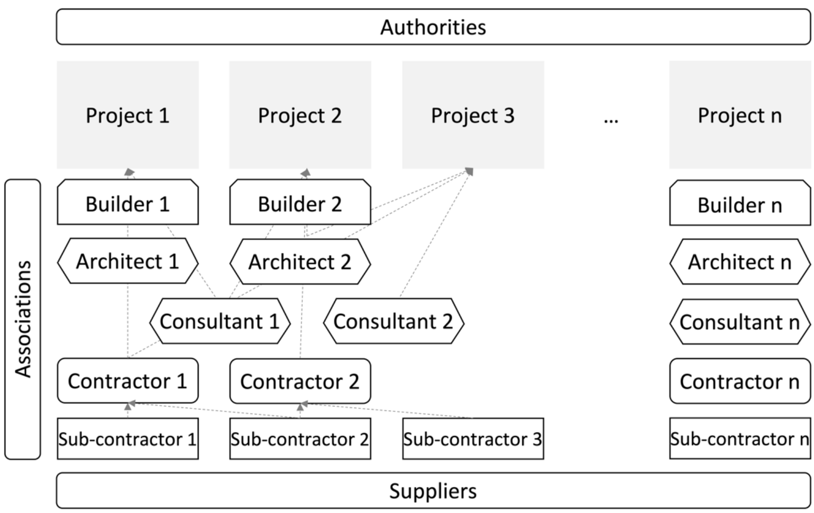

Figure 6: A generic model of the variety of actors in construction projects

The Norwegian construction industry had around 270,000 persons employed or self-employed in the industry in 2020, spread over more than 58,000 enterprises and was the third largest industry after human health and social work activities and wholesale and retail trade concerning the number of employees (SSB, 2022c). Additionally, groups not employed in the industry can work within the industry, such as hired labour or other workers registered in another sector. Most of the enterprises in the Norwegian construction industry, around 91 per cent, employ less than ten persons, which comes to about 99,000 (36 per cent) of the employees in the industry. This includes sole proprietorships. Only around 210 enterprises had 100 or more employees, constituting 22 per cent of the workforce in the industry (61,000 persons) (SSB, 2022c). Figure 7 illustrates the large number of small enterprises in the Norwegian construction industry and the number of persons employed across different enterprise sizes.

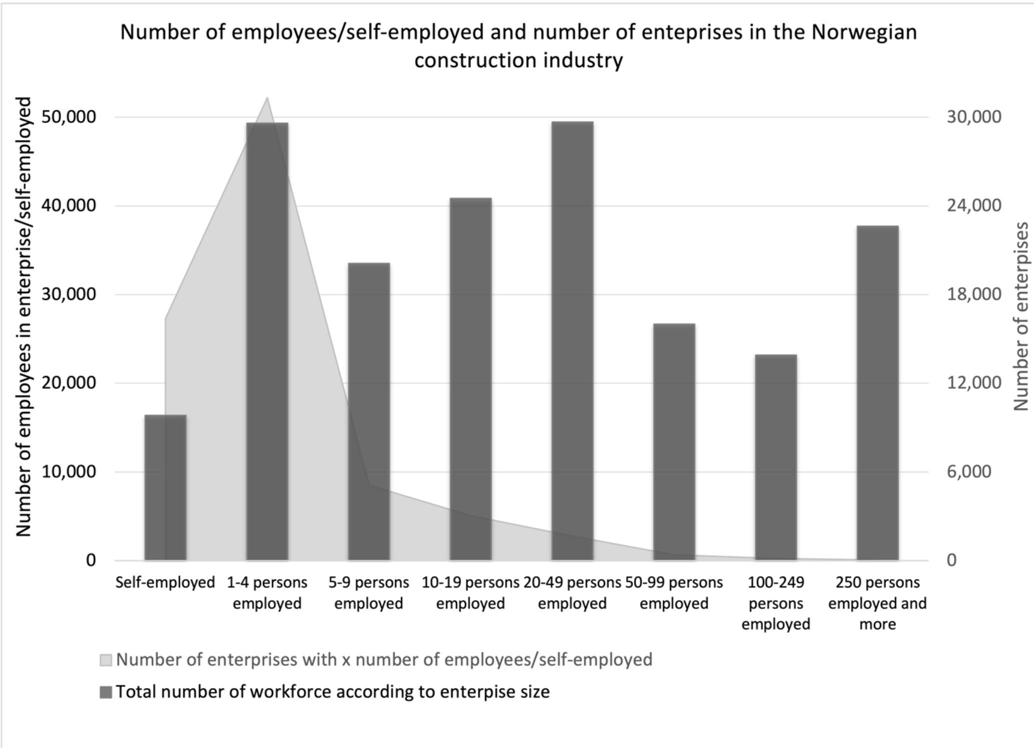

Figure 7: Number of employees and number of enterprises in the Norwegian construction industry in 2020 (based on numbers from SSB (2022c))

The Norwegian labour inspection authority (NLIA) supervises and guides all mainland industries in Norway, including the construction industry. The supervisory activities on the preventive working environment, health and safety and ensuring proper working conditions consist of internal control audits, verifications or inspections, and accident investigations (NLIA, 2021b). These activities are a large part of NLIA's work, and more than one-third are aimed at the construction industry (NLIA, 2021a).

2.2 Laws and standards

Laws and standards are among the framework conditions influencing the whole industry. They are well-established, mostly stable, and thus easy to relate to. In Norway, a few acts and associated regulations are important for occupational safety in the construction industry.

Overall in the workplace, the *Working Environment Act (2005)* aims to ensure a healthy and safe environment. The law requires the employer to undertake systematic health, safety, and environment (HSE) work and provide a safe workplace through hazard identification, training, practice, instructions, electing safety delegates and promoting employee cooperation. Furthermore, regulations related to the act ensure work is executed safely, e.g., the Regulations concerning the Performance of Work (2011), the Workplace Regulations (2011), and the Regulations concerning Organisation Management and Employee Participation (2011).

The *Internal Control Regulations (1996)* require enterprises to systematically take measures to promote safety and prevent incidents and accidents through adequate planning, organisation, execution, safeguarding and maintenance of activities undertaken. The regulations promote continuous improvement work within HSE, adapted according to the enterprise's nature, activities, risk and size.

For the construction industry in particular, the *Construction Client Regulations (2020)* deal with safety, health, and working environment risks at construction sites. The regulations put responsibilities related to risk assessment and management on the clients and their representatives, coordinators, designers, employers, and sole proprietorships, requiring them to take precautions during project planning and execution. Risk assessments and plans for safety, health and working environment are to be made and followed up, making the actors responsible for the risks they bring into the project.

Furthermore, several other laws and regulations relevant to different suppliers indirectly ensure workers' safety, such as Regulations on construction, design and manufacturing of personal protective equipment (PPE) and Regulations on Machinery and the Fire and Explosion Protection Act, to mention a few.

There are also standards related to safety that are optional to follow. ISO 45001:2018 is a general occupational health and safety standard and sets requirements to handle the working environment and prevent illness and accidents in workplaces (ISO, 2018). Additionally, industrial codes of best practice can also influence safety positively. However, these too are optional.

2.3 Project phases

A construction project consists of several phases. Bygg21, a Norwegian collaboration program for the construction industry, has developed a framework of steps in construction projects called ‘Next Step’, intending to have a common terminology in the industry (Bygg21, 2016). The framework comprises eight steps: 1. Strategic definition, 2. Program and concept development, 3. Processing of selected concept, 4. Detailed engineering, 5. Production and deliveries, 6. Delivery and commissioning, 7. Use and management, 8. Liquidation. For occupational safety, the first five steps are the most relevant. They can be clubbed into three main stages: Project development covering steps 1-3, Engineering consisting of step 4 and Construction consisting of step 5. Project development and engineering are the early phase of a project, while construction is in the execution phase. Procurement is a step that happens throughout the project and involves project actors and suppliers. When an actor enters a project phase depends on the procurement/contracting model used for the project. Some actors, such as the client, are a part of all the phases, while others are only part of a specific phase, e.g., sub-contractors. Figure 8 gives an overview of the eight steps divided into four project stages, focusing on the five first steps relevant to the thesis.

In the early phase, the project is initiated by the client, conceptual ideas are created, and aspects such as feasibility and constructability are assessed. The project is designed in detail in the second stage, and more actors are chosen for the further stages. Also, procurement of materials and services begins. The main value creation of a construction project happens during the execution phase where the construction happens. In these phases, some re-engineering and smaller procurement will also occur. The final phase is delivering the project.

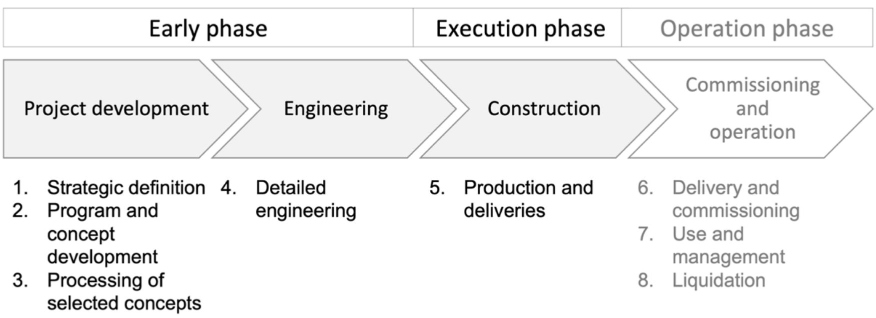

Figure 8: Main phases in a construction project based on steps from ‘Next Step’ (Bygg21, 2016)

Safety is a topic throughout a construction project, emphasising different aspects at each phase. In the early phase, coarse risk analyses are performed, emphasising aspects such as soil conditions and technical safety. Further on in the project, occupational safety receives more attention. In the execution phase, actors are through the Working Environment Act (2005), the Construction Client Regulations (2020), and other regulations, responsible for ensuring a safe working environment for the workers. According to the Construction Client Regulations (2020), from the early phase and through the project, the actors are responsible for the risk they bring into the project. The possibility of influencing safety during a project varies with the project timeline, being higher earlier in the project (Szymberski, 1997). Several researchers point to decisions in the early phase as important for safety in the execution phase (Behm, 2005; Åsgård and Jørgensen, 2019). At the same time, the knowledge about the construction process varies during the project timeline. It is higher later on in the project, such as knowledge of materials and methods (Lingard et al., 2015). However, such information can be beneficial in the early phase of a project to enhance safety decisions. Therefore, experiences from the execution phase need to be fed back to earlier stages (Lingard et al., 2015).

2.4 Industry challenges

There are numerous characteristics and influencing factors that challenge activities in the industry and, thus, safety. Some are directly related to industry activities; others are project-related (Zou and Sunindijo, 2015, p. 3). A larger number of actors within a project increases complexity and is perceived as a limitation to improving safety (Hale, 2005). Based on findings in a review article, Swuste et al. (2012) characterise the construction industry as organic, meaning the work performance is somewhat standardised, and add that attitudes towards rules and procedures can be poor. Several elements contribute to the complexity of the industry and, in particular, influence construction management, including available resources, the environment, interactions in projects, uncertainties in the system, and interdependencies between technologies, workflows and trades (Gidado, 1996). Dynamics with regard to the frequent establishment and liquidation of companies are also among the factors characterising the industry (Bygballe et al., 2019, p. 21). Lingard and Wakefield (2019, p. 10) highlight fragmented arrangements, e.g., between actors, precarious employment conditions and rough industry culture, as reasons impeding an integrated approach towards HSE. The hierarchical actor structure puts the consequences of safety on actors closest to the hazard, although the overall responsibility is on the builder according to the Construction Client Regulations (2020). However, the responsibilities in the industry are fragmented and unclear, calling for more commitment to safety from the different actors (Swuste et al., 2012).

Other challenges are incomplete specifications, lack of uniformity and a changing environment, which necessitate local adjustments and decision-making (Dubois and Gadde, 2002). Furthermore, work in the industry is labour-intensive, with technological advancements, including automation making slow headway. Certainly, new technologies, including automation, smart systems, software, devices, and tools, provide the potential for safety improvements. Solutions such as prefabricated elements and modules, drilling robots, masonry robots or collaborative robots that can, for example, lift glass or plasterboard walls, and can ease and make work safer, are becoming more available. Another example is a knowledge graph to identify hazards at specific sites using computer vision with predefined entities, defining the visible hazards to assist in the management of safety during construction (Fang et al., 2020). The variety between project and actor types and sizes, and related aspects such as time and economy, can hold up the implementation of recent solutions.

2.5 The Norwegian construction industry

In the last two decades, the construction industry in Norway saw a pronounced upturn with several new public infrastructure projects (road and rail), as well as house-building activities. As a result, numbers for the building and real-estate sector (excluding real-estate rental) between 2008-2018 show growth in value creation by 68 per cent (Bygballe et al., 2019, p. 25). In comparison, the industry sector had a growth of 53 per cent, and the oil and gas sector a reduction of 3 per cent. Furthermore, it is Norway’s second largest value-creating sector, behind the petroleum industry (Bygballe et al., 2019, p. 25). In 2018, the sector created value for 267 million Norwegian kroner (NOK) (Bygballe et al., 2019, p. 23). This indicates the importance of and the activity level of the construction industry.

Since the mid-2000s, the Norwegian construction industry has seen an uptick in migrant workers from Eastern Europe, which is also closely related to the increased activity in the industry. In 2008 the number of migrant workers from Eastern European countries in the European Union (EU) in the construction industry was about 10,000, doubling towards 2012 and further increasing and stabilising in 2018-2020 at around 30,000 migrant workers (SSB, 2021). A diverse workforce, in age, nationality, and skilled and unskilled workers across many vocations, is a part of the industry.

In addition to an increased number of migrant workers, the developments from the 2000s to 2010s included a higher pressure on costs and a larger focus on HSE work (Bråten et al., 2012, p. 7). Between 2013-2016 the NLIA had a project initiative for injury prevention and better work conditions in the construction industry based on risk areas, and its focus on the construction industry continues. Furthermore, in 2017, based on an earlier collaboration called the HSE Charter, the industry established a cooperation called ’Working together for safety in the construction industry (SfS BA). SfS BA works for an injury-free construction industry by sharing experiences and increasing knowledge on HSE, where actors across the industry contribute in working groups addressing various topics (SfS BA, 2020).

3 THEORETICAL FRAMEWORK

This section provides a background to the concepts relevant to the PhD thesis, including those related to information sharing, safety management, and an integrated approach to safety. Numerous literature reviews are available in the field of safety management, adding to the scientific discussions and offering a historical overview of concepts in the area, which are included in this presentation.

3.1 In between data and actions

The eminent ambition of this thesis is to emphasise how information sharing can contribute to improving occupational safety through advancing safety management and performance in the construction industry, which, lastly, requires actions. Towards this, what is meant by information, related terms and the relationships between information sharing, developments of safety management and performance are relevant to be explained.

The relations between the concepts of data, information, knowledge, and experiences and how these are linked to actions are essential to understand this work and its boundary. The data, information, knowledge, and wisdom, in short, the DIKW hierarchy, is a simple and well-known model representing the fundamental relations between these concepts, thus a good starting point for the explanation. Additionally, some models expand the DIKW hierarchy with results or actions. The DIKW hierarchy has been criticised, for example, for presupposing true data and information and not permitting inductive inference (Frické, 2009). However, to show relations and boundaries, it is seen as adequate for the purpose of the thesis. Another challenge with DIKW is that the boundary between each of the terms can flow over to the next, resulting in some of the terms sometimes being used interchangeably both in literature and in practice. For example, the distinction between information and knowledge is often perceived as unclear (Braf, 2002; Solouki, 2016), and the terms can thus merge (Frické, 2009).

Data are unprocessed symbols (Ackoff, 1989; Aamodt and Nygård, 1995), such as values, audio/visuals and signals, such as sensory readings of lights, in other words, raw facts, files or materials (Liew, 2007; Zins, 2007).

Information is a refined form of data containing meaning (Aamodt and Nygård, 1995; Liew, 2007). Information is relatively easily collected, stored and transferred. Frické (2009) writes that all data is information, but not all information is data. Data being input can return an output of relevance, transforming the data into information (Ackoff, 1989).

Knowledge goes a step further, with one of its attributes being that the information is understood, with the purpose being value creation (Liew, 2007), and it comes with learning (Aamodt and Nygård, 1995). Nonaka and Takeuchi (1995, p. 58) distinguish information from knowledge by the former being necessary to create knowledge, while the latter is about beliefs, commitment, and action. They exemplify information as a flow of messages, with knowledge created from that information flow when met with a receiver's beliefs and commitment. Knowledge can be divided into *tacit* and *explicit* and *internalised* and *externalised.* Tacit knowledge is personal and context-specific (Nonaka and Takeuchi, 1995, p. 59). It can be based on experience, intuition, or practice. Tacit knowledge can be skills, know-how, or be mental-models, and it is hard to formalise and share (Nonaka and Takeuchi, 1995, pp. 59-60). Explicit knowledge, on the other hand, is more objective, related to past events, and characterised by being easy to transfer (Nonaka and Takeuchi, 1995, pp. 58-60).

Nonaka and Takeuchi (1995, pp. 62-73) have a model that explains four different modes for converting knowledge. The SECI-model refers to the following conversions: socialisation (tacit to tacit), externalisation (tacit to explicit), combination (explicit to explicit) and internalisation (explicit to tacit). Parts of the model, except for externalisation and combination, are outside the scope of this thesis. The externalisation of knowledge refers to the process of sharing knowledge and thus making it available to others. This process can be undergone through written documents, images or concepts. In other words, when knowledge is externalised for the receiver, it becomes information and thus becomes a basis for new knowledge. The combination mode refers to organising and merging knowledge. Since it is explicit, it is information. It can be shared and used directly, for example, through databases. When the receiver understands it or learns by doing, it internalises and becomes tacit knowledge again (Nonaka and Takeuchi, 1995, p. 69).

Another term that is of relevance is *experience.* To experience means getting knowledge by being involved or affected, for example, through doing, seeing or feeling things (Cambridge Dictionary, n.d.). Experiences are inputs to tacit knowledge. With regard to safety, an example of experience are unwanted events, which can be experienced through one or more senses.

Further, a*ctions* are applications based on knowledge, such as decisions made, initiatives, or even behaviour. From actions and knowledge, a loop back to feeding with new information and data is possible, as the knowledge is first tacit and can then be externalised, becoming explicit and turning into information and data (Liew, 2007). All information is not knowledge, but knowledge externalised is information. In the same way, knowledge management should include information management, but information management cannot include knowledge management (Zeleny, 2006).

The last element of the DIKW model is *wisdom*, which is related to understanding and judging knowledge, information and data (Ackoff, 1989), reflecting upon and utilising it. However, this term is not discussed in the thesis.

Figure 9 illustrates the relationship between the abovementioned terms. Data is raw, and when processed, it turns into information. Information becomes internalised through, for example, learning, which becomes knowledge. Experiences can also be input to knowledge. Based on knowledge, one can make decisions, which are actions. Knowledge can be transitioned from tacit to explicit through externalisation, and by this becomes information. Further, in the last step of the DIKW model, one can move from knowledge to wisdom (as this is not relevant to the thesis, this link is greyed out).

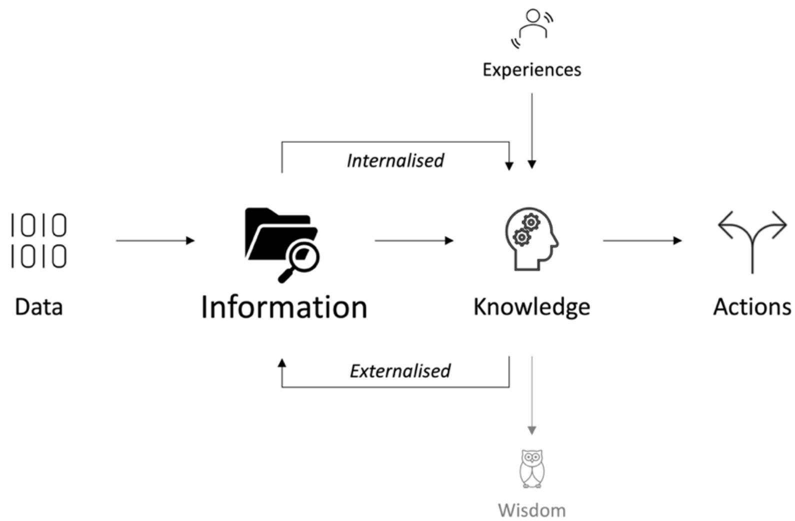

Figure 9: The relation between data, information, knowledge, wisdom, actions and experiences

Using risk as an example, data can be input to risk assessment; information is the description of risk; knowledge is about understanding the risk description and how to do the risk assessment; and wisdom is related to the utilisation of the assessment results (Aven, 2013). In this example, the action is to perform the risk assessment based on the knowledge. Actions are, in fact, not a part of the standard DIKW model; however, they fit well in. Aven (2013) attempted to link the DIKW hierarchy to the risk concept and concludes that there is less focus on, for example, risk assessments based on knowledge and wisdom as compared to those based on data and information. Although the aim should be more knowledge, rather than more information, which can lead to information overload (Zeleny, 2006), data and information are required as they are inputs towards knowledge and wisdom. Sharing of information is thus important to see connections and the larger context. With regard to safety, it is crucial as it can contribute to a safe and proper functioning of an organisation, and be an indicator of how the organisation actually functions (Westrum, 2014).

The boundary of the thesis is on sharing of explicit data, information, experiences, and knowledge related to safety. This can also include factors that are not directly related to safety but can affect safety, such as weather conditions or project management aspects. The terms information and information sharing are used throughout the thesis, as they encompass the concepts of data, information, explicit knowledge and explicit experiences. For example, this may include raw data, databases, instructions, observations or experiences made explicit and codified or structured into information. These sources can contribute with information for safety descriptions (for example describing events), safety inquisitions (explaining casual relationships), safety predictions (predicting future safety phenomena), safety decisions and actions (based on feedback or feedforward) (Huang et al., 2019). A key point is that what is shared is explicit and gives opportunities for development regarding safety management and safety performance. In other words, it is limited to sharing practices and possibilities of information sharing as input towards actions leading to safety improvements and can also contribute as input to knowledge creation and to the learning process. However, learning itself is not treated in this work. The focus is on sharing information, which is one step in the learning process (Lindberg et al., 2010).

3.2 Safety management

Although many definitions and perspectives on safety exist, the common goal of safety management is the same. It is to ensure safety by avoiding unwanted events and protecting people, organisations, materials, and nature from harm (Li and Guldenmund, 2018). Safety can be defined as a state where the risk, including potential consequences, is at an acceptable level (Aven, 2014). This definition sees safety in the light of risk, which is seen as a combination of uncertainty about and severity of the consequences of an activity (Aven, 2014). As important as safety is for systems and processes, all risks and hazards cannot be eliminated as that restricts how work can be executed (Hollnagel, 2014, p. 121) and must therefore be managed and reduced to an acceptable level.

Safety management is the process of controlling and preventing risks and hazards (Harms-Ringdahl, 2004) by realising safety functions through certain activities (Li and Guldenmund, 2018). This includes all formal and informal activities in an organisation performed to control hazards (Hale, 2006), such as practices and structures, for example, manuals, checklists, accident investigations and reports, safety records, safety training schemes, safety meetings and audits (Cheng et al., 2012). Safety management pervades all parts of an organisation (Hale et al., 1997), from leadership commitment to worker participation. This is to control and improve the safety aspects of business processes which are related to value creation, as well as by providing decision-makers with essential information about past, current and future safety performance. The ISO 45001 standard for occupational health and safety systems describes the need for the management to be responsible, involved, supportive and promoting safety and health to achieve safety and health objectives and continuously improve, as well as fulfil legal requirements (ISO, 2018). However, safety management also competes with other goals and resources in a company and is dependent on good engineering and human factors as well (Hale, 2005).

The safety management field was founded on many general management concepts, including quality and knowledge management. Safety management has now developed to have its own identity. It is, however, not completely independent, as safety management is closely related to all processes, phases, and operations of a system. According to Hale and Hovden (1998), safety management, including aspects such as culture and climate, developed as a field of safety science in the 1950s and increased largely in the late 1980s, including organisational factors and management systems. Accident investigations have made a ground for safety work, accident models and experience feedback on safety (Kjellén and Albrechtsen, 2017, p. 25) and are important in understanding safety and safety practices. A better understanding of accidents through their causes and effects can lead to more precise measures, remedies and interventions which can prevent or reduce the impact of accident situations (Swuste et al., 2012).

Traditionally, safety management has been more of a reactive nature, correcting safety issues and applying remedial actions to issues (Kontogiannis et al., 2017). However, with time, the approaches towards safety have become more integrated with business activities and more proactive (Kontogiannis et al., 2017). Aven (2014) suggests including dynamic aspects in safety management, such as perspectives from Rasmussen (1997) that, amongst other aspects, account for adaptations of actors to changes and dynamics of external influencing factors. Hale (2005) points out that safety management should be seen as 'a dynamic learning process' where change is the driver.

Safety management systems (SMSs) are management systems or parts of such, with the aim to control risks and prevent hazards from causing harm and injuries to workers and provide safe and healthy workplaces (ISO, 2018, p. 3). The SMSs are based on feedback about processes in the system (Kjellén and Albrechtsen, 2017, p. 25; Kontogiannis et al., 2017), which is an essential element for an SMS to function well (Hale, 2005). In a reactive SMS, the control mechanisms are implemented and measured, and information about the state of the process is fed back and corrected (Kontogiannis et al., 2017). This is similar to safety management based on Juran's feedback cycle (Kjellén and Albrechtsen, 2017, p. 95). In this reactive model, there is no possibility to anticipate and monitor future hazards. On the other hand, a proactive model makes use of aspects of resilience engineering and includes the ability to monitor and anticipate processes and feed information forward (Kontogiannis et al., 2017), as illustrated in Figure 10. Feedforward is about anticipation and modifying actions before something occurs rather than after something has happened and using that as feedback later. Experience feedback through information sharing is an integral part of the system to ensure continuous improvement, while feedforward through, for example, leading indicators, is important for adaption and monitoring.

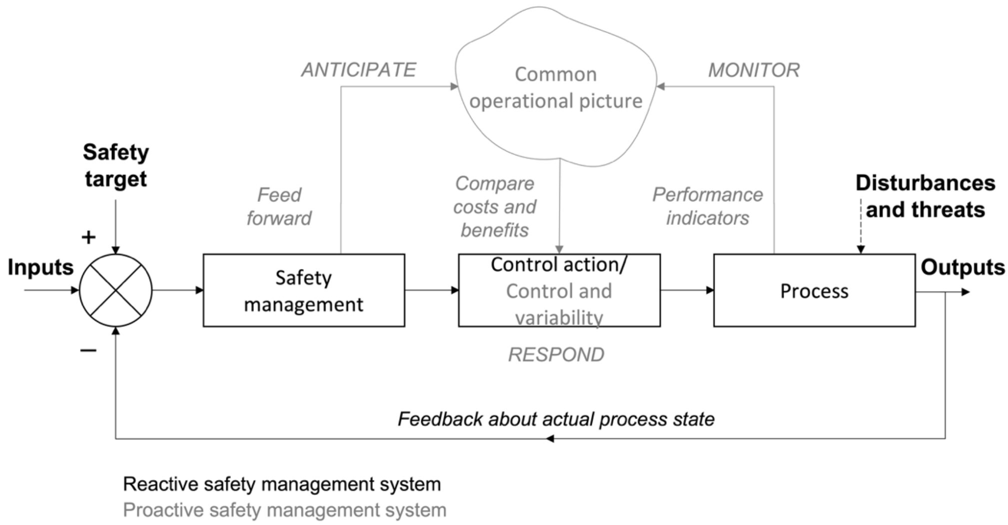

Figure 10: Feedback process by Kontogiannis et al. (2017)

SMSs encompass all phases of a project and focus on relationships between elements of the total system or organisation that significantly affect safety (Hale et al., 1997). According to Hale (2005), a good SMS 1) is linked with a proper understanding of the overall systems' process, in which safety analyses are rooted, 2) has a life cycle approach to safety management, meaning that all phases are included as well as prediction and learning loops, 3) has problem cycles at operational, tactical and strategical levels which identity, control and monitor risks, 4) assesses performance against indicators through feedback and monitoring, and 5) ensures the functioning of barriers and controls through qualities such as competence, commitment, communication, procedures, rules and goals, hardware, interface and availability. The relevant elements of the total system are a part of the aspect system, which comprises the SMS (Hale et al., 1997). Thus, safety management should be handled as an aspect system in the organisation and the task of everyone in the organisation rather than a disconnected sub-system.

Transient locations, temporary project organisations, and involvement of multiple companies are characteristics of the construction industry creating dynamics and complexity (Baccarini, 1996) which can challenge safety management (Milch and Laumann, 2016). This dynamic nature differentiates the construction industry from industries with a fixed location and a linear production process (e.g., the manufacturing and process industries), where safety programs seemingly have an impact (Swuste et al., 2012). Therefore, these aspects must be kept in mind when looking into the improvement of safety management and safety performance.

3.2.1 Management of safety through experience feedback

Experience feedback is a process at the organisational level of a company to provide decision-makers with information to improve their systems (Kjellén and Albrechtsen, 2017, p. 91). Another related concept is feedforward, where anticipation is applied as a mechanism to obtain information used to monitor a system (Kjellén and Albrechtsen, 2017, p. 91). The loops of the systems require feedback and monitoring to assess the actual performance and its ability to improve (Swuste, 2008). The safety-related information fed forward can contribute to actions that reduce risks or change disturbances, so they do not result in unwanted events. The safety-related information fed backwards can be deployed at different levels, from top management, where it is used for goal setting and monitoring purposes, to HSE responsible personnel and supervisors close to the sharp end that follow up and implement specific measures at a site (Kjellén and Albrechtsen, 2017, pp. 92-93), as well as at a strategic level where regulations and policies have their place (Hale, 2005).

The experience feedback concept is based on the aspects of Deming's plan-do-act-check cycle, which is a basis for most continuous improvement processes. Kjellén and Albrechtsen (2017, pp. 94-96) describe two main mechanisms for experience feedback; the feedback cycle, where the process state is compared against norms, and the diagnostic process, which begins with identifying deviations to implementation of remedial actions. Input to the process can be past safety performances such as deviations and unwanted events, current performance based on audits and inspections or future risk assessments (Kjellén and Albrechtsen, 2017, pp. 91-94). The level of control can be monitored through metrics, such as safety performance measured by indicators (Hale, 2005; Kjellén and Albrechtsen, 2017, pp. 118, 281-283)

The process can be considered an improvement spiral where consolidated information is used to raise the safety level by improving decision-making and gaining control over risks. It is an important process in safety management systems for the prevention and improvement of safety activities and safety performance (Kjellén and Albrechtsen, 2017, p. 94), as well as for future safety planning (Kartam, 1996; Chua and Goh, 2004), for example as an input in risk assessment processes (Kjellén and Albrechtsen, 2017, pp. 341-342). However, to improve new projects, among other aspects, the lack of integration of experience feedback into risk management must be overcome (Lindberg et al., 2010).

Mechanisms to ensure systematic experience feedback are safety information systems, which collect, process, systematise and distribute relevant information (Kjellén and Albrechtsen, 2017, pp. 104-107). Collecting, processing, and disseminating information are essential principles for improvement and learning to support the prevention of future incidents as it gives input to learning processes. However, it does not necessarily result in learning, as learning requires actions or changes in practice (Hale, 2005).

3.2.2 Sharing as a premise for improvement

Sharing more safety-related information can be considered an expansion of experience feedback, which can contribute to learning within and across organisations. However, learning is dependent on mechanisms other than sharing itself. The uniqueness, temporality and involvement of many different actors in each construction project pose challenges for passing on project experiences (Duryan et al., 2020). Complexity and fragmentation in the construction industry lead to blurred and non-linear communication lines and information sharing (Carlan et al., 2012). Although each project in the construction industry is unique, many processes are repeatable, which can be passed on to future projects.

Drupsteen and Wybo (2015) argue that sharing and learning from incidents across organisations in the construction industry have an immense potential to help prevent future incidents. Similarly, sharing and learning from activities and other business fields and across organisations can contribute to safer work execution. Rather than keeping information in silos, which is often how teams in projects operate (Carrillo et al., 2013), and therefore how projects then operate, the different actors can gain valuable information from other peers, enhancing the safety during construction. However, it is important to be aware that just collecting incident data without a plan on how to utilise it, will not necessary contribute to learning (Hale, 2005). Additionally, filtering risk and incidents, supporting the development of solutions and supervising how learning is applied is also needed (Hale, 2005). Sharing of relevant information is thus an important step on the way.

Dissemination of information is one step in the learning process after incidents (Drupsteen and Guldenmund, 2014), and a step towards improvement and change. However, the dissemination of information from past incidents itself is not enough to prevent future incidents (Lukic et al., 2012). The learning process brings about change (Argote and Miron-Spektor, 2011), and thus requires both incident information together with changes in practice (Margaryan et al., 2017). One of the primary challenges that need more attention in learning from incidents, according to Drupsteen and Guldenmund (2014), is sharing and processing of information. Furthermore, dissemination of accident investigation results, which is one source of information, is weak with potential for improvement (Lindberg and Ove Hansson, 2006). Hallowell (2012) studied safety knowledge management strategies in construction companies in the USA. Although knowledge is on the border of what is selected as the scope in the thesis, the research shows limitations which are also relevant for information sharing. As mentioned earlier, the definitions of information and knowledge particularly, are not consistent in the literature. It is therefore of relevance to also include references related to knowledge. In the article, Hallowell (2012) found that acquisitions, storage and dissemination of safety knowledge are ineffective. Most of the safety knowledge from external sources came from regulatory agencies and employers or professional society organisations. Albeit identifying both external and internal safety knowledge sources, the focus of dissemination was only on the sharp end. Duryan et al. (2020) highlight the importance and need to transfer knowledge across actors in the construction industry to improve occupational safety performance further, as regulations, norms and guidelines cannot comprehend all possible hazards and situations. In their article, they point to a fallacy in systematically learning from past incidents, as there are large variations in systems for knowledge management between companies. There is also a tendency to keep safety information in project silos, while there is a need to share between organisational levels and projects for which mechanisms are currently lacking. The sub-process that dissemination represents in the learning process, is underexposed, the literature on learning from incidents is fragmented, and empirical and applied research is scarce. However, managing information is a key to safety improvement, including continuous learning from past incidents (Duryan et al., 2020).

In an editorial for a special issue on learning from incidents, Stanton et al. (2017) stress the need for more interdisciplinary and methodologically diverse research, as well as moving from 'information acquisition' towards focusing on collective sensemaking, exercising changes, continuous knowledge flow and more aspects of the complex sociotechnical system. Margaryan et al. (2017) emphasise the need for more integration of theories, disciplines, and methodologies, and a cross-sectional focus on learning from incidents. This calls for research on broader information sharing across fields and industries and exploration of the opportunities to utilise safety-related information.

3.3 An integrated approach to safety and production

Hazards in the construction industry, such as work at heights, are a part of the nature of the industry. While eliminating such hazards is not possible, mitigation and limiting the risk related to such work activities is. Organisational activities such as planning and execution of work can prevent accidents by avoiding situations with a lack of control over hazards. However, when there are deviations from planned work, a lack of control of hazards occurs (Kjellén and Larsson, 1981; Kjellén and Albrechtsen, 2017, pp. 31-33). When deviations occur, barriers should prevent the lack of control leading to loss of control of the hazard and transition of energy to victims. Safety is thus created both by general management as well as safety management. This can include management processes such as project management (see section 3.4 for definition).

Figure 11 illustrates the normal production process that leads to value creation and the incident process when deviations in production take place that can lead to losses. Thus, a normal production process without deviations creates both safety and value. Further, as illustrated, contributing factors lead to normal operation, and their inadequacy can lead to incidents and losses. It is assumed that many of the same factors contribute to a normal production process and safe operations (Edwin et al., subm. 2023).

The boundary of acceptable performance can be stressed by, e.g., production pressure (Rasmussen, 1997), increased complexity, or conflicting goals (Ghodrati et al., 2018) and drift the system to the limits of safe practices (Rasmussen, 1997). However, safety and productivity do not necessarily compete against each other, especially over time. Choudhry (2017) found in a study of the Hong Kong construction industry that safety and productivity can be improved simultaneously. A study from New Zealand found that certain management intervention programs to improve labour productivity, particularly related to labour management, supervision and leadership, planning and construction management, positively influenced safety performance (Ghodrati et al., 2018).

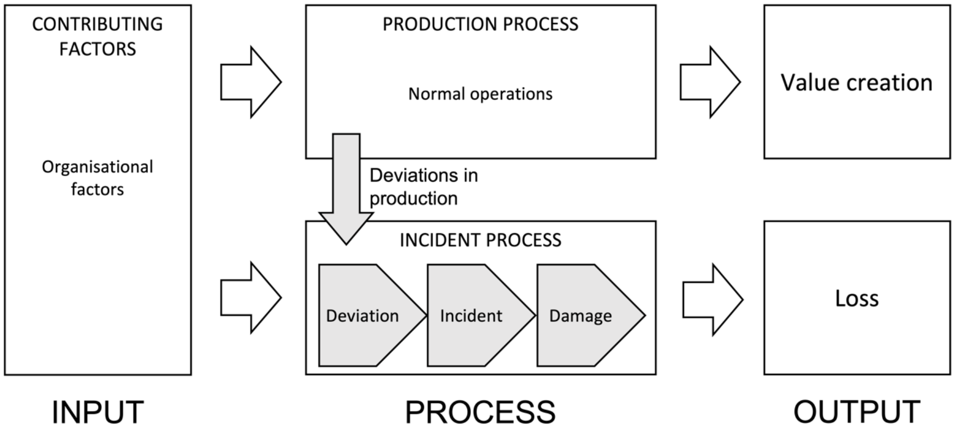

Figure 11: Common factors of value creation and deviations leading to loss in a process model based on Kjellén and Albrechtsen (2017, p. 52) in Edwin et al. (subm. 2023)

Managers and supervisors also have an important role in safety. Among other aspects, the engagement of supervisors, available resources in time and money for safety, having good safety knowledge and promotion of safety have been pointed to as important for safety improvements (Choudhry, 2017). Safety management information (e.g., accident investigation and report, safety records, statistical analyses of accidents) and safety management committees are significantly and positively related to construction project performance (Cheng et al., 2012). An article by Pagell et al. (2014) looking into productivity and safety in manufacturing and distribution facilities in Canada also found that safe and efficient production is feasible. The article disclosed that plants with above-average operational and safety performance had two things in common – a supportive culture regarding safety and operations and a joint management system.

Several researchers across industries emphasise that safety and operations should be seen and managed together (Hale et al., 1997; Hovden, 2004; Hale, 2006; Hale et al., 2012; Shevchenko et al., 2018; Hasle et al., 2021) as a joint effort involving all actors (Woolley et al., 2020). A need for integrating safety into specific parts of the management of projects has been advocated in several studies for the prevention of accidents, e.g., in the project team (Haslam et al., 2005), project management (Mohammadi et al., 2018; Lingard and Wakefield, 2019), in planning (Kartam, 1997; Saurin et al., 2004), production, cost or human resources (Guo et al., 2015). Kontogiannis et al. (2017) point out that integrating safety management with other organisational processes can be challenging. However, well-functioning and proactive safety management can benefit other parts of a business and create synergies, such as improving quality, and reliability, promoting innovations and improving reputation. Unfortunately, in daily operations, safety is managed distinctly from other management practices (Benjaoran and Bhokha, 2010). Very often in the construction industry, safety is managed as partly detached from the main processes or system and arranged together with other fields like health, work environment, and sometimes also environment.

3.4 Definitions of other key terms used in the thesis

So far, the key concepts in the thesis have been explained. Further, there are some other terms and concepts of importance for the thesis, particularly the discussion. Table 3 presents these terms.

Table 3: Descriptions of other terms relevant for the thesis

Term	Description
Project management	Management of a project organisation to reach its objectives (Rolstadås et al., 2014), by the application of knowledge, skills, tools and techniques (Project Management Institute, 2017). The project manager uses technical project management, leadership, strategy and business skills, and is supported by the project team to fulfil project requirements and objectives (Project Management Institute, 2017).
Safety-I	The Safety-I perspective is often defined as looking into 'as few things as possible going wrong' and accidents are explained by failures or malfunctions and looking into contributing factors (Hollnagel, 2014, p. 147).
Safety-II	The Safety-II perspective looks at 'what goes right', aims at learning from successes and safety is managed by being proactive and adapt to developments and events by anticipating them (Hollnagel, 2014, pp. 147-149).
Safety performance	An expression of an organisation's effectiveness in controlling hazards in its activities (Kjellén and Albrechtsen, 2017), and the provision of safe workplaces (SSB, 2022a).

4 RESEARCH APPROACH

This section elaborates on the design and methods used to approach the research objective and answer the research questions. It also provides considerations regarding scientific quality and ethical aspects. The three articles adopt different approaches that jointly examine information sharing and safety management in the construction industry.

4.1 Methodology

The interest in the research topic came through working with safety research related to the construction industry and other industries. Construction being an industry with high activity and exposure to high risks with relatively many accidents and fatalities, made the candidate want to explore safety management processes, particularly related to information sharing. Initially, the focus was on accident investigations and sharing related information for better understanding and accident prevention. However, with the initial research and insight into the literature, the scope was expanded to sharing safety-related information and developing safety management. Three studies were conducted to investigate further prevention of occupational accidents in the construction industry, resulting in two published research articles and a manuscript submitted to a journal. In the thesis, these contributions are further referred to as Article 1, Article 2 and Article 3.

Research can be categorised according to the objective, methods used, data analysed and other factors. Often research is divided into fundamental research and applied research. Fundamental research, also called basic or pure research, is concerned with increasing and generalising knowledge about a phenomenon, whereas applied research is related to a practical problem in society or in an organisation and finding a solution or potential for practical application by using general knowledge (Kothari, 2004, p. 3; Guthrie, 2010, p. 5). The conducted research is of an applied nature, seeking to find ways to improve occupational safety in the construction industry.

Since three separate studies were undertaken, the approach to the three articles, research scope and origin of data used differs across them. The overview of the research types for each of the articles included in this thesis is given in Table 4. The main types of research methods can be divided into qualitative, quantitative, and mixed methods, combining techniques related to qualitative and quantitative research in one study. Overall qualitative research emphasises words and can be characterised as an inductive approach, generating theory, whereas quantitative research is deductive, testing a theory (Bryman, 2012, pp. 35-36). Qualitative research is criticised for being too subjective and difficult to replicate, which also delimits possibilities of generalisation (Bryman, 2012, pp. 405-406). However, it also gives rich and deep data (Bryman, 2012, p. 408). Quantitative methods are, in contrast, structured and generalisable, resulting in hard data (Bryman, 2012, p. 408) and are replicable. However, critique is the suitability of using natural science on social phenomena (Bryman, 2012, pp. 178-179). Articles 1 and 2 used qualitative methods. Interviews were used to generate new data, also categorised as primary research since the data was based on first-hand sourcing. Article 3 used quantitative methods, mainly obtained from existing data, and thus classified as secondary research.

Another classification of research is related to its objective or scope, with common classification being exploratory, descriptive, and explanatory research (Grinnell and Unrau, 2011, pp. 21-28). Exploratory research, as the name suggests, is often conducted on topics with little prior research to explore more of the topic and the research approach for such topics. Usually, the data are qualitative, e.g., literature searches and large amounts of collected unstructured data. Descriptive research aims at describing the topic, for example, characteristics, trends and correlations of samples. Collected data can be both qualitative and quantitative. Explanatory research aims to identify a phenomenon's causes and effects and is based on set hypotheses, with the data being quantitative. The first article looked into what sharing arenas exist in and across the construction industry (descriptive), explored the potential of information sharing for improving occupational safety (exploratory) and laid the ground for the following two articles. The second article was exploratory, looking into the potential of information sharing across industries. The third article was of an explanatory nature, looking into relationships between factors of project management, safety management and safety performance.

Table 4: Overview of the research types covered in the articles

Type		Article		
		1	2	3
Data type	Qualitative research	x	x	
	Quantitative research			x
Data source	Primary research	x	x	
	Secondary research			x
Depth of scope	Exploratory research	x	x	
	Descriptive research	x		
	Explanatory research			x

Approaching the overall research question on *how incorporating additional inputs can develop safety management in the construction industry* from three different angles (articles 1, 2 and 3) and combining different research approaches brings a wider perspective to the research and thus signifies the potential of the findings. The data sources and various methods strengthen the research as the articles build on each other for the overall objective of the thesis (see Table 2 and Figure 4). Especially the studies in articles 1 and 2 are closely related, and specific findings were confirmed across the studies, such as SfS BA and its background. This contributes to the credibility of the results and gives the thesis more comprehensive data to build the discussion.

4.2 Data collection

The three articles were designed with a common topic, answering the overall research question. However, each article had a different objective, research questions, and approaches. As shown in Table 5, qualitative and quantitative approaches were used for data collection and analysis, and various research methods were applied.

Table 5: Data research methods used in the three articles

Data type	Method	Article		
		1	2	3
Qualitative	Literature review	x	x	x
	Interviews	x	x	
	Document review	x		
Quantitative	Survey sample from Nordic 10-10 database			x
	Company data on accidents			x

Literature studies are useful for gaining insight into a field and building on it. A literature review is essential for research and to situate the research in relation to existing work. This helps define the research scope by identifying gaps in the existing research, thereby not repeating existing work. Reviewing existing literature also identifies relevant theories, research methods common in the field, and whether there are inconsistencies in the findings (Bryman, 2012, p. 98). The literature searches aimed to build a foundation for the research rather than to write a literature article. The searches were, therefore, only conducted in a semi-structured manner. Selective search strings related to safety management, such as data, information, knowledge sharing, learning after accidents, experience feedback and more, were used in the search engines (e.g., Scopus, ScienceDirect, Google Scholar, NTNU University Library/Oria). For some topics, the searches performed were more comprehensive and structured, noting the number of found results and reviewing them systematically. Before starting the work with the three articles, identified literature was reviewed extensively and assessed to be comprehensive enough to form the basis for the research. Throughout the PhD work, literature was continuously reviewed, including new research, to keep updated and to explore other relevant topics. Email alerts on specific topics were used extensively to identify new literature.

Semi-structured interviews were chosen as the primary data collection method for articles 1 and 2 to study safety information sharing within the construction industry and compare the safety in the construction and petroleum industries, respectively. This qualitative method collects comprehensive data and goes in-depth into the collected material. In such interviews, an interview guide is used with set questions, but the order in which they are asked can be varied, and additional questions can be added to follow-up (Bryman, 2012, p. 716). The interviews were aimed at providing insight into industry practices. For both articles, several levels of actors were interviewed to get a broader viewpoint and to include practices and experiences across the industries and actors. When different data sources are used, for example, data from different people and groups, this can be referred to as data source triangulation, leading to a better understanding of the phenomena of interest (Carter et al., 2014).

The research behind the two articles was built up similarly, as described further. To conduct the interviews for each of the two studies, an interview guide was made. The interview guides were adapted for the different actors (for more details, see the attached articles). The study in the first article had one interviewer, while the study in the second article had two interviewers for most of the interviews. A majority of the interviews were recorded and transcribed. A few interviews were not recorded in the study in Article 2. However, these interviews were conducted by two interviewers, where one was taking detailed notes, close to transcribing the interview in real-time. The interviews were conducted in person or over the telephone, depending on availability and convenience, as interviewees could be in different parts of Norway. This geographical spread gives the study a representative sample across the Norwegian construction industry. The researchers did not notice any noteworthy differences in the quality of the results. The experienced difference between face-to-face interviews contra telephone interviews was mainly the length of the interviews. Before the interviews, the interviewees were informed about the study and the possibility of withdrawing from it without consequences. During the interviews, the interviewers focused on openness and not assumptions, avoiding leading questions, letting the interviewee speak the most, and ensuring the interviewees' points were understood correctly by asking for examples and explanations.

Document reviews are helpful to both triangulate information from interviews and get more insight. Supplementary documents obtained from the interviewees were reviewed for the study in Article 1, giving more insight into companies' after-incident experiences and how they share such information. Furthermore, publicly available documents were collected to enhance the data for articles 1 and 2.

The third article was quantitative and thus very different from the first two. It can be classified as a secondary analysis, as the authors were not involved in the primary data collection (Bryman, 2012, p. 312). Instead, the study used an existing dataset previously collected in a benchmarking project. Most of the data material for the third article was collected by the Nordic 10-10 consortium researchers, who run a benchmarking tool for performance assessment in the Norwegian construction industry. The Nordic 10-10 Programme is a Norwegian translation and adaptation of the CII 10-10 benchmarking tool developed by the Construction Industry Institute (CII) at the University of Texas (Yun et al., 2016; Nordic 10-10, 2021). This tool collects different project aspects by collecting data from several project phases through questionnaires (Construction Industry Institute, 2021). For more information, see nordic10-10.org. Data initially collected for another purpose brings some limitations to the article, such as the available variables that can be used in statistical analyses. However, the use of this data can be justified as it is collected through a large program with thorough international research behind it. Furthermore, such use of previously collected data gives opportunities for analyses on additional areas allowing new interpretations and relations to be found (Bryman, 2012, p. 315), such as the included article. The questionnaires used in Nordic 10-10 consist of different types of questions, including multiple choice (with one and more possible answers), binary questions (yes-no) and Likert questions. A new variable (for project management) was created based on the available questions from the Nordic 10-10 database. For this, only Likert questions were used to ensure compatibility across the questions. Additionally, for this particular article, safety performance results from the same construction projects that were involved in Nordic 10-10 were requested from the companies by the authors.

In this thesis, the combined research strategy contributes to the completeness of the research. Through this approach, a broader part of the topic is studied, and diverse views are analysed to provide answers to the different research questions. By this, the overall thesis provides the opportunity to understand information sharing in safety management from a broader perspective. It opens for various contributions to develop safety management and to contribute to improvements in safety performance. As each article contributes to a part of the overall research objective, the diverse approaches give different inputs to the overall purpose. The qualitative approach contributes to more detailed insight into the sharing opportunities of safety-related information across the construction industry (Article 1) and between industries (Article 2). The quantitative approach in Article 3 is based on a larger data set, looking for more general relations between project management and safety management. Altogether, these approaches give an opportunity to advance safety management through different inputs.

4.3 Participants

The data collection for the three articles was performed in the construction industry, and for Article 2 was also performed in the petroleum industry. Table 6 gives an overview of the number of participants, sample size and industry for the three articles.

Purposive sampling was used for choosing informants for qualitative interviews, where the aim was to sample participants strategically so that they were relevant to the research questions (Bryman, 2012, p. 714). The interviewees were chosen based on information through contact persons from earlier projects and collaboration, as well as snowball sampling for Article 1, and based on contact persons, snowball sampling and approaching relevant interviewees based on their earlier or current work position (for example, working for a trade union) for Article 2. The reason for such an approach was the research topics, which required persons within a particular industry and position (for Article 1, it was HSE personnel, while for Article 2, interviewees from both the construction and petroleum industry with HSE competence). Such sampling can result in more consistent data (Tjora, 2012, p. 147), as the topic is logically narrowed. One challenge with recruiting interviewees, for example, in purposive sampling, is that one does not always get access to all the desired persons, which can result in less comprehensive data. One measure adopted to ensure that sufficient data was captured was to ensure that a saturation point on the topics was reached, and few new points emerged in the interviews. Therefore, the candidate and the researchers were satisfied with the samples for articles 1 and 2.

The third article was quantitative and dependent on the available data from the Nordic 10-10 project (N=63), as well as on available data for safety performance at companies (N=32). A higher sample, especially for safety performance, would have been preferred. However, it was assessed by the research group to be adequate to conduct the study. The study, as is, gives insight into the topics and can in, the future, if a larger sample is available, provide the basis for a more profound study.

Table 6: Number of participants, sample size and industries covered in the articles

	Article		
	1	2	3
Semi-structured interviewees	19	36	-
Survey sample size	-	-	63
Safety performance sample	-	-	32
Construction industry	x	x	x
Petroleum industry		x	

4.4 Data analysis

4.4.1 Qualitative data analysis (Article 1 and 2)

Based on the transcriptions or detailed notes of the interviews, analyses of the data were done. The study data in articles 1 and 2 were analysed using the same approach. The interviews were analysed in a structured way and coded twice, first based on the existing topics from the interview guides while transcribing and then by reading the transcriptions and adding new topics and sub-topics. As the interviews were conducted in a semi-structured manner, the responses and follow-up questions could reveal topics of interest that were not specifically included in the interview guides and break up the topics. NVivo version 12 was used to code and analyse the data. Based on the coding of the data, all data within a topic were systematically analysed, which resulted in the findings in the two articles.

All interviews were conducted in Norwegian, except one in English. The interviewees were cited in the final articles (ensuring anonymity was observed). Their statements, therefore, had to be translated from Norwegian to English. The researchers did this by ensuring the wording was as similar as possible. However, the researchers rephrased some citations to capture the meaning of statements or adjust for cultural, lingual, or contextual expressions.

4.4.2 Quantitative data analysis (Article 3)

The data material in Article 3 was analysed through statistical analyses to test for, and identify significant relationships between project management, safety management and safety performance. The data used for the project management and safety management variables were from an existing dataset (Nordic 10-10). Data for safety performance results (rates for lost time injuries (LTI) and total recordable injuries (TRI)) for the same projects were additionally collected. The statistical tool, SPSS Statistics version 26, was used for the analyses. The study started with three hypotheses on the relationships between project management, safety management and safety performance.

The project management variable had to be created based on questionnaire items from the Nordic 10-10 database that relate to characteristic features of project management. The relevance considerations of the items were based on previous research (Luu et al., 2008; Ling et al., 2009; Project Management Institute, 2017) and the research group's considerations. The items were results of responses presented to the respondents as statements, indicating their agreement on a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). In the database, the responses were given as averages for all respondents from a particular project phase, meaning there was one number for each case in the database. An exploratory factor analysis was performed to create the project management variable. Principal component analysis (PCA) with varimax rotation and Kaiser normalisation resulted in a final set of thirteen items. Tests in the preliminary analysis, involving the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity, gave satisfactory results. After a listwise exclusion, 62 cases were included in the factor analysis. Kaiser's criterion and the scree plot suggested three factors, explaining 73 per cent of the variance. The first factor had eight items thematically addressing the *project team members and system functioning,* accounting for 38.7 per cent of the variance. The second factor consisted of three items addressing *project leadership,* accounting for 22.7 per cent of the variance. Factor 3 included two items addressing *compliance with systems and requirements*, accounting for 12 per cent of the variance. Pearson's correlations between factors indicated satisfactory discriminant validity, meaning that the factors are not greatly related. Cronbach's alpha was calculated to check whether the questions included in the index reflect the same aspect. Cronbach's alpha above .7 indicates adequate internal consistency and reliability (Nunnally, 1978, pp. 245-246), which it was for factors one and two. The third factor did not meet this criterion and was therefore not included in further analysis.

Independent-sample Mann-Whitney *U*-tests were finally performed to examine the relationships between project management, safety management and safety performance. The test determines if the mean ranks in two groups are significantly different. This test was used as the normality criteria for parametric tests were not met.

The Kolmogorov–Smirnov test scores were non-normal for the safety management and safety performance variables ($p<.05$). The differences in safety management and safety performance between projects that perform well and poorly on project management, as well as differences in safety performance between projects that perform well and poorly on safety management were studied by comparisons of means using ranking. One-way tests were applied as the hypotheses were directional, with the significance level set at .05. A r-value for effect size was estimated from the z-scores (using the formula $r=z/\sqrt{N}$), where r below 0.3 is considered a small effect, r up to 0.5 is considered a medium effect, and r above 0.5 is a large effect (Field, 2018, pp. 117, 295-296).

The project management variable included two indices: *teams and system functioning* and *leadership*. The safety management variable was developed by the CII 10-10 Program (Yun et al., 2016), and the numbers for this index were taken from the Nordic 10-10 database. The last variable was for safety performance, using LTI and TRI rates obtained from companies. The cut-off criterion for the project management and safety management variables was set to the median. The analyses resulted in ranks between good and poor performance of the different variables, and the significance of the rank determined whether the three hypotheses were supported or rejected. Hypothesis one was supported, where a positive relationship was found between project management and safety management. Hypothesis two, looking at a relationship between project management and safety performance, and hypothesis three, looking at a relationship between safety management and safety performance, were rejected.

4.5 Scientific quality

The quality of research can be assessed by specific criteria. Reliability and validity are particularly important for quantitative research (Bryman, 2012, p. 389). These criteria can also be used for qualitative research (Bryman, 2012, p. 390), and they tell something about the objectivity and credibility of the research (Peräkylä, 2004, p. 283). The scientific quality of the work undertaken in this PhD is reflected upon here with respect to internal validity, reliability and generalisation. For further limitations, refer to the attached articles and section 1.3.

4.5.1 Internal validity

Validity refers to the accuracy of the representation of a phenomenon (Silverman, 2006, p. 289) and the integrity of the conclusions from the research (Bryman, 2012, p. 717). It tells something about whether the selected measures actually measure what is supposed to be measured (Field, 2018, p. 15). The concept of validity comes from quantitative research, where assessing the validity of findings may be easier and more precise. However, the concept is also important for qualitative research.

Internal validity is most relevant for explanatory and causal studies and less for descriptive and exploratory studies (Yin, 2003, p. 34). In this thesis, this is therefore primarily of relevance for the quantitative, explanatory study in Article 3. Internal validity is concerned with the causal relationship of a finding, meaning whether a finding considers the link between two or more variables (Bryman, 2012, p. 712). As this study uses statistical analyses, a relevant and common measure for internal validity is

Cronbach's alpha (Bryman, 2012). Cronbach's alpha is between 1 (perfect internal validity) and 0 (no internal validity), with alpha >0.7 being the limit for acceptable alpha based on Nunnally (1978, pp. 245-246). Bryman (2012, p. 170) writes that an alpha >0.8 is commonly used as a rule of thumb when it comes to internal validity, however, some also use 0.7. In Article 3, the alpha limit was set to >0.7. The three constructed factors for the project management index had alpha scores of 0.939, 0.836 and 0.578. The last factor did not satisfy the criteria and was not included in further analyses. The two first factors exhibited very good and good Cronbach's alpha scores respectively. Pearson's correlation between these factors was reported through cross-loading, which indicated a satisfactory discriminant validity with the highest load of 0.706 (between factors 1 and 2). Discriminant validity refers to what degree the designed measure tests the concept it was intended to measure. This is also important to ensure the quality of the research conducted.

For the studies in Article 1 and 2 validity has been tested by presenting their preliminary findings at conferences and getting feedback and viewpoints from the research community. The studies have resulted in two research articles published in journals and a manuscript submitted to a journal. Tjora (2012, p. 206) writes that putting the research out to the research community, for example through conferences or by publishing in scientific journals, shows that the researchers relate to relevant theories and perspectives and previous research ensuring the quality of the research.

4.5.2 Reliability

Reliability concerns the consistency of findings, such that accidental circumstances do not influence a study. In quantitative research, reliability is connected to replicability, meaning whether a study could be repeated with the same results (Silverman, 2006, p. 282). For qualitative research, it is harder to replicate a study. However, transparency about how the study has been designed, how interviewees have been chosen, and how the study has been conducted and analysed increases the reliability of qualitative studies (Tjora, 2012, p. 205). It has therefore been important for the candidate to describe the process of the studies well. For interviews in particular, the interviewer and interviewees need to have the same understanding of questions, and reliability can be increased by analysing the same data by more researchers (Silverman, 2006, p. 288).

The two qualitative studies (in articles 1 and 2) were designed with a set of research questions based on previously acquired knowledge from working with the construction industry and the safety field, as well as reviewing related scientific literature. Interview guides were prepared based on this. For further descriptions of the approach, refer to earlier parts of section 4, and the respective articles. The interview guides were discussed with other researchers with practical and research experience from the construction industry. The previous experience of the candidate in the field and opinions from other researchers increase the reliability. The interview guide was important to ask good questions and to avoid leading ones, for which previous interview experience was helpful. Furthermore, it was an important point during the interviews if in doubt, to ensure the correct understanding by asking additional questions, such as 'Do I understand this correctly, that …?', as well as asking follow-up questions such as 'Can you give an example of such a situation?'. Two researchers conducted the interviews for the study in Article 2, ensuring a more correct understanding. Also, during the data analysis, two researchers separately did the initial coding and analysis, which also improved the reliability of the analysis. In the two first studies, the interviews were recorded and transcribed, which helped present precise citations and increase reliability (Tjora, 2012, p. 205).

The study in Article 3 was limited to examining the relationships between specific aspects of project management, safety management and safety performance. It was based on data collected as part of the Nordic 10-10 program, where the authors of the article themselves were neither involved in constructing questionnaires nor in collecting the data. The benefit of using data from existing sources is that the method has been tested and researched thoroughly. The disadvantage is that the authors are bound to the available questions and the format available from the database. During the data collection for the Nordic 10-10 program, a certified coordinator facilitated the respondents while responding to the questionnaire and had the opportunity to clarify doubts. This enhances the uniformity of the understanding of the questions and strengthens the reliability and validity of the data. Participating in benchmarking might also affect the results since these construction projects devote resources to responding to questionnaires, which might create a bias in the answers. The companies themselves reported the safety performance data to the researchers. Thus, the accuracy and quality of the data could not be controlled. However, companies have internal control procedures for their incident data collection. The common use of LTI and TRI rates in the industry justifies using these rates in the research, helping provide new insights. The analysis part of the study is repeatable based on the data used as it is statistical in nature with a carefully described repeatable process.

4.5.3 Generalisation

Generalisation refers to whether the research findings can be generalised beyond the studied context (Bryman, 2012, p. 711). It can also be referred to as external validity. Quantitative and qualitative research are very different regarding the question of generalisation. While it is an aim in quantitative research, generalisation is not a necessity in qualitative research as the purpose can also be to give insight in local practices or build theories. (Silverman, 2006, pp. 304-306). Silverman (2006, p. 311) writes that purposive and theoretical sampling can increase generalisability in qualitative research, where resources are applied the best to get the best possible sample.

For the studies in articles 1 and 2, purposive sampling was applied for several reasons, including studying specific aspects regarding information sharing in specific industries, as well as for practical reasons, as all companies in the construction industries could not be reached and studied. The two studies were exploratory, and do not aim for generalisation. However, the insights gained from the studies are of relevance to the Norwegian construction industry and to the construction industry in general, as they describe common information sharing practices and possibilities for information sharing as a means to develop safety management.

The study in Article 3 is relevant to the construction industry and practices in particular related to project management and safety management. Though the study had a limited sample size, it showed a positive relationship between project management and safety management factors across different construction projects.

The research conducted mainly involved large actors in the construction industry, making the results more relevant for larger actors in the industry. The results are primarily related to managerial levels, as they are preoccupied with information sharing on the level of HSE personnel and managers and improvements related to project management and safety management.

4.6 The researcher's role and ethical aspects

The researcher has an important role that can affect the research and its quality. The researcher can influence the aspect of objectivity, which relates to neutrality and possible bias in a study. Prior knowledge about a field or an industry can be an asset in doing research to ask accurate questions, but it could also limit openness to new inputs because of prejudice (Tjora, 2012, p. 204). Being familiar with the field and industry, but not an expert, and being open and aware of such consequences from the start has helped keep an as neutral as possible role during this research. Another important point to avoid bias and enlarge both the theoretical and practical research perspective has been to discuss the research with other researchers (supervisors and other researchers from the construction and safety fields) and in different forums (e.g., in the STERNA project and at conferences).

Data management is an important part of working with research. Therefore, from the beginning, the candidate has been aware of data protection considerations regarding storing data and processing any personal data. This is important when doing interviews or other data collection that involves people. In addition, guidelines for research ethics by the National Research Ethics Committees in Norway were followed.

Furthermore, the Norwegian Centre for Data Research (NSD) was notified about the different studies and the studies were performed according to the advice given on data management and data protection (study in Article 1 – ref. no. 55634, 1 September 2017, study in Article 2 – ref. no. 56954, 23 November 2017, the study in Article 3 did not require notification). For the two studies where notification was applicable (Article 1 and 2), all the participants were informed about the respective research that they participated in, informed consent was received from the interviewees, the interviewees were informed about their right to withdraw without reason, the interview data and personal data were separated while storing, the interview data were anonymised, and all personal data were deleted at end of the project. Article 3 was based on previously collected data and notification to NSD was not required as the data did not contain personal data and the data material was not sensitive. The construction projects studied were anonymised in the research reporting.

The PhD was founded by the Department of Industrial Economics and Technology Management (IØT) at the Norwegian University of Science and Technology (NTNU) from September 2016 to August 2021. The candidate had 25 per cent teaching duties and did work such as supervision of master's students, was responsible for exercises in courses and gave lectures. Furthermore, the candidate was part of a research and teaching collaboration project between three universities in Brazil and NTNU through the STERNA project (Resilience Engineering and Safety Management for Complex Socio-Technical Systems) funded by CAPES (Coordination for the Improvement of Higher Education Personnel in Brazil) and Diku (Norwegian Agency for International Cooperation and Quality Enhancement in Higher Education in Norway). In addition, the candidate collaborated with researchers from the Federal University of Rio Grande do Sul (UFRGS). The candidate also had a research stay for three weeks in September 2018 in Porto Alegre, Brazil, at UFRGS. This was helpful in giving more insight into different perspectives of safety, particularly Safety-II and resilience engineering.

During parts of the PhD, the candidate was employed part-time at SINTEF Technology and Society/SINTEF Digital. The candidate also was on parental leave. After the employment at NTNU, the candidate finalised the PhD thesis while employed by PricewaterhouseCoopers (PwC). The employers did not influence the PhD work or its results.

5 SUMMARY OF RESULTS

This section presents an overview of contributions from the three articles. The work has explored information sharing and aspects of project management for developing safety management in the construction industry. The three research questions link the articles and substantiate the overall research objective. The overview in Table 7 shows how the articles are related and which research questions each article contributes to.

Table 7: The research questions and the consistency between the articles

Research question		Article		
		1	2	3
Over-all	How can incorporating additional inputs develop safety management in the construction industry?	x	x	x
1	What opportunities for safety management exist in broader information sharing across the construction industry?	x		
2	How can the construction industry improve safety management by looking at practices from the Norwegian petroleum industry?		x	
3	How is project management related to safety management in construction projects?			x

5.1 Information sharing after incidents in the construction industry (Article 1)

The first research question of the thesis, *'What opportunities for safety management exist in broader information sharing across the construction industry?'* is explored in Article 1. This article studies sharing practices post incidents across companies in the Norwegian construction industry. For this purpose, interviews were performed with safety personnel across actors in the Norwegian construction industry. The article aims to explore: 1) how information after incidents is currently shared across the construction industry, 2) what gaps exist in the sharing processes between organisations, and 3) how collective safety information can be obtained.

The findings show that several arenas for sharing information across actors do exist. However, the sharing is not structured, occurs occasionally, and there are no set routines for sharing across companies. Across actor levels, safety-related information is shared in written form through seminars, conferences, networks and groups. Much of the information sharing occurs between similar actor types (e.g., contractor to contractor, client to client), although some arenas for sharing across actors exist (e.g., seminars and conferences, such as HMS-konferansen [The HSE conference for the Norwegian construction industry] and the SfS BA network). Such arenas are used sporadically and only for selected experiences and unwanted events. Furthermore, the meeting arenas and interactions between actor types are limited. As a result, the information largely stays in silos and is not shared across all actors in the industry for whom it could be valuable. For example, early-phase actors, such as architects and consulting engineers, received limited feedback after accidents, which sustains the limited factual knowledge of these actors on risks during the construction phase. There is potential to better utilise the available safety-related information across the industry by broader sharing. This includes more information on safety from the construction phase to early phase actors, who can use it in planning and design early in a project.

Further, technological opportunities are not exploited optimally for information sharing. Standardisation of taxonomy in reporting and in the industry are among identified impediments against enabling wider sharing of safety-related information. Also, characteristics of the industry and framework conditions, such as industry organisation with many companies in the project value chain, rapid and constant changes, time and progress pressure in projects, and costs, were found to fragment and hinder information sharing across the industry. Nevertheless, although challenges were identified, overall, a willingness to improve safety, sharing of information and enthusiasm towards new technology and the opportunities it can bring for safety, were seen among the actors across the industry.

Collective safety information was in the study proposed as a way forward to improve information sharing across projects and actors in the construction industry. Steps are already taken in the construction industry by establishing arenas such as the SfS BA inspired by the Norwegian petroleum industry. Although many are positive towards sharing information, factors such as the risk of prosecution can limit the willingness to share, which is one of the obstacles that need to be investigated and handled for broader information sharing.

A roadmap was laid suggesting sharing information through technological solutions and using it as input, for example, in building information modelling (BIM) and risk assessments. The roadmap includes the identification of user groups for the development and testing of a solution, standardisation of taxonomy to ease the information sharing for technological solutions, information processing to analyse the data, dissemination of the processed information and application of the information as input to other systems or in development of other tools.

5.2 Looking to other industries for practices and experiences (Article 2)

Article 2 contributes to the second research question of the thesis: *'How can the construction industry improve safety management by looking at practices from the Norwegian petroleum industry?'*. This article looks at occupational safety in the Norwegian petroleum and construction industries. It aims to explore 1) what effects industry characteristics and framework conditions have on the level of safety in the two industries and 2) what areas from the petroleum industry can contribute to improving safety in the construction industry.

The Norwegian petroleum industry is by many perceived as a world leader in safety and has had a significant influence on regulations and practice of safety across industries in Norway, which, together with accident statistics, form a base for the study. Rasmussen's socio-technical system (Rasmussen, 1997) was used as a theoretical framework comparing safety in the Norwegian petroleum industry and the construction industry, particularly focusing on occupational accidents and risks. The study aimed to understand the factors and reasons behind the steep improvement in safety performance in the petroleum industry compared to the more gradual slope in the construction industry. Interviews were performed with actors from safety authorities, top management, employer and employee organisations, and HSE personnel in both industries.

The system characteristics of the industries are very different, especially in terms of complexity, fragmentation and trends related to the structural systems. Furthermore, industry characteristics and environmental factors can influence safety. The petroleum industry additionally has a major accident risk exposure during operations, whereas in the construction industry, during building, the risk is mainly related to occupational accidents. Furthermore, historically high revenue in the petroleum industry and rather tight margins in the construction industry were mentioned as factors enhancing safety engagement in the petroleum industry over that in the construction industry. Despite major accident risks in the petroleum industry, the safety level was perceived as better in the petroleum industry than in the construction industry. The results show that major events have to a high degree contributed to the petroleum industry's safety level. Furthermore, changes in technology, standardisation, emphasis on planning and close dialogue with the Petroleum Safety Authority Norway (PSA) also contribute to maintaining a high level of safety in the petroleum industry.

Although the safety level in the construction industry has improved over the years, it was found that better planning, communication, and more standardised processes could further enhance the industry's level of safety. Several methods and tools for safety from the petroleum industry have already been adapted to the construction industry. However, the different nature of the industries makes a direct transfer of concepts and practices from the petroleum industry challenging. Therefore, the potential and value of practices and experiences from the petroleum industry, which can be shared with the construction industry, must be considered with industry-specific conditions in mind. Identified aspects that the construction industry can borrow from the petroleum industry included: industry standards and adopting similar safety requirements across the whole of the construction industry, such as uniform tools, methods and practices, barrier thinking and risk awareness, detailed planning before operations, sanctions for non-compliance and more systematic information sharing arenas on safety, for example through digital solutions.

5.3 Exploring safety management from a project management perspective (Article 3)

The third article explores the relationship between project management factors, safety management factors and safety performance in a sample of Norwegian construction projects (see section 3.2 and 3.4 for definitions of terms). A statistical analysis was performed to explore the relationships between these factors, using data from a benchmarking tool for performance assessment (Nordic 10-10) and incident data from construction projects. The article contributes to RQ3 of the thesis: *'How is project management related to safety management in construction projects?'*.

In practice, safety management in a construction project is often performed with a weak connection to general management. However, safety management and performance are influenced by the same contributing factors as value creation in a production process (Kjellén and Albrechtsen, 2017, p. 52). Further, value creation is driven through project management. Safety management systems implemented in construction projects are advantageous for project management (Yiu et al., 2018; Yiu et al., 2019). This refers to safety management being combined with normal operations by integrating safety management systems, project management, safety knowledgeable project engineers, and cooperation between the project engineers and safety personnel (Yiu et al., 2019). Safety performance is in the construction industry widely measured with injury rates, which are easy and evident to understand, although criticised for being poor measures.

The article explores if projects that perform well on project management also do well in safety management and safety performance and if those that perform well on safety management also do well in safety performance. Selected aspects of project management, in particular *teams and system functioning* and *leadership,* are explored by looking at the relationship between safety management and safety performance. The results confirm the hypothesis that overall good project management positively impacts the safety management of construction projects. This demonstrates that the same contributing factors are important for value creation and safety. This supports and emphasises the need to have safety management as an integral aspect of all management activities in a project rather than as a function on the side. Overall, project management puts essential conditions on the execution of safety management in projects. Safety in construction projects is created and maintained by project management aiming to reach a project's objectives and safety management aiming to support decisions for hazard control.

The results did not confirm two other hypotheses that good overall project management and good safety management of a project have a positive impact on personal injury rates. By this, injury rates are demonstrated to be an inadequate measure of safety performance measurements in projects alone. Additional measures based on project management aspects are recommended for monitoring safety performance in construction projects. By using existing project management indicators, factors of safety management can also be monitored. Available project management measures related to safety management, for example, related to the characteristics of a project manager, the project manager's leadership and factors related to information flow and project management systems, are low-resource actions to anticipate and improve safety management. There is, however, a need to further describe aspects of project management and safety management together.

6 DISCUSSION

The thesis aims to contribute to enhancing safety performance in the construction industry, which is found to be stagnant (see section 1.1), by exploring opportunities within the development of safety management. The background for the discussion is the overall research question, which explores how incorporating additional inputs can develop safety management in the industry. The three presented articles have investigated different ways to contribute to this development. Based on the presented results from the three articles and the related research questions, discussions about 6.1) expanded information sharing as input for safety management developments and 6.2) advancing safety management through an integrated safety approach are given.

6.1 Expanded information sharing as input for safety management

Both sharing and learning from incidents across organisations in the construction industry have a considerable potential to help prevent future incidents (Drupsteen and Wybo, 2015). For example, sharing safety information is an underexposed step in learning from incidents (Drupsteen and Guldenmund, 2014). The literature reviewed by Drupsteen and Guldenmund (2014) and Drupsteen and Wybo (2015) shows a large focus on information sharing within an organisation or a project. Further, empirical studies on sharing across the construction industry are limited. The three articles in this thesis contribute to the discussion on expanded information sharing as a catalyser for safety management developments.

'Most accidents are not inevitable, but preventable' (Dechy et al., 2020). As experiences are one of the inputs into safety management (Kjellén and Albrechtsen, 2017, pp. 92-93), available information based on the experiences can be better utilised and serve as a catalyser for the development of safety management and improvement of safety performance. They can improve the decision-making (Westrum, 2014) in the safety management system and contribute to the learning process (Drupsteen and Wybo, 2015). Knowledge gained through information sharing can be used to understand better, predict and prevent the occurrence of accidents (Tixier et al., 2016a). As other types of actions than what is usually done are required to surpass the stagnation point in the accident numbers and to develop safety management further, different types of information sharing are investigated. This aligns with Ashby's law of prerequisite variety (Ashby, 1956, p. 207), where variety is required to overcome different problems.

6.1.1 A broader information base across actors and phases

The construction industry has several specific characteristics, such as constant changes and project progress, challenging a good and standardised safety management process.

The processes are simultaneously customised and tuned to the specificities of a project. Although each project in the construction industry is unique, many activities and processes across the industry are well-known and repeatable, especially in specific trades, which can be learnt and applied to future projects (Carrillo, 2005). Site-specific conditions occasionally make the operations and process different from usual, although most can be anticipated and planned for or adjusted to be handled before any incident occurs.

The varieties of characteristics found across different construction projects point toward using a broad information base across the industry and from other industries when characteristics or trends are similar or other aspects make information and practices transferable. Furthermore, experiences in one project or a company may be limited. For example, there are only a few severe and fatal accidents in each company individually, whether small (Hale, 2005) or large. Gaining safety-related information from others might therefore be helpful.

A broad information base, including conditions, influences and possibilities, can help to manage project safety. This is because of the expanded opportunity to identify appropriate actions for emerging problems, in line with Ashby's law of prerequisite variety (Ashby, 1956, p. 207). It can further provide input in coming projects from incidents that have happened, identifying risk factors and control mechanisms and a broader selection of possible mitigating actions. Figure 12 illustrates different dimensions that information can be shared across to expand the information base. Information sharing can happen within or across *industries*, *actors* and *processes*. In addition, the sharing can occur in one or more dimensions, for example, sharing across the same actor operating in two industries, sharing between actors across project phases (from clients or contractors in the construction phase and back to consulting engineers and designers in the early phase), or sharing across processes (from project management to safety management).

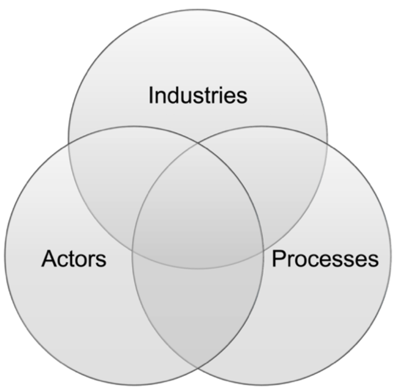

Figure 12: Information sharing across three dimensions

To contribute to a broader information base, information needs to be shared and saved in systems. Experiences can contribute to this by being explicit. Nonaka and Takeuchi (1995, pp. 70-73) distinguish between tacit and explicit knowledge in knowledge creation. Through a spiral process of changing modes, the knowledge level can go from individuals to groups to organisations to inter-organisations. Experiences can also be looked at similarly, and tacit experiences are of immense value. Through externalisation, tacit experiences can become explicit. A further step is to connect the explicit experiences in the form of information with other explicit experiences by combination. It can lead to an even broader information base and understanding and be input to new practices for safety management. An example of this from across industries is when aspects relevant to safety from the construction industry are combined with good practices from the petroleum industry. This combination can lead to new or improved safety management practices. It is relevant to improvement for things that go right and should be continued, things to be further improved, and for things that have gone wrong and can be rectified.

The results in Article 1 point to a limited sharing of safety information after incidents across companies in the Norwegian construction industry. This alone is a large limitation to an information base. Furthermore, sharing across different project phases and corresponding actors is also limited. This implies that actions in early project phases relevant for safety in the execution phase can continually be repeated without being corrected. The many involved actors and phases also contribute to fragmentation in the industry. In the organisational learning literature, fragmentation and weak ownership because of the use of external consultants in the petroleum industry have been found to hinder learning (Størseth and Tinmannsvik, 2012). In the same manner, fragmentation through the existence of many phases and actors in the construction industry can hinder acquiring a shared understanding and improvement. This points to the need to facilitate the underlying processes, such as information sharing across actors and phases, to overcome these challenges. Expanding the information base and, to a greater degree, making it available for different actors and increasing relations across actors and phases can increase the understanding of the whole project process. It can also create awareness of how actions at one end may affect or improve safety during construction.

Furthermore, safety-related information across industries can be used to improve safety management in the construction industry. Article 2 points to the benefits of informal information sharing across industries, which has been achieved through, for example, resources bringing experiences from the petroleum industry to the construction industry. The petroleum industry can be seen as a role model for the construction industry concerning great improvements in safety over time and with great potential to draw experiences from. Also, Duryan et al. (2020) suggest looking into other industries to learn from their experiences and promoting information transfers across the construction industry.

The second article also points out that for safety management, the differences in frame conditions between industries are essential to consider when looking to other industries for patterns to adapt or learn from. For example, the level of maturity in the construction industry is lower compared to the petroleum industry. More developed or advanced methods and tools for safety management can therefore be used merely for inspiration or be transferred and altered for use in the construction industry (Edwin et al., 2021). Furthermore, practices and safety activities related to different frame conditions or upcoming trends in other industries, which still have to a lesser degree, influenced the construction industry, can prepare the construction industry to anticipate safety risks and take early and appropriate measures to cope with them. Sharing information across the construction industry and looking to other industries expands the information base, which in turn can be used as input to several activities and systems, such as safety management. Sharing information is a way to make decisions and actions, which can lead to improvements.

The third article looked into the relationship between project management and safety management and suggests using aspects of project management as leading indicators for safety management in the construction industry. The topic is also related to information sharing across the industry. A broad information base is required to find important traits related to project management that influence safety management and safety performance. Such an approach also requires information from different companies and sites across the construction industry to develop indicators that can be generic for a trade or the industry. This can contribute to the feedforward process in the safety management system. Looking across industries and the construction industry in particular, the actual relationship between different management aspects influencing safety (such as the relationships found between *teams and system functioning* and *leadership*, and safety management in Article 3) can be substantiated and better adapted to specific traits if the information base is large enough. For example, *teams and system functioning* refers to how processes and systems function. The *leadership* factor refers to selected aspects or traits of leaders, such as communication skills or whether they are open to hearing 'bad news' and recognise outstanding personnel or results. This shows that soft skills related to project management are also important for safety management, such as the human element with the support of systems is essential.

6.1.2 Premises and opportunities for expanded information base

Some traits must be in place for an expanded information base to be implemented and used for safety improvements. These are premisses that allow the information from one organisation to be shared with others and relate to own practices.

Article 1 indicates a substantial willingness to share information about unwanted incidents. This is despite opposing opinions across the industry related to trust and intention of use-related issues. Factors necessary for sharing information across organisations were identified in the article. Table 8 shows factors that can contribute to effectively sharing safety-related information. A willingness to share, or openness, is likely the most crucial factor for success in sharing and using such information for improvements. This factor is also closely related to trust and intention of use. Potential consequences for an organisation of sharing information will affect the willingness to share if it can lead to a negative outcome. For instance, in Article 1, it was reported that information from accidents could affect reputation, chances of winning contracts or even result in sanctions.

Furthermore, the contents, level of detail and format of the information shared play an important role when used as input to systems. A common taxonomy for safety information and categorisation of information in a standardised way can contribute to better utilisation. This enables a broader sharing and easier extraction of relevant information for other actors. This is also important for the databases for storage and extraction that rely on metadata for data integrity. Developments in digitalisation and technological solutions open more avenues for effectively sharing and utilising safety-related information across actors.

Table 8: Premises for effective sharing of safety-related information between actors (based on Edwin (2022))

Domain	Factor	Description
Organisation	Openness: Willingness to share	Safety has been highlighted as an area where cooperation can be beneficial, as one actor is often dependent on, as well as can influence the safety of another actor. Openness or willingness to share is therefore critical for effective sharing.
	Trust: Intention of use	Trust has been pointed out as important for willingness to share, as it should not have negative consequences to be open about what does not go right and can be improved.
Data	Taxonomy and standardisation	A common taxonomy in the industry regarding safety data, standardisation and structure of information in terms of classifications of activities, types of incidents etc., was found important for sharing and utilising information.
Technical system	Platform/ Technological solution	Digitalisation, new technological solutions, and possibility to integrate collective safety information into available systems (e.g., managerial systems) give an opportunity for broader use and utilisation of shared information.

Furthermore, the following aspects have been found important for good flow a of information in organisations; relevance, meaning that it provides the answer the receiver needs; timeliness and clarity, meaning that it is presented in a manner that can effectively be used for the receiver (Westrum, 2014). The receiver of the information, therefore, needs to be in focus. There can be more types of users and needs among the actors, divided by organisation types (e.g., authorities responsible for legislation or supervision) or levels within an organisation (e.g., top management, operative management, staff). The information, therefore, needs to be adapted to the user's needs. As suggested in the first article, user groups should be identified and recruited to collect and share safety information across the construction industry. Adaptation to different types of users is particularly relevant for the construction industry, where there are many trades and work tasks with various occupational risks and a large variety in size, management and professionalism of actors.

A common taxonomy and standardisation were found important for sharing and utilising shared information in Article 1 (see Table 8). The development of safety in the construction industry in Norway, as mentioned in Article 2, is considered less mature than in the petroleum industry. Similarly, the standardisation efforts in the construction industry regarding safety management are at a less mature level. This also includes information sharing practices. In the petroleum industry, the standardisation efforts have involved cooperation across actors, such as oil companies, suppliers and trade unions. This has resulted in the development of common standards based on common experiences (Engen, 2019, p. 261). Further, other actors, such as researchers, have contributed, and the organisation of the standardisation efforts have been further formalised (Engen, 2019). The two compared industries in Article 2, differ in size, i.e., the number of companies, projects and even types of activities. The differences in safety management practices in the construction industry can therefore vary to a larger degree as compared to the petroleum industry, especially as companies might develop more independently in the construction industry. Some collaborative initiatives exist in the Norwegian construction industry. These are, however, limited in extensiveness and practical solutions for expanded information sharing. Common work regarding the standardisation of HSE taxonomy across actors, as seen in the petroleum industry, can open for more sharing and further developments regarding HSE practices and the maturation of safety in the industry. This is especially relevant for utilising digital solutions for sharing safety-related information. For example, Article 1 illuminates the relevance of standardised entity typing for information sharing, where taxonomy and classifications for categories should be structured across, or at least be compatible or easily translatable for activities, incident types, contributing factors and so on. The importance of this for the input data is related to the value of the output and the possibilities to find and utilise previous relevant information.

A study looking into sharing practices in selected companies found that to succeed, it is important to fit the approaches towards sharing to the existing culture and practices and have a clear connection to business goals (McDermott and O'Dell, 2001). Industry characteristics and frame conditions were found to contribute to fragmented information sharing in Article 1. Therefore, only creating a sharing space or platform will not be sufficient for sharing information across the construction industry. Other incentives, such as connection to business goals, relevance for the company, building on existing networks or requirements or expectations from the community, will also be needed (McDermott and O'Dell, 2001).

6.1.3 Digitalisation increasing the potential for expanded information sharing

Digitalisation and technological development bring opportunities to all sectors and business aspects. The digital era has lifted practical barriers to information sharing and allows extensive opportunities to evolve in the construction industry regarding safety management. For example, digital solutions can easily overcome challenges such as keeping information up to date and making it available for different actors (Lingard and Wakefield, 2019, p. 69).

Already by the 1980s, Kjellén (1987) was looking at computer support in safety practices. This was done using a database to collect and extract incident information for decision-making. Since then, the technological possibilities have increased considerably. Article 1 suggested a roadmap towards collective safety information, where technological solutions for processing and disseminating the information are highlighted as necessary for an expanded information base. In a study review, Zhou et al. (2015) observed two approaches towards safety that are common in the literature – a management perspective and a technology perspective, where innovative technologies can support safety management. Many new information technologies have the potential to be applied for safety purposes in the construction industry, such as artificial intelligence (AI), Radio Frequency Identification (RFID), ultra-wideband (UWB), global positioning system (GPS), Geographic information systems (GIS), visual monitoring (VM), virtual reality (VR), simulations, augmented reality (AR), BIM (Zhou et al., 2012; Zhang et al., 2015; Hallowell et al., 2016), and drones (Irizarry et al., 2012). Most of these technologies are better suited in the execution phase to monitor performance rather than share incident information or other safety-related information or for safety management in early construction phases. Some, such as GIS, VR and BIM, are suitable for use in the design and planning phases (Hallowell et al., 2016) and can improve safety in the execution phase. Hallowell et al. (2016) highlight the possibilities of integrating incident information processes through machine learning algorithms into BIM and forecasting safety-related outcomes. This can communicate safety concerns from consulting engineers or designers downwards to the sharp end (construction managers and work crews). A literature review on construction hazard prevention through design by Hardison and Hallowell (2019) shows broad possibilities for using BIM in safety, e.g., to link safety information with scheduling, product information, and other technological solutions. In other industry segments besides construction, there are several examples of success stories and practical solutions related to safety and digitalisation, for instance, by integrating operations and activities with risks to separate tasks that should not be performed simultaneously by using information based on past incidents (Birnie et al., 2019). Article 1 stresses the value of applying the collected information through tools and systems, such as in risk assessments or by integration into BIM as support in safety management.

The use of new technologies, such as robotics, sensors, cameras, computer models, programs, and software applications, which examples of are described above, are frequently suggested in safety management literature to improve safety at construction sites. However, Hardison and Hallowell (2019) found in their review article that most tools for hazard prevention in construction through design, which relates to safety management in early phases of construction, are mostly suggestions from theoretical studies and close to none are implemented solutions in practice. Furthermore, information across project stages must be shared to improve the knowledge in early project stages. Thus, the opportunities in early project phases and throughout the project are evident and can largely be enhanced by more digitalisation in data collection and information sharing.

Digitalisation can integrate safety information better into existing tools and systems. For example, safety information systems are structured to minimise the cost of searching for and analysing information and maximising its utility for it (Kjellén and Albrechtsen, 2017, p. 111). This is also essential for expanded information sharing and is made feasible with technological developments. As mentioned in section 6.1.2, standardisation is one of the identified premises to leverage digital solutions for information sharing. This opens for the use of a variety of technological solutions. Although many ideas and solutions exist for safety, Article 1 found that they are not broadly linked and used in safety management in the construction industry in Norway. Zhou et al. (2015) point out the academic focus on innovative technology for safety, which needs to be turned towards practical applications.

To use the technologies mentioned above and opportunities for improvement of safety, the first step is to have reliable data available from incidents and other experiences that can be fed into the systems. According to Hallowell et al. (2016), the focus in research has been on technological developments only needs more focus on how to access reliable safety information through more empirically driven feedback. One benefit of ensuring a broader and more structured information collection is that the information becomes less biased. Furthermore, AI and cloud services provide sharing possibilities which can give accessible platforms for sharing tailored by users and to user needs. Applications in machine learning (Tixier et al., 2016b) and natural language processing (Kim and Chi, 2019) have been discussed in the literature in relation to safety in the construction industry for collecting and structuring large amounts of information and making the sharing process easier and more automated. For example, new technology can extract data from written injury and investigation reports (Tixier et al., 2016a; Kim and Chi, 2019). Moreover, machine learning, e.g., by application of AI, can make such extraction processes even more manageable.

6.2 Advancing safety management through an integrated safety approach

The three articles contribute to the discussion on advancing safety management through an integrated safety approach looking at safety management as an aspect system

(Article 1 and 3) and looking into two safety perspectives to enrich safety management (Article 1, 2 and 3).

6.2.1 Advancing safety as an aspect system

One reason behind the stagnation in accident statistics in the construction industry (see section 1.1) is that management systems do not incorporate the right components to prevent accidents and enhance safety (Swuste, 2008). Traditionally, risk management in construction projects is broken down and treated under the particular activities where the risk poses a threat. This is also true for occupational health and safety risks (Lingard and Wakefield, 2019, p. 232). This leads to divided safety management and limits the possibility of managing risks and hazards that cross over different activities. Furthermore, keeping data silos (Carrillo et al., 2013) and not relating it across processes are challenges in construction. Systemic hazards which arise from work design, organisation and execution are also not captured well with a traditional approach (Lingard and Wakefield, 2019, p. 232).

Some recent studies advocate for perceiving safety along with other systems, fields or activities (Griffin et al., 2015; Reiman et al., 2015; Kontogiannis et al., 2017; Le Coze, 2019; Lingard and Wakefield, 2019). Article 3 contributes through a discussion on safety as an integrated aspect of all project management activities. This is based on the positive relationship found between project management factors (*teams and systems functioning* and *leadership*) and safety management. The results suggest that well-functioning project management indicates well-functioning safety management. It underlines the value of looking at different project processes together. The results imply that the same contributing factors create value and enable the control of hazards in construction projects (see Figure 11, p. 26). Therefore, safety must be essential to the overall system to provide value across business processes. As the responsibility and authority in a project, also with regard to safety, lies with project management, this is also where project success, including good safety management, can be influenced, Article 3 highlights. The *teams and system functioning* factor show the importance of integrating safety into overall management, as project management is already largely related to safety management. Also, Badri et al. (2012) point out poor knowledge of safety risks in project teams and poor integration of safety management into project management.

Furthermore, poorly integrated safety management into production management can result in low safety performance (Winge et al., 2019). The need for top management and project managers to continuously prioritise safety and risk management was highlighted in an analysis of Norwegian construction accidents in 2019 (Mostue et al., 2020b). An analysis of construction accident investigation reports from Australia found that accident investigations do not sufficiently consider system-wide relations that influence safety performance (Woolley et al., 2018).

Advancing safety as an aspect system can help bring more focus and understanding of safety and what influences it throughout the processes, from the start to the end of a project. An integrated management system is more advanced than systems in one area of the organisation management, such as safety (Li and Guldenmund, 2018). It allows to manage multiple aspects of its operations, such as safety, quality, and other important project aspects, in a coordinated and holistic manner. Kontogiannis et al. (2017) highlight the need to develop and model aspects of safety, quality, and productivity together. This helps establish a common operational picture, create synergies across different operational aspects, and render them visible. System integration of more areas could enhance safety management and be a limitation for it, depending on the focus safety receives. Therefore, there is a need to highlight safety as an aspect of the whole system. Article 3 points to the need for safety to be a vital component of the overall system, to encounter the system's complexity and provide value across business processes.

Another element related to an integrated safety approach is to include and increase safety aspects throughout management processes across project phases. The first article reported that early-stage actors, such as consulting engineers and designers, are not often included in information sharing from project execution and that contractors are seldom included in early project stages and have few possibilities to influence decisions early in the project. This can influence safety in the execution phase. Including safety-related information more in earlier project phases, such as project planning and project engineering and in the management processes in these phases, can improve safety in the execution phase if safety aspects are considered and dealt with early. This calls for including more phases and actors in the feedback process by sharing information across actors and project phases.

Furthermore, an integrated approach towards safety also opens up additional opportunities to relate, measure, and monitor safety management by other monitoring measures. This can be done using data from sub-processes of a system or parts of it, such as project management. The effectiveness of safety management systems is conventionally measured through safety performance based on a set of indicators, e.g., fatality rates (Swuste, 2008; Li and Guldenmund, 2018). Many safety indicators are directly related to safety aspects and do not consider other aspects which also can influence safety (Lingard et al., 2011; Rajendran, 2013; Akroush and El-adaway, 2017). The third article suggests complementing safety performance indicators with leading safety management indicators that measure the expected control of hazards by measuring project management factors. They can provide scores close to real-time and before incidents. Leading indicators predict future developments before the safety performances have changed, contrary to lagging indicators, which change based on past events (Kjellén and Albrechtsen, 2017, pp. 284-285). In other words, leading indicators monitor safety conditions and provide foresight for proactive safety management (Guo and Yiu, 2016). They provide early warnings to support mitigating actions in time (feedforward)(Kontogiannis et al., 2017). Combining indicators can give better measurements of safety management and safety performance (Lingard et al., 2011; Reiman and Pietikäinen, 2012; Hinze et al., 2013; Oswald et al., 2018). This is especially true for indicators that consider the complexity and dynamic dimensions of organisational conditions influencing safety (Kongsvik et al., 2010). Article 3 points out that using supplementary indicators to support hazard control and provide early warnings can also counteract deficits with traditional loss-based safety indicators, such as LTI rates. LTI rates can be relatively easily manipulated (Kjellén and Albrechtsen, 2017, p. 289), and TRI rates are criticised for statistical invalidity, among others arguments (Hallowell et al., 2020).

In particular, soft elements are worth looking into further as the human element within support systems were in Article 3 found to be essential for safety management. Examples include *teams and system functioning* and *leadership*, such as the characteristics of a project manager, the project manager's leadership, factors related to information flow and project management systems. The input used in such indicators can be data already collected from earlier projects, thus mitigating the need for additional resources. Through digital solutions, such data can be connected and matched with safety aspects. Examples of other available data in projects which could serve this purpose are data related to the project manager, such as the manager's formal competence, years of experience, handling and speed of deviations closure, previous safety performance results and equivalent project experience (Andreassen et al., 2020). Relevant experiences from across the construction must be gathered, collated, systematised, and analysed to find the proper connection between aspects important for predicting safety management and safety performance. This will help obtain a broad foundation to base such indicators on (Guo and Yiu, 2016). As discussed in Article 1, expanded information can also contribute to such developments.

As pointed out in Article 3, treating safety management as an aspect system is linked to interactions between management areas. This emphasises the advantages of exchanging information across disciplines within a project. The success of a project depends on not just one discipline doing well but the whole. Also, regarding sustainable development in the industry, a holistic approach is recommended across business areas, particularly economic, environmental, and social (of which safety is a part). This is because the different areas can influence each other, and trade-offs may be required (Solaimani and Sedighi, 2020). Moreover, the disciplines can influence each other, as exemplified by the relationship between project and safety management. It requires an understanding of developments in technology and organisational forms across disciplines so managers can recognise the fields for them to become more integrated (Hasle et al., 2021).

6.2.2 Fusing safety perspectives to develop safety management

Safety management can be advanced through the theoretical approach to breaking through its present safety level (see section 1), allowing safety in the construction industry to mature further. Safety science has progressed through developments in technology, society, and more complexity in systems with the adaptation of concepts from different fields and experiences from past accidents (Dekker, 2019). However, safety science is also varied and fragmented, differing in sectors, actors, scientific communities and research traditions (Le Coze et al., 2014). It has been suggested to complement traditional safety management with more adaptive approaches enhancing complexity and everyday work (Reiman et al., 2015). A further development need for safety science based on empirical evidence is expressed since the field is seen to advance slowly and research is constrained within confined theoretical frameworks (Rae et al., 2020). The discussion in this section contributes to this expressed need by looking outside the boundaries of the Safety-I and Safety-II perspectives. This is done by fusing both perspectives and removing rigid boundaries. It intends to demonstrate how safety management can be developed and further contribute to the safer execution of construction work.

Modern safety perspectives, such as Safety-II, Safety Differently, Resilience Engineering, and Safety-III, offer new or advanced views on safety management. The goal is not to replace what the so-called traditional approach Safety-I offers but rather to complement it with new insights and other ways to explore safety influences. The new perspectives come with new elements, however, they do not actually change what safety is and its goal, although they might have other definitions of safety. An important point is that safety in practice is not based on either one or the other perspective. Furthermore, the borders between perspectives are not definite. For example, comparing Safety-I and Safety-II, the Safety-I perspective also includes components that may be considered primary characteristics of Safety-II, such as proactive elements (for more details, see Table 9). Although Hollnagel originally emphasised how the two approaches are complementary rather than competitive and even proposed to combine Safety-I and Safety-II to meet increasing complexity in socio-technical systems (Hollnagel, 2014, pp. 146-148), in the literature, they are often portrayed in a way that can give the impression that these two perspectives are distinct from one another rather than being complimentary. However, Wahl et al. (2020) write that the lines between the two notions become vaguer in empirical assessments of safety practices. This further speaks for more empirical research related to safety perspectives.

The safety approach in the construction industry relies in many ways on the traditional safety perspective, Safety-I (Peñaloza et al., 2019). In particular, the formal safety management approach includes written procedures and control mechanisms based on Safety-I. On the other hand, construction workers are adaptive to surroundings and can accordingly assess safety and adapt their behaviour, which are traits of the Safety-II perspective. Overall, the traditional approach is dominant in formal safety management in the construction industry. Pillay (2015) reviewed articles related to accident causation and found that the ones from the construction industry employed what he called either a contemporary or an advanced approach towards safety management, which refers to Safety-I. Although the traditional safety approach incorporates some elements of Safety-II, there is a further opportunity to include more adaptive and proactive elements to formal safety management. This does not in any way exclude the Safety-I perspective but instead speaks for combining perspectives, which can complement each other for an overall more integrated and broader safety approach.

In the traditional Safety-I perspective, safety management uses technological, behavioural, human error, socio-technical and cultural strategies. In contrast, Safety-II uses adaptivity as the primary strategy to manage complexity and varying conditions through positive capabilities and looking at what goes right in everyday work (Borys et al., 2009; Pillay, 2015). A comparison of selected characteristics between the two approaches is given in Table 9. Although the approaches are different, the aim is the same; a successful project and a safe working place.

Table 9: Comparison of Safety-I and Safety-II approaches for safety management (based on European Organisation for the Safety of Air Navigation, 2013; Hollnagel, 2014, p. 147; Martinetti et al., 2018; Peñaloza et al., 2019; Cooper, 2020;2022)

	Safety-I	Safety-II
Understanding of safety	Limit what goes wrong and limit losses	Increase what goes right
System ontology	Bimodal functioning (either works correct or wrong)	Everyday performance is variable and flexible
Progress of unwanted occurrences	Unwanted events are caused by failures and malfunctions	The sequence of events happens in the same way, regardless of the outcome
Experience basis	Unwanted occurrences (e.g., accidents and near-misses)	Everyday work (work as done)
Safety management principle	Mainly reactive in terms of acting when something happens. Proactive in terms of risk-based approaches, e.g., plans and measures to avoid accidents	Proactive in terms of anticipation of developments and events (expected and unexpected conditions)
Practices and tools	Mostly reactive and somewhat proactive in terms of addressing failures, accidents, and unacceptable risks and use of tools such as risk assessments, inspections and audits	Reactive and proactive in terms of understanding successes and surprises in everyday work
Human factor	Regarded as a liability or a hazard, but can also be a resource/solution, e.g., as a barrier-element. Proactive elements include training and competence	Regarded as a resource needed for system flexibility, resilience and thus solutions
Stand towards performance variability	Harm should be prevented, e.g., by barriers, standardised processes, compliance with procedures, and handled by, e.g., identification of remaining risks	Variability is unavoidable, and needs to be monitored and handled, e.g., by reconciling work as imagined and work as done

The table presents the main characteristics of the two safety perspectives. The two approaches are two processes leading to the same story and desired outcome, or as Martinetti et al. (2018) write, it is related to how the glass is looked at, half-full or half-empty. In practice, it is not black or white. In both perspectives, success is not just an effort to ensure non-harmful practices by limiting what can go wrong but also about adapting and adjusting to ensure things go right. Safety-II is more than counting what goes right, and Safety-I is not only assuming that things go well because people follow the procedures and work as imagined (Hollnagel, 2014, p. 149).

Both approaches have their benefits and disadvantages. Safety-II practitioners criticise the Safety-I approach for sometimes having oversimplified explanations when something goes wrong (Hollnagel, 2014, p. 141), and the inability to embrace complexity in systems due to the increased socio-technical environment (Hollnagel, 2014, p. 113). This might be sufficient for simple accidents; however, such simplifications can lead to an incomplete understanding of complex accidents. Criticism towards Safety-II includes, among other aspects, a lack of original processes, tools and activities to improve safety, except for the FRAM tool, a lack of empirical studies on how Safety-II actually influences safety performance questioning its validity (Cooper, 2020) and not considering technical constraints of systems which can influence safety (Leveson, 2020, p. 104). Cooper (2020) summarises his critical review of Safety-II by stating that in many ways, the Safety-II practitioners do not recognise many of the capabilities and merits of Safety-I, as many proposed things are already present in the traditional approach.

Having these two divisions of safety does not mean that there is a clear boundary between them in practice and that only one can be used at a time. Safety-I does not need to be replaced by Safety-II. Furthermore, even Safety-II practitioners, to some degree at least, recognise that Safety-I can still explain a large number of situations which do not require methods and techniques of Safety-II (Hollnagel, 2014, p. 148). A combination fitting the complexity and risk level of an operation or a project, together with a safety management approach based on both Safety-I and Safety-II, can be progressive for safety in the construction industry. One example of how such a combination is relevant is to look at the human element (e.g., managers and workers). In the construction industry, the human element is an essential resource for safety. It can detect changes and adapt activities according to the situation. However, it is also prone to errors. This is why it is important to support it through systems, practices, tools, and experiences.

The first article relates to this discussion by presenting state-of-the-art for information sharing related to safety incidents. This mainly takes a Safety-I perspective with opportunities to incorporate elements from the Safety-II perspective. According to Hollnagel (2014, p. 150) certain incidents are easy to notice because of their outcomes; however difficult to explain due to non-linear causes and changing and managing the events that lead to the incident can be hard. To overcome the challenges and understand specific types of incidents well, gathering information can provide a set of possible causes, enhancing understanding of the type of incident. The first article gives a roadmap to enhance the power of sharing information from practices and using them as input into safety management systems. Safety professionals can be an important resource for such information flow. They can coordinate actions that enable better decision-making for safety, an activity of guided adaptivity (Provan et al., 2020). This is a practical approach to Safety-II.

The second article considers information sharing across two industries. Herein, both experiences on what works well and also what does not are relevant, thus embracing both the Safety-I and Safety-II perspectives. The comparison of the two industries can by this contribute to safety management improvements, in particular in the construction industry. Adopting and adapting successful practices and concepts from one industry can benefit the other industry by broadening the information base with what goes right. A combined approach can enhance the value of shared information across the construction industry and across industries by incorporating them as a part of learning for future projects and combining past experiences with new project characteristics and current project conditions. Information sharing, as discussed in articles 1 and 2, is thus very relevant. Furthermore, in Article 1, the inclusion of different actors from different project phases in information sharing was found to be limited. The focus on safety needs to be designed from the beginning (Leveson, 2020, p. 106). For this, information from earlier projects, different phases and actors are needed to avoid hazardous activities and to allow managers and workers to anticipate and safely adapt their work to current conditions. A broader information base also forms an input to risk management in different phases of projects. Sharing across the industry can contribute to identifying contributing factors as well as potential risks. It also concurs with Ashby's law of prerequisite variety (Ashby, 1956, p. 207), as mentioned earlier, wherein using a broader base looking at what goes right can support the handling of variety.

The third article explores safety management from a project management perspective. It contributes to the discussion with the idea of tweaking leading safety indicators for safety management based on project management factors. In the latter, the Safety-II approach is relevant and makes safety management a crucial, explicit part of the whole system to a larger degree. Based on results from Article 3, safety management can be monitored by more general management indicators, such as those related to project management. In accordance with the Safety-II perspective, this information can be used to predict and prevent conditions from diverting from normal operations and thus ensuring normal and safe processes. In addition, success factors from past projects can contribute from a Safety-II perspective to monitor conditions, anticipate risks that can become unwanted incidents and make adaptations when needed in following projects to direct them towards desired accomplishment. In many ways, this is also what another perspective – Safety Differently, is partly about. It looks into new practices while enduring old practices and how other fields can be used proactively and anticipatively for safety management (Gantt, 2017). Safety Differently has elements of Safety-I and Safety-II (see Cooper, 2022). However, the aim is not to make new divisions but build upon and develop safety management by fusing perspectives. There is a conscious focus on incorporating additional elements that can bring value to safety management and performance from other perspectives.

A joint view on safety theory, without creating unnecessary boundaries in practice, can contribute to a more holistic safety approach in the industry (discussed in section 6.2.1), thereby maturing safety management and improving safety performance. An approach looking into both Safety-I and Safety-II can be well suited for safety management in the construction industry and its characteristics and has the potential to uplift systematic safety work. A pure Safety-II approach is not recommended because the performance variability in the construction industry and the many things that can go right are particularly large. However, expanded information sharing gives opportunities to learn from what has gone wrong, from near accidents and good practices, and use it proactively across the industry. Furthermore, a joint approach includes a variety of actors across phases in the construction industry from the beginning of a project. Meeting the safety approach in between, with flexibility in use related to complexity and needs, is a middle approach. This means acknowledging the strengths and weaknesses of the two approaches and seeing them as complementary. This thereby broadens the perspective on safety and utilises processes and tools which can lead to success in the project with regard to safety. This is somewhat similar to what Leveson (2020, pp. 27-29) calls Safety-III, which seems to be Safety-I in practice with building on experiences and having a proactive approach; however, from a systems perspective having much focus on design.

Neither approach by itself is ideal in the construction industry. A good approach depends on the specific characteristics of an operation and of the whole project. In practice, neither Safety-I nor Safety-II is used by themselves to manage safety. Both reactive and proactive approaches are favoured (Peñaloza et al., 2019; Leveson, 2020, p. 105) as there are always changes and variability that need to be accounted for. Both theories bring value to the construction industry with their advantages and disadvantages. This makes each suitable for specific areas or practices. For example, for formal purposes, the Safety-I theory is better suited for documentation (reporting incidents etc.). In contrast, operatively in daily work, Safety-II is, to a large degree, used by workers in construction, e.g., by assessing and adapting to surrounding conditions. Therefore, the solution is not to adopt either Safety-I or Safety-II, as these are just theories. In practice, there will always be more factors that can affect an operation and safety. Therefore, adaptations for either of the theories are required unless the system is closed and controlled with all known factors, which is impossible in the described industry.

7 PRACTICAL TAKEAWAYS

This section summarises the main contributions of the thesis. It gives recommendations for researchers and practitioners to further develop and mature safety management to enhance safety performance in the construction industry. Also, the significance, novelty and implications of the work are highlighted.

7.1 Contributions

The thesis is based on three articles with a common topic of inputs to develop safety management through expanded information sharing and an integrated safety approach. The main contributing elements of this thesis to scientific research are the following:

- Compilation of accident statistics substantiating the development and current stagnating tendency of safety performance in the Norwegian construction industry
- State-of-the-art of information sharing across the construction industry in Norway and opportunities for expanded information sharing across the industry
- Comparison of industry characteristics relevant to safety and safety management aspects between the petroleum and construction industry and the potential for using practices and experiences for safety improvement across the industries
- Exploring the use of project management aspects to monitor and develop safety management in the construction industry
- Calling further attention to the importance of looking at safety as an integral part of overall project processes, including project management, for the success of the whole project, as well as success with regard to safety
- Combining the perspectives of Safety-I and Safety-II for safety management in construction projects, especially with a focus on expanding the information base by using past experiences and success factors as input for ongoing and future projects.

The above-listed contributions highlight clear development opportunities with practical recommendations and further research needs (section 8.1).

7.2 Recommendations

A broader information base through safety-related information sharing across actors and phases in the construction industry can improve safety management and safety performance. The benefits of sharing information from unwanted incidents and successful practices can outweigh the drawbacks associated with information sharing. Actors in the construction industry are highly dependent on each other's safety approaches, as many actors are involved in a project, and one actor can influence the safety of other actors. This can happen across project phases or within a phase. For example, where activities done by consulting engineers or designers can affect the safety in the execution phase or where the safety of a sub-contractor can affect the safe work of other contractors (see Figure 6). Consequently, other actors can affect the builder's overall responsibility for safety in a project. Thus, it is beneficial for all parties to work together to mature and develop safety management and performance in the industry.

It is therefore recommended to work with information sharing, not only within a project or a company but across the different actors and phases, thus having a broader approach towards safety. In addition, certain premises (see section 6.1.2) are recommended to be considered for collective safety-related information. Table 10 summarises the rationale and required resources for four main actions to further advance safety management in the construction industry. It includes a practical approach to obtain an expanded information base through sharing opportunities and getting a more holistic and integrated approach for safety management.

Table 10: Actions to advance safety management

Action	Description	Rationale	Required resources
1	Expanded information base	Collective information sharing from across the construction industry	Dedicated resources*, representatives from across industry actors
1.1	Stakeholder analysis	Which actors in the industry can benefit from what information and, what do they require from an expanded information base?	Dedicated resources*, representatives from across industry actors, researchers
1.2	Standardisation and a common understanding of taxonomy in the industry	To classify and structure data as a preparation for collection, storing, sharing, and utilising information across companies	Dedicated resources*, representatives from across industry actors, researchers
1.3	Establish criteria for the expanded information base	Criteria for information sharing and related practicalities, such as structuring of information, anonymity, access etc.	Dedicated resources*, representatives from across industry actors, researchers
1.4	Administration responsible	Place the administrative rights and authority to take decisions, maintain, develop and update the base	Dedicated resources*, representatives from across industry actors

1.5	Digital platform and data processing	Selection of a platform which meet required criteria and can handle the available information	Dedicated resources*, technical developers
1.6	Collection and sharing of information across the industry	A common understanding with regard to sharing requirements	Various stakeholders across the industry
2	Looking into practices from other industries	Are there practices in other industries with regard to safety or information sharing that can be useful?	Dedicated resources*, researchers
3	Safety as an integral part of all project processes	Acknowledge and embed safety as an essential part of other management processes	Management
4	Expanding the safety framework in practice	Use a joint safety approach by Safety-I and Safety-II for safety management	Management

*For example, an established group in the construction industry or a dedicated actor

Integrating safety more across corporate governance and management processes, such as in project management, requires management in companies to engage and understand the relationships between activities. To have an integrated safety approach, the different interrelations and how one process affects another, in this case, safety management processes, must be mapped, understood, and considered. In early phases, such as risk assessment, integration of safety using an expanded information base can detect potential risks that could otherwise be challenging to find. Furthermore, results from accident investigations can, through expanded information sharing, serve as input data for risk assessments in early phases, provide a knowledge base for early phase actors, and as modification requests to suppliers. Furthermore, project management aspects can be used to monitor aspects of safety management processes.

7.3 Significance, novelty and implications

The incident numbers presented in section 1.1 underline the importance of this research. Reducing the number of accidents is one of the industry's greatest challenges and require finding more innovative ways to safely plan and perform work for effective value creation and a sustainable industry. The evident practical impact of this thesis is the empirical research on sharing safety-related information and the emphasis on the importance of safety management development through integration and a more holistic approach.

The thesis provides reasoning for sharing safety-related information based on current practices and the potential to use them across project phases and actors. Based on the empirical results, the thesis provides practical suggestions to the industry on better utilising information through broader sharing. Traditionally safety management by experience feedback has been centred around unwanted incidents. Expanding sharing to other types of information can provide more input to safety activities throughout a construction project, from risk assessment in early phases to safety management in the execution phase. Furthermore, information is a medium to create knowledge (Nonaka and Takeuchi, 1995, p. 58). Acquiring information and knowledge, sharing and storing it, and using it for improvement are important input elements to the learning process (Drupsteen and Guldenmund, 2014). Although knowledge creation and learning are not direct outcomes of this research, the suggested recommendations and an expanded information base can provide input to the mentioned processes.

Another key theoretical principle in the thesis is understanding safety management as an integrated aspect of production. This is done by relating it to project management, on which there is limited research. In practice, most safety aspects are treated separately. Information sharing and an integrated safety approach can advance safety management and improve safety performance across phases and actors in the construction industry. For this to succeed, the information must be continuously used as input in risk assessments and to develop safety management. This can be achieved, for example, by using indicators based on other project processes that can foresee safety management effects.

For researchers and academia, besides empirical research, the emphasis on a combined safety theory brings novelty to the research. Traditionally, safety management by experience feedback has been centred around unwanted occurrences. Although theories state that Safety-I and Safety-II are complimentary perspectives (Hollnagel et al., 2015, p. 26), the focus of a combined perspective in scientific literature and in safety management practices is limited. The thesis highlights the relationship between Safety-I and Safety-II in the construction industry. The characteristics of the construction industry and the complementarity of the Safety-I and Safety-II theories advocate for a more joint approach towards safety in the industry. Also, regarding information sharing, there are opportunities to combine safety approaches and include practices, activities, mechanisms and tools that work well across the industry and industries.

The research is based on the context of the Norwegian construction industry, while the input to the research from academia is based on international research. Although the thesis itself looks at the construction industry in Norway, the results and implications are also relevant outside the Norwegian construction industry. Safety management and safety performance have the potential to further mature in the construction industry both in Norway and other places. Although the work execution, processes, tools, and safety methods vary across countries, many hazards are similar in the construction industry across countries. One example is the fall from height hazard, which is also high in other countries (Winge and Albrechtsen, 2018; Choi et al., 2019). Other hazards can be more location and condition specific. Nevertheless, with increased globalisation and commonalities across countries regarding technology, materials, tools, working methods, and the workforce, many aspects can influence each other and safety. This can also lead to more similar execution and safety hazards across industries. Furthermore, there is and will in the future be an increased potential to look to practices from construction industries across countries. This can either be from safety management developments or other types of conditions that can lead to new hazards and require specific safety management solutions. Examples of these are weather (heat or cold), migrant workers or the use of new tools, technology or working techniques like the use of wood, precast concrete, or robots. In this way, developments from the Norwegian construction industry can be of value in other countries as well. In conclusion, expanded information sharing and advancing safety by greater integration is a universal opportunity, not country-specific, to enhance safety management and performance.

8 CONCLUSION

The starting point of the thesis is the number of fatalities and reoccurring accident types in the Norwegian construction industry (see section 1.1). To further prevent accidents and thus contribute towards sustainable development of safety in the construction industry, the thesis has explored the advancement of safety management through safety-related information sharing and through a holistic approach in terms of integration of safety throughout a construction project and widening the safety approach in practice. Even though many correlations and connections are known on what influences safety at construction sites, further improvement is essential, especially with new trends and developments. Therefore, safety performance constantly needs to be improved to ensure it stays low and meets expectations.

The dynamic nature of the construction industry calls for a compound approach towards safety management. Various aspects and frame conditions affect safety in the sharp end. Therefore, measures that can enhance safety are required from the top to the bottom of the chain of roles. Safety management is a broad field encompassing several proficiencies, and no one factor or effort can make construction entirely safer. However, all efforts can collectively contribute to better safety. The findings from the presented articles offer advancement opportunities to parts of safety management which can contribute towards safer construction sites for workers.

The overall question for the research was *'How can incorporating additional inputs develop safety management in the construction industry?'.* Three articles contribute to answering this question through different approximations and three research questions. Together, they contribute as input for an expanded information base for safety management and advancing it through an integrated safety approach.

The first research question looks into *'What opportunities for safety management exist in broader information sharing across the construction industry?'.* Sharing safety-related information in the Norwegian construction industry is limited and mainly ends up in silos within a project or actor. This hinders improvement and broader access for practitioners (Kontogiannis et al., 2017). Through expanded information sharing, safety management throughout a project, from early phases to execution and factors outside projects, can be improved. Through an expanded information base, various actors can get input into safety-related activities, such as risk assessments performed by consulting engineers or designers in early project phases. Suppliers can gain more aggregated data, which can improve materials or tools. A broad safety-related information base covering cases from various trades, situations, project types and frame conditions grounded on data from various actors across project phases can be a blueprint for the whole industry.

It opens up opportunities to analyse and find relationships between factors affecting a hazard or activity. Thus, the varied information from across actors can provide insight into situations and conditions, which would be hard to find without aggregated data. Collected and sorted information can contribute to a better shared understanding of safety issues, methods, and measures across the industry. An expanded information base can be utilised in research to find new risks specific to trades or in general for the industry and improve monitoring and anticipation of risks in particular projects. This input can be used further to develop, for example, indicators for safety management based on a broad base of information from across the industry, which can help strengthen the relevance of the measures.

The second research question is *'How can the construction industry improve safety management by looking at practices from the Norwegian petroleum industry?'.* The second article focuses on industry characteristics and frame conditions influencing safety management and performance. Companies in the Norwegian construction industry have utilised many practices and implemented safety management tools from the petroleum industry through transferred experiences, e.g., by workforce changing industries. There is further potential to share information across industries, from what works well in one industry to looking into trends and developments, what risks they bring, and what mitigating actions are practised. Furthermore, safety in the petroleum industry is perceived as more mature, which provides the potential for the construction industry to look at this industry as a role model.

The third research question is, *'How is project management related to safety management in construction projects?'.* In the third article, a significant relationship between selected aspects of project management and safety management is found. On this basis, looking at other management processes, such as project management, is suggested to monitor and anticipate safety management. According to Ashby (1956, p. 212), information about the corresponding complexity and dynamics of what is controlled needs to be in place to manage a system and have control. The information can thus be used to diminish disturbance in the system. This implies that what is controlled is what is known. In other words, it is determined by experiences and shared information. Thus, a broader information base provides an opportunity for better management and control, for example, regarding hazards. This also implies that information from other project processes, such as project management, can be used for better hazard control and thus contribute to safety performance improvements. Two areas of possible relevance were looked at more closely; *teams and systems functioning,* with aspects related to project team members and system characteristics, and *leadership*, with aspects related to project leadership. Connecting aspects of project management and safety management is a way to advance safety management through an integrated safety approach. One point discussed regarding an integrated safety approach is acknowledging and practising safety aspects as a part of other project processes. The second point discussed takes the approach towards safety from a more theoretical point, recommending a broader safety approach based on both Safety-I and Safety-II perspectives to advance safety management. Such an approach allows for improved integration of safety into other project processes, and in monitoring safety management by using a more proactive perspective utilising aspects that go well in, for example, project management. However, this does not imply a replacement of the traditional Safety-I approach but rather a combination of approaches fitting the characteristics and dynamic conditions of the construction industry.

Improvement of safety management through information sharing is not the only solution to the reduction of safety incidents in the industry. However, it is a subset that can contribute to a better understanding of preconditions and situations and improved capturing of potential risks or errors based on more available and structured information. This can result in a better, more informed, open and transparent decision-making (Westrum, 2014), as broader information can facilitate decisions regarding change and improvement, including learning.

The thesis was limited to investigating information sharing, which can be a part of the learning process, but is not learning per se, and exploring an integrated approach toward safety management. However, there is a potential to utilise broader information for organisational learning. Furthermore, though the research contributing to this thesis is concentrated on the Norwegian construction industry, the results and recommendations can be relevant for other countries, given similar challenges concerning risks and framework conditions.

8.1 Further research

Compared to the Norwegian petroleum industry, the Norwegian construction industry is less mature regarding safety management, both theoretically and in formal practice. The traditional safety approach is prominent in formal safety management and safety management systems, although it holds some proactive elements. Also, safety is, to a large extent, managed as a sub-process, though it can influence and be influenced by various other business and project processes. In the following, further research is suggested to develop safety management in the construction industry and adapt it to societal trends and developments.

- Firstly, to succeed in having an expanded information base across the construction industry, there is a need to develop practical solutions for the industry. In terms of research, this involves understanding stakeholder needs regarding information, including all project phases and actors. Additionally, there is a need for a collective understanding across the industry regarding safety-related taxonomy. For this, one possibility is looking at taxonomy practices in other industries. Later, development and implementation can be combined with research through close interaction and collaboration with the industry. Finally, the outcome must be adapted to stakeholders' needs and thus prove useful in practice.

- Secondly, new trends and developments can increase construction industry risks, thus influencing safety management and performance. In this regard, other industries, such as the petroleum industry, can have practices of value for the construction industry. There is also further research potential to study characteristics and practices in other industries and look into what works well, which risks can be transferrable and which not, and why between industries.
- Thirdly, looking at safety-related processes as an integral part of other project processes is suggested. Further research needs are related to identifying which processes and aspects within specific processes affect safety management and safety performance and to what degree. The third article looked into aspects of project management, safety management, and safety performance regarding the number of incidents. More comprehensive data and in-depth studies should be performed to find more such relations and develop indicators for safety management based on data other than those directly related to safety.
- Finally, using more safety perspectives for safety management can help advance it, including also looking at practices that work well, for example in other parts of the business or production process. A joint approach looking both back at incidents, but also forward by anticipating possible disturbance is beneficial for safety management. Based on findings and available input data, leading indicators not based directly on safety-related data are suggested to be developed, tested, and put into use. An example can be data related to project management or specific project characteristics and use these as input to monitor and manage safety in a project. An important point in such work is to start with easily available and accessible data to set up potential indicators. Data collected in projects can be one source for such a data source. The data for this purpose should also be able to satisfy needs with regard to criteria for good indicators.

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PART II: COLLECTION OF ARTICLES

ARTICLE 1

Sharing Incident Experiences: A Roadmap towards Collective Safety Information in the Norwegian Construction Industry

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Sharing incident experiences: a roadmap towards collective safety information in the Norwegian construction industry

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Sharing incident experiences: a roadmap towards collective safety information in the Norwegian construction industry

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ABSTRACT
This article presents a study on sharing practices after incidents across organizations in the Norwegian construction industry as a means towards improvement of occupational safety. Interviews were performed with safety personnel from different actors, including clients, contractors and designers. The findings show that several arenas for sharing of safety-related information across actors exist; however, the sharing is limited, not structured, and occurs occasionally. Furthermore, the information is not widely shared across all actors in the industry for whom the information could be valuable, e.g., early phase actors. As a willingness to share and an excitement for new technology are present, the work goes on to propose how and where the industry can improve on information sharing after incidents to move towards inter-organizational learning. A roadmap for the Norwegian construction industry is suggested for collective information sharing with a focus on technological and digital solutions.

KEYWORDS
occupational safety; accident prevention; inter-organizational learning; safety information sharing; digitalization

1. Introduction

The past 5–10 years have shown stable numbers of non-fatal incidents in the construction industry in Europe [1]. Statistics from the Norwegian construction industry also show that the numbers of fatalities and incidents have stabilized and the improvement rate has flattened out in the past years [2]. Furthermore, the same types of accidents reoccur [3–5], where the three topmost common types in the years 2015–2019 in the Norwegian construction industry were fall, struck by object and cut by sharp or pointed object [4]. This repeating nature of accidents and the stable numbers indicate that a deeper learning is missing [6], and that safety-related experiences can be utilized better.

Experience feedback is an essential principle for improvement and learning to support the prevention of severe incidents [7], i.e., to collect and analyse data of past and present safety performance to support decisions on mitigation actions and to improve safety management. Since the number of severe incidents is relatively low, most construction companies experience a limited number of incidents that in turn limits the amount of available information in a company and the possibility to use the experiences for improvement and learning.

The industry is characterized by temporary project organizations consisting of different actors and companies working together on tasks with a time and cost limit. Actors may be simultaneously involved in multiple projects. The nature of the industry contributes to complexity, interdependencies between actors, where one actor creates a foundation for the next actor and one vocation can influence the safety of another vocation, and by this challenge safety work [8]. Complexity and fragmentation lead to blurred and nonlinear communication lines and information sharing [9]. Rather than keeping information in silos, which is often how teams in projects operate [10], the different actors can gain valuable information from other actors, enhancing the safety during construction. Although each project in the construction industry is unique, many processes are repeatable and can be learnt from for future projects [11].

Sharing and learning from incidents across organizations in the construction industry have large potential to help prevent future incidents [12]. The literature on learning from incidents is found to be fragmented, empirical and applied research is scarce and the step of sharing of safety information is underexposed [6]. Furthermore, the reviewed literature to a large degree focuses on information or knowledge sharing in an organization or within a project, and empirical studies on inter-organizational sharing and learning in the construction industry are limited.

This research addresses sharing of safety-related information across companies in the construction industry in Norway as one knowledge-enlarging way contributing to the reduction of unwanted incidents and accidents. The following research questions are framed: how is information after incidents currently shared across the construction industry; what gaps exist in the sharing processes between organizations; and how can collective safety information be obtained?

2. Exploring inter-organizational learning from incidents

Information can be described as a refined form of data which are relatively easy collected and transferred, whereas knowledge goes a step further, where the information is understood and applied by the holder. Nonaka and Takeuchi [13] distinguish knowledge from information by the first being about beliefs, commitment and action, and the latter to be necessary to create knowledge. The exact distinction between information and knowledge is often perceived as unclear [14]. In this article, the focus is on information sharing as an input towards learning and improvement.

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In the process of organizational learning, knowledge is created from experiences in the organization [15], and brings about change [16]. Learning from incidents is related to the organization's safety approach and can involve all levels as well as systems in the organization [17,18]. Experience feedback is an important process in safety management systems for prevention and improvement of safety activities, for safety performance [7] and for future safety planning [19,20]. Managing knowledge on safety is a key emergent issue for safety improvement, including continuous learning from past incidents [21], which require safety information as input.

Learning can also happen between organizations across the industry. The definitions of inter-organizational learning in the literature are related to creation of collective knowledge, e.g., knowledge acquisition and transfer (see Mariotti [22]). Inter-organizational learning has in recent years gained more attention in different fields to evolve companies in terms of innovation, effectivity and performance [23], but is limited for the construction industry and for safety.

Several models for learning from incidents in an organizational perspective are available (e.g., [18,24,25]). The steps in the models slightly vary, but mostly include steps related to collection and reporting, investigation and analysis, dissemination, and implementation and prevention (see Drupsteen and Guldenmund [6]). The steps are assumed to be similar in an inter-organizational learning perspective. These steps determine the effectiveness of learning after incidents [26,27]. Dissemination of investigation results is found to be a weak link with the potential to be improved [28]. Obtaining and use of safety knowledge in the construction industry is found to be more frequently discussed in the literature than sharing [29], but sharing of information and knowledge is a premise for learning. Drupsteen and Guldenmund [6] point to sharing and processing of information in learning from incidents as one of the main issues that need more attention, as applying lessons learned in new situations could make it possible to prevent other incident types. Also, storage and transfer systems for safety knowledge in organizations are found to be ineffective [30], while being a premise for experience feedback and to be able to serve as input to safety management in the next projects.

A model to describe inter-organizational learning in the construction industry is presented in Table 1, based on the orders of feedback and memory of control systems in complex systems by Hare [31] and the adaptation of it for safety by Kjellén and Albrechtsen [7]. Further, Jacobsson et al. [32] and Jacobsson et al. [18] have used a similar model for organizational learning. The model in Table 1 presents the different ways learning from incidents can take place across the construction industry and illustrates the importance of information sharing for inter-organizational learning.

On the lower level, experiences from an incident are shared within a project, e.g., from a contractor involved in the same project to a client. On the medium level, single or few experiences and incidents are shared across actors, either between a few actors (also across actor types) or several actors of the same type. A higher learning level indicates industry-wide experience-sharing across the industry. A fifth level could be added for learning across industries.

2.1. New technological solutions and integration of safety

Developments in information and communication technologies can integrate safety information better in existing tools and systems and make exchange of information across organizations become more feasible and useful. Many tools and technologies are available for safety, such as databases for collecting and extracting near misses [33], incident information for risk assessment [34] and tools for knowledge capturing, safety planning and training [35], but mainly within organizations. New technologies have the potential to be applied across the construction industry. Several technologies are suggested in the literature, such as artificial intelligence (AI), visual monitoring (VM), virtual reality (VR), simulations, augmented reality (AR) and building information modelling (BIM) [36–39], although not all for sharing incident information across actors. A literature review on construction hazard prevention through design shows broad possibilities for the use of BIM in safety, e.g., to link safety information with scheduling, product information and other technological solutions [40]. Although technology and solutions are developing, Hallowell et al. [39] found that the research is lacking a focus on how to access reliable safety information through more empirically driven feedback.

3. Method

This article is based on a qualitative research study, where interviews with actors in the Norwegian construction industry have been conducted.

3.1. Data collection and analysis

The interviews were undertaken with various actors from the construction industry concerning information flow after incidents and accident investigations. A semi-structured interview approach was chosen, where the interviewees were given the opportunity to comprehensively describe their views and new aspects which were not anticipated by the interviewer [41]. Tjora [41] points out that these types of interviews give the interviewees' subjective perspective; however, through many interviews it is possible to find phenomena within delimited areas.

An interview guide was created with the following topics: introduction, accident investigation procedures, results of accident investigations, information flow of the results, learning arenas, improvement potential and closing questions. The questions in the interview guide were adjusted to three different actor types.

In total, 13 interviews with 19 individuals working with safety at clients, contractors and designers (consulting engineers and one architect) were undertaken. Interviewees were recruited based on convenience selection, and through contact persons in the industry. Table 2 presents an overview of the interviewees. The interviewees represented 10 different companies. All of the interviewees were employed in large, professional organizations which are well established in the Norwegian construction industry (Table 2).

The interviewed safety personnel had a viewpoint from a company perspective, and not from specific projects. This gives more validity to the data as the responses are related to the routines in the company, rather than in a specific project.

Table 1. Levels of inter-organizational learning in the construction industry.

Level			Learning potential	Information sharing
	0	Organizational learning (no learning between organizations)	n/a	n/a
Lower	1	Learning within a project	Typically involves learning from local incidents within the project. Information is shared between actor levels and actors in the project. Mainly short-term memory limited to the project duration.	Information is managed and communicated through deviation processes within a project. Limited documentation, e.g., incident reports or entry in deviation register.
Medium	2	Learning from another project	Involves an actor sharing experiences with another or more actors independently of a common project, processed and implemented into the overall organization. Medium-term memory limited in the organization to relevance of the incident for the organization.	Informal or semi-formal sharing of information through dialogue or discussion during planning activities or other meeting arenas.
	3	Learning across similar actor types	Involves experience sharing between similar actor types, e.g., clients, contactors, etc. Medium to long-term memory through common grounds and understanding.	Informal or unstructured, e.g., dialogue meetings. Formal or structured, e.g., actor networks or associations.
Higher	4	Learning across all actors (industry-wide)	Experience sharing on an industry level across several actor types. Long-term memory in a commonly accessible system.	Informal or unstructured, e.g., conferences. Formalized and structured information, e.g., industry networks and associations, common groundwork.

Note: n/a = not applicable.

Table 2. Overview of interviewees.

Actor	Interviews	Informants
Client	2	2
Contractor	8[a]	10
Designer	3[b]	7

[a]One group interview with three interviewees.
[b]One group interview with representatives from five companies.

This also shows the variety across projects. Additionally, relevant documents on investigation practices and examples of information sharing were divulged by the interviewees. The data, especially sharing practices with other actors, were triangulated through interviews with different actor types.

The interviews were conducted between October 2017 and January 2018. Each interview lasted between 30 and 80 min. Most of the interviews took around an hour. Eight of the interviews were conducted in person, and five by phone. All of the interviews except one were recorded and transcribed. Detailed notes were taken for the interview that was not recorded. The interviews were transcribed and analysed with NVivo version 12. Preliminary analysis categories were taken from the interview guide, and later, while transcribing, new categories and sub-categories were added. In the next step, all of the interviews were gone through over again, using all of the established categories. This resulted in the addition of paragraphs to new categories, as well as restructuring. Thereafter, an analysis based on the final categories was performed. All of the data within each category were systematically analysed, which resulted in the findings.

All interviews were conducted in Norwegian except one which was in English. The citations from the interviews were translated into English by the author as close to verbatim as possible, albeit with a focus on not losing the meaning. Therefore, when necessary, to keep the meaning, some rephrasing was performed.

4. Empirical results

The focus of the empirical results is on information sharing after incidents across the Norwegian construction industry. The results are presented as three main topics: information sharing practices; potential of information sharing across the industry; and hindrances and promotors for information sharing.

4.1. *Practices of information sharing across the construction industry*

The interviews indicate that the arenas used for sharing of safety information in the construction industry include written information, seminars and conferences, groups and, to some extent, training. A large part of information sharing which occurs outside an organization is not formalized, and often takes place based on acquaintanceships. Moreover, it was found that information shared externally generally takes place on a management level (including safety personnel). Most of the information channels available are concentrated around clients and contractors (including sub-contractors). Table 3 presents an overview of the information sharing channels and recipients, as well as the potential inter-organizational learning level based on Table 1.

Information shared externally in written form included accident investigation reports and learning sheets, but no set routines for sharing between companies were found. When accident investigation reports are shared between actors, this often takes place within the project where the incident occurred, if the incident was relevant for more actors. In some cases, it was mentioned in the contracts from the client that the contractor needs to share incident data. Accident investigation reports were reported to be shared with the Norwegian Labour Inspection Authority (NLIA) and the police if requested. Otherwise, the authorities only receive limited information, which is mainly used for statistics.

Learning sheets, also called ‘one-pagers’, have become popular, and more and more companies are using these as a means for information transfer. The criteria for creating learning sheets are not standardized; however, they are usually created if an incident has learning potential, e.g., a near miss with high injury potential or a serious accident. The format is usually one A4 page, where the most important aspects of an incident with causes are summarized. Sharing within the organization

Table 3. Information sharing channels, recipients and inter-organizational learning potential.

		Actor				Learning potential
Type	Means of information transfer	R	CE	C	CO	Level
Written	Learning sheets	–	–	x	x	1/2
	Accident reports	x	–	–	–	1/2
Seminars and conferences	Yearly industry conferences, other conferences, e.g., the HMS conference	x	x	x	x	4
	Seminar/morning meeting after an accident organized by a company	–	–	x	x	2
	Seminars by the NLIA	x	x	x	x	4
Groups	'HMS Charter'/SfS BA	–	–	x	x	4
	Expert groups (consulting engineers etc.)	–	x	x	x	3
	Regional network	–	–	–	x	3

Note: C = clients; CE = consulting engineers; CO = contractors/sub-contractors; HMS = health, safety, and environment; NLIA = Norwegian Labour Inspection Authority; R = regulators; SfS BA = 'Working Together for Safety in the Construction Industry'.

where the incident occurred, or at the best across actors within the project, was found to be most common, but also examples of sharing across companies at projects were also found, e.g., through morning meetings among workers and supervisors.

Dissemination arenas outside companies included seminars, conferences and different groups, e.g., expert groups. Examples of conferences are those held by associations, such as the national conference 'HMS-konferansen' (health, safety and environment [HSE] conference) and other smaller seminars and conferences on specific topics. Some are only for members, while others are also open to all interested parties. Some companies have started to organize seminars or so-called breakfast meetings after specific accidents where they invite parties from the industry and use a learning sheet as the meeting topic. The NLIA also periodically holds seminars or workshops on chosen topics where the sector is invited:

> I think that the idea of learning sheets is very good. […] I was at a workshop at a client where they presented learning sheets after two blast accidents, it was great. (Safety manager, contractor)

It was also mentioned that regional networks exist, where safety managers from more than 20 companies (contractors) are present and meet several times a year. One of these networks has on a regional basis agreed to have the same requirements for sub-contractors on safety and a common standard for internal control.

In 2014, the 'HSE Charter for an injury-free construction industry' was established involving actors from clients, contractors, trade organizations, labour unions, authorities and academia. The Charter was working on initiatives and projects to improve safety. There were expert groups (e.g., for consulting engineers and clients) where, among other aspects, they created guidelines and checklists related to safety work. During 2018 and 2019 the Charter was developed into a network, 'Working Together for Safety in the Construction Industry' (SfS BA), which many of the interviewees believed in and had high expectations for. The goal of the network is to share experiences and work for a safer construction industry. SfS BA was established with inspiration from a similar network in the Norwegian petroleum industry (Working Together for Safety [SfS]):

> Eventually, we hope that the Working Together for Safety cooperation will become an arena where we actually share lessons learned. (Safety manager, contractor)

A challenge with information sharing across the industry mentioned was that the different actors in the industry have poor interaction and that meeting arenas are lacking:

> The contact between the consultants, the developer, and the contractor is poor. You know too little about each other, about each other's challenges. Then there are crashes where you deeply disagree, and you may end up in court. So, the construction industry lacks some meeting places where one can sit to discuss things before they happen, and preferably also after, such as the oil and gas industry has. (Safety advisor, consulting engineer)

On the question of whether some incidents were more suitable for sharing, many interviewees mentioned near misses. One reason is that in near misses there are aspects that can be learnt from without having negative consequences. Moreover, unwanted events often only focus on what went wrong, while for near misses it is easier to also look at what was done right and what should be continued. Incidents related to equipment were another example of incident type useful to share with other companies and suppliers, especially to modify or redesign equipment resulting in the whole industry becoming safer:

> Some incidents are suitable for workshops because the target group is relatively limited. If you take the incidents where there is a very large audience, then I think it can be good to establish collaboration for safety through a web page, where the information is available. (Safety manager, contractor)

4.2. Potential of information sharing across the construction industry

4.2.1. Inclusion of early phase actors

The consulting engineers themselves thought it would be beneficial for them to be involved in other project stages in relation to safety, e.g., in safety meetings and in accident investigation. They said that they were seldom included in accident investigations, seldom received results of investigations that they could learn from or seldom were otherwise included in information sharing that could improve safety, unless there were some calculation errors behind the incident. Also, contractors found information sharing to be lacking to earlier project actors. It was suggested that more attention could be given if an incident was related to the design by asking during investigations or in reports of unwanted events 'Did this have anything to do with design?':

> They have created some learning sheets for learning after the events, where they will try to look back. In the presentations that I have been to, they have not really managed to get back to the designers. They haven't figured out what more we could have done. (Safety advisor, consulting engineer)

One of the consulting engineers pointed out that information transfer is important to them to make better decisions in early phases and plan and design better for safety, as they are not able to understand risks in the execution phase as well as the executing actors. A specific example of an incident which was related to design was when choosing railing solutions. This decision needs to be taken prior to ordering the structural floors, as attachments are prepared and made ready to use in these floors. Another issue is that, in many cases, when the designers could have a bigger role in safety, they were not aware of it, as adaptations were done at the site to avoid hazardous situations, but never reported back to them:

> If we are to be able to see risks for the executors, the executors need to bring their knowledge into design. Otherwise, we will never be able to see such risks. (Safety advisor, architect)

4.2.2. Technology development as an enabler for information sharing

Several interviewees pointed out improvement areas for information sharing in the construction industry including new technology and the inclusion of more actors. It was mentioned that using new technology, i.e., three-dimensional (3D) models, can be beneficial for designers to communicate and receive feedback from later project phases:

> It has not come that far with safety in 3D yet, but it may be that it could be something if the models became interconnected. Then maybe we could get some feedback though that. (Safety advisor, consulting engineer)

Related to the phenomena of learning sheets it was suggested to have a common database for sharing of experiences between companies. A few interviewees suggested that the new safety forum in the construction industry, SfS BA, could be the place to organize such an initiative. At the same time, there was warning of an inflation of learning sheets, where learning sheets are created and disseminated but not used actively:

> I miss that we had experiences in a pot, by gathering the experiences in a common database. For example, to be able to see if there is anything we could have done differently in the design to avoid this incident. (Safety manager, client)

A possibility for safety was seen in BIM according to some interviewees; however, this is not prevailing in the industry. One interviewee stated that they were using BIM in the company, and that they had also tried to use it in one project for safety, going through safety aspects. The interviewee had a vision for the future where all projects use BIM, and rules for safety are available in BIM, so that already during design one can mark and eliminate hazards. Others mentioned the opportunities of AI and information sharing not only within the Norwegian construction sector, but also abroad:

> What I really believe in is when we start to get algorithms, or when we start to put AI on top of this, and that we can start to draw experience from thousands of construction projects, maybe not just in Norway, but also in all of Europe. Then it starts to get good. And it's coming. (Safety manager, contractor)

4.3. Obstructions for information sharing

4.3.1. Challenging frame conditions

Framework conditions of the industry were mentioned as a challenge for safety work. The rapid and constant changes were one of the challenges mentioned, especially compared to other more static industries, such as manufacturing. Moreover, aspects such as time pressure and progress were mentioned as hindering information sharing and learning combined with an underestimation of the potentials of incidents. Costs were also brought out as possible obstacles, e.g., how the sharing arenas will be financed, and who should bear the costs for participating. Another concern was related to how the industry is organized, with many companies in the project value chain, and thus whether it would work to create a forum similar to what is found in the Norwegian oil and gas industry:

> In the construction industry we now want to make something like the oil and gas industry, which is called Working Together for Safety. The disadvantage in the construction industry is that the clients do not have their own organisation. In oil and gas, you have the Norwegian Oil and Gas Association, which organises all the oil companies. They distribute a lot of information. (Safety advisor, consulting engineer)

4.3.2. Lack of standardization in taxonomy and reporting

Where systems for information management exist, they were often based on an internal system at one specific company. These systems often also seem to be used separately on different projects, meaning that there is often little or no connection between the information within the same company on different projects. Furthermore, definitions and categorizations regarding safety vocabulary flourish, whether in contracts, related to accident categorizations, when and what to investigate or indicators. Some companies use similar ones that they have agreed upon between the companies, others use definitions from associations, while others again have their own. To utilize available information and be able to share it across the industry, standardization and categorizations were mentioned as key elements. It was also perceived that the NLIA is not sufficiently precise in their categorizations and reports, e.g., what is meant by lack of planning as a contributing factor - if it is in an early project stage by consulting engineers or during construction by contractors.

Competence of safety personnel was found to be important for systematizing events, choosing events for investigations, during accident investigations, in analysis of events and for working with measures and proactive safety management. In the interviews, the quality of accident investigations was reported as a limitation for sharing and learning. Furthermore, it was pointed out that there is also a need for requirements for filling out documentation, so it is actually performed and information becomes available. It was suggested that a common template for the industry could be established:

> Often, we have forms to use, but then one skips to fill in some field, which could have been useful. So, it is about requirements and documentation. Filling in forms is probably not the most fun thing people know and it takes time. But you can see in hindsight, what the benefit of it is, because the human brain it doesn't remember very well. (Safety manager, contractor)

4.3.3. Willingness to share

The opinion as to whether the industry is open to sharing information, experiences and practices somewhat varied between the different interviewees. Many pointed out that the industry is very open for this, and that safety is not what they compete on:

> I have attended the HSE conference for many years, and I think that it is sort of a characteristic for the largest [companies], that they are very good and generous when it comes to sharing. That is not point we compete on. (Safety manager, contractor)

Some, however, had the opposite viewpoint, where safety was looked at as a competitive advantage and also related to reputation. A client gave an example where after an accident, information about a contractor was put into a supplier database, which resulted in the company not getting a tender another time and therefore having to do improvements before they were qualified again. It was mentioned during the interviews that some interviewees had experienced legal charges based on the accident investigation reports. This was said to affect what is included in the reports:

> When we investigate, we have burned our fingers a couple of times, because the investigation report has been used as a basis for a prosecution. All injuries in the workplace are punishable under the Working Environment Act, and if you then have some available work capacity with a police lawyer, then our investigation report is the whole basis for the prosecution. So, we have managed to incur a couple of fines due to investigation reports. (Safety manager, contractor)

The results point to some regular weaknesses with regards to information sharing, but they also highlight opportunities for collective safety information for the construction industry which will be discussed in the next section.

5. Discussion

Experience feedback is important for the learning process and accident prevention [7,24], but sharing of information after incidents across actors is persistently weak. The study shows the following:

- several arenas for sharing safety information in the industry exist (Table 3), but they are predominantly unstructured, approaches are unformal and sharing is limited to few actors;
- characteristics of the industry contribute to fragmented information sharing and are one of the main roadblocks foreseen for collective safety information;
- taxonomies and reporting processes after incidents are not standardized, challenging information sharing and inter-organizational learning after incidents;
- a willingness to share safety information amongst many actors in the industry exists and achieving collective safety information is seen as an advantage for the whole industry;
- there is excitement in the industry for new technology and how technology can help to facilitate structured and effective information sharing.

These aspects are further discussed across this section and finally a roadmap to achieve collective safety information in the construction industry is proposed.

5.1. *Collective safety information for the construction industry*

Although accumulated experiences of the actors are far more comprehensive than within a project or a company, there is still a deficit to transfer information across actors other than to those directly involved in the incident. As inter-organizational learning is based on the experience of one organization [15], the limited sharing is preventing learning and safety improvement across the industry.

The results from this study show that majority of the shared safety information is shared through arenas that contribute to inter-organizational learning at lower and medium levels (see Tables 1 and 3). This means that the majority of information sharing happens within projects or mainly between similar types of actors, and the information sharing is not contributing largely to the industry-wide learning potential and safety improvement. Some arenas for information sharing on a higher level exist; however, such sharing is rather unstructured and non-systematized, and the numbers of actors receiving such information is small, as these channels are not frequently used. To facilitate inter-organizational learning, safety information after incidents as input to the medium and especially higher levels is needed. Earlier studies from other countries have found similar weaknesses with external information sharing in the construction industry. A study from the USA found sharing to be limited to written materials from regulatory agencies, and oral material through meetings organized by associations [30]. In the UK construction industry, a lack of systems to transfer experiences across projects to clients and their supply chains was found [21]. It is also reported that available collective safety information from authorities, agencies and other existing records is unstructured and fragmented, and the content is limited in its thoroughness [34,36,42].

Early phase actors such as designers and consulting engineers in this study expressed a need for more safety information back from the building phase, indicating a need for broader information sharing also across project phases. Earlier research show that designers can influence safety early in a project through the decisions they make [43–47], and lack of information sharing across projects is a barrier for hazard identification as information is not available [34,39]. Some attempts at practical information and decision support for designers exist (see Cooke et al. [48]); however, in practice in the Norwegian industry, few feedback mechanisms were found. The lack of information sharing back to early-phase actors (e.g., consulting engineers and architects) is thus hindering inclusion of solutions in early project phases, which could improve safety during construction.

Stagnating accident numbers [1,2], interrelations between companies in projects [8], new developments and evolving risks require advancements in safety work. Achieving systematic inter-organizational learning through collective safety information is one possible solution. Collective safety information may be seen as a shared register of incidents. Increased sharing of safety information across the industry gives a broader experience base through the greater collection of data, which can be fed back to various actors. This can improve and help decision-making and increase learning opportunities for different actors and companies, and serve as an input to proactive safety management throughout project phases.

The objective is that collective safety information should be available to all relevant actors. There are, however, several potential challenges to collective safety information, many related to the characteristics of the construction industry, including the actor types, number of actors of different size, several phases influencing risks, various risk types between vocations, projects with constant changes, time pressure and costs. Information needs to be understood, accessible and relevant for the receiver, whether a small or large company. Having basic knowledge and similar problems and structure to another organization are beneficial with regards to learning between organizations [49]. For learning from past safety incidents, it follows that a common safety understanding, having a similar structure and sharing information are important.

5.2. Willingness to share

A premise for safety information sharing, and thus collective safety information, is the willingness to share information by actors. The empirical data point to an opportunity for cooperation and sharing experiences across the industry, and importantly a quite large willingness to improve on safety through sharing experiences. Even though some possible inconveniences were pointed out in the interviews, such as prosecution, many of the larger companies, both clients and contractors, have realized that they are dependent on the safety performance of their sub-contractors, and thus need to contribute to pulling the smaller companies up. It was also highlighted by most of the interviewees that safety is not what the companies compete on, and that everyone is served with good safety in the industry as one actor can influence the risks of another actor.

Positive steps are taken through knowledge areas, showing that there is a demand for safety developments in the industry, as well as a willingness to learn. One example of the willingness to share experiences is proven by the establishment of the SfS BA collaboration, inspired by the Norwegian oil and gas industry, where actors across the industry work with specific problems to improve safety in the whole of the Norwegian construction industry. The collaboration has established project and working groups across actors in the industry, trade unions and academia on specific topics [50].

Although there is positivity towards sharing safety information, protection of information could be a concern with regards to sharing, as found in other fields [51]. Factors such as blame, shame and prosecution can limit the willingness of information sharing by individuals [52]. These factors are also relevant for sharing across organizations, e.g., incidents can affect a company's reputation and competitiveness. A company which had experienced that the sharing of accident investigation reports resulted in some negative consequences such as fines was more aware of what they included in the next accident investigation reports and more reluctant to share reports. On the contrary, trust has been found to be an important factor to enhance sharing [53,54]. Also, the interviews implicitly show that trust is an important factor for willingness to share.

5.3. Roadmap towards implementation of collective safety information

Information sharing across actors is a premise to facilitate the higher levels of inter-organizational learning with regards to safety, and to contribute to proactive and predictive functions for safety. The complexity of the construction industry requires a more holistic course of action for safety management including interactions between systems, people in the organization, procedures and sub-cultures existing [21]. Collective safety information can be a means for this. The potential for sharing experiences across the industry is increasing with digital and technological developments, which can also allow for a better integration between other managerial systems and safety. To move towards collective safety information, a roadmap for the Norwegian construction industry is proposed based on the results, summed up in Figure 1.

The figure illustrates the path towards collective safety information and the means to reach it at each step in an iterative process regularly being updated with new data, as well as a periodic validation of the taxonomy.

5.3.1. Identify user groups

Relevant user groups need to be identified and recruited for development and small-scale testing towards collective safety information through, e.g., available networks. The process is iterative, where more actors and companies can be incorporated as the system develops. The start should include actors from the execution phase, such as contractors and clients, where data can be collected. In the final stage, actors across project phases should be included, especially for dissemination of information, such as designers in early phases as well as other actors in the executing phase. It is also relevant to involve trade unions and labour inspection authorities in the dissemination process. Including a wide range of actors will directly respond back to the empirical findings and the need for better involvement of actors across project phases, who expressed a need for more safety information back from the execution phase.

The challenge is to ensure that the results and means of dissemination are relevant and accessible for companies in the whole industry. Not all accident types are relevant for all vocations or activities, and a sorting possibility differentiating the needs and to access relevant information is required. With digital solutions, sharp-end workers can also access relevant information, through tools such as smart phones and apps [55].

5.3.2. Standardized entity typing

Standardization was mentioned by many of the interviewees as being important for information sharing and the further utilization of it. The taxonomy regarding safety in the Norwegian construction industry and use of the definitions needs to be structured and standardized for collective safety information. Technical vocabulary requires language models to describe work tasks and tools [56]. Type classifications for activities, incidents, causes, contributing factors, damages and application areas need to be agreed upon centrally in the system to categorize and systematize the ingoing information. This can further enhance the value of the output data returning to the industry and serve as an input in safety management across project phases and companies in the industry. Existing work related to machine learning models for safety performance can be used including factors for input and sub-factors, e.g., categorizing risk management during execution, work systems in the projects, project management, external conditions, etc. [57]. Furthermore, use of the same incident causation models can also uplift the feedback process and make the information transfer smoother [20]. Similarly, the lack of standard processes between the different organizations involved in projects can challenge learning from incidents [11]. This does not mean that all actors need to use the same systems or categorizations internally; however, to analyse the information collectively, it should be classified in the same manner. Also, Le et al. [58] highlight the need for an ontology to classify and structure the safety information. Such taxonomy can be built upon already established classifications used by, e.g., the NLIA or other actors in the industry. Through a common

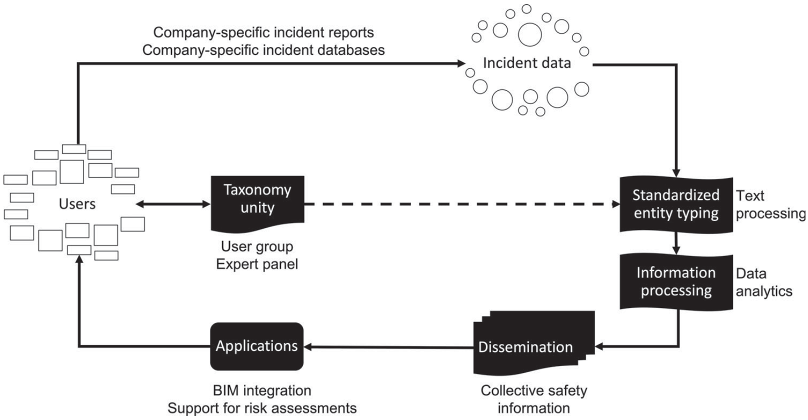

Figure 1. Roadmap towards collective safety information in the construction industry. Note: BIM = building information modelling.

initiative, a taxonomy for collective safety information should be established.

Systematization and standardization are also premising the use of new technology and digitalization. Ouyang et al. [59] point out the lack of standardization as a challenge to obtain useful information, and low integration between data stored different places as a challenge with big data in use for safety. Almklov and Antonsen [60] argue that there is an increased tendency towards detailed standardization in safety science, where digitalization is a catalyst for this. Although standardization might not necessarily be beneficial for sharing of information in all situations [61], in an inter-organizational perspective, more standardized definitions, categorizations and practices within the industry could enhance sharing and cooperation on safety aspects.

5.3.3. Technological solutions for information processing

The benefit of ensuring a wider and structured experience collection is that the experience base becomes larger with more possible hazards and the information becomes less biased. In the past, storing safety information in databases has been common, although mostly internally, and the use of the databases for safety prevention has been seen to be limited [24]. New technological applications provide the opportunity to ease collection and make information widely accessible, which can be beneficial for safety management across actors and phases in the industry. The results show that few new technologies and solutions are commonly in use for safety management throughout construction projects in Norway, and lesser for experience sharing from incidents and to feed information back to safety management.

The collected information needs to be structured and analysed to later serve as an input for other tools. Technology can be used to extract data from written injury and investigation reports [62,63]. One example is applying machine learning, making such extraction processes and labelling of incidents easier and less time consuming [64]. Recently, scientific literature on machine learning and safety has grown also for the construction industry. A review by Sarkar and Maiti [65] shows that the scientific papers among others analyse patterns of accidents, predict accident outcomes and severity, and predict injury risk. Examples from other industries show how use of natural language processing can be used in operation planning to consider safety-relevant aspects based on multiple data sources and reducing the dependence on individual experience [56]. Brundage et al. [66] promote technical language processing as an evolvement of natural language processing to serve for technical descriptions in industry with domain-specific adaptations, where the human is a part of the processing loop, to reduce errors in the text analysis. Similarly, errors can occur in pre-processing and analysis of incident information, and the suggested human-in-the-loop approach can ensure validated information to be shared and as an input to, e.g., risks assessments in early phases or safety management during construction. Also, other text classification models have been developed for classification of near-misses from safety reports [67]. As technology and models are being continuously developed, improved and validated, the way towards collective safety information for the industry is shortened.

5.3.4. Dissemination of the processed information

The fast developments in technology also bring about smoother opportunities for information sharing. In the literature, different tools have been suggested to centralize safety information for risk assessments, safety planning and training [34,35,58,68]. Le et al. [58] proposed a social network platform using a wiki-web solution for sharing health and safety information. Hegde et al. [68] proposed the use of blockchain technology as a solution for operational follow-up of safety instrumented systems to enable the exchange of failure information. Through blockchain technology, information can be anonymously and securely exchanged. This decentralized platform between multiple actors also makes it possible to restrict access to selected information, e.g., sensitive information [68]. For the construction industry, such application could gather safety information towards collective safety information, as well as feed safety systems with reliable experience data back from the collective safety information. Relevant information can in this way be shared across project phases and actor types without overloading other actors with irrelevant information. Such information can further be used as an input in other digital solutions, such as BIM. Potential challenges with the aforementioned options need to be considered and solved, such as the possibly vast amounts of data, which require a great deal of storage space [68].

Greater use of BIM for safety was a future hope from some interviewees, although it is evident from the data collection that use of BIM for occupational safety is not yet common in the Norwegian construction industry. In Norway, more clients are starting to use BIM throughout the lifecycle of their projects, but far from all. One example of connecting BIM and risk management in practice is through the RiskBIM project in the Norwegian railway, aiming at supporting, among others, safety, health and working environment processes in BIM [69]. Hallowell et al. [39] highlight the possibilities of integrating incident information processes through machine learning algorithms into BIM and forecast safety-related outcomes. This can be used to communicate safety concerns from designers or planners downwards to the sharp end (construction managers and work crews). Although research describes possibilities using new technology, the examples from Norway show that in practice it is not much in use.

Similar tools to the outlined exist within companies or corporations, compiling information from different databases and different projects [57]; however, in practice they only contribute to internal information sharing. An example from the petroleum industry shows the potential of compiling information across several data sources into one interface, making the information more accessible and visualizing it for the operation planners [56]. Possibilities include barometers for the industry or for trades indicating the safety level. In an inter-organizational perspective, such information can be useful also across actors, including authorities, clients and contractors.

The described outline gives an opportunity for expansion of tools and possibilities towards inter-organizational learning, and to share experiences also with smaller actors with less accumulated experiences to improve safety for the whole industry.

5.3.5. Establish use cases

The progress towards collective safety information should start with involving selected users in the processes in Figure 1. The starting point is to agree upon an industry taxonomy and classification which are understandable in the industry. This step is highly important at the beginning of the work towards collective safety information, but it should also be updated and verified with time. A group of users should be involved in the steps of collection, processing and dissemination of safety information to develop a model. The same users or additional users then apply the available information through application pilots. Once the developments progress and the content of the collective safety information expands, the number of involved users can be expanded. The aim must be to have relevant and available information for all potential users, to contribute to proactive safety management. It is important that user needs and the collected data are verified and updated to remain relevant, through the taxonomy and application processes as a sub-process parallel to the main collective safety information process.

Furthermore, based on the collected information, further potential applications can be developed, e.g., proactive safety indicators or safety level barometers overall for the industry, which can further service as input to processes such as industry initiatives on specific topics.

6. Conclusions and further research

The construction industry as a whole experiences a large variety of incidents. However, the experiences within a project or a company are far smaller than the accumulated experiences across projects and actors. Comprehensive data provide an opportunity to better understand the possible scenarios and factors affecting safety, and the potential to improve safety during construction through capturing the broadness of the different types of incidents that can occur. This study has looked closer at one activity of the learning process: sharing of information from past experiences, as a means towards safety improvement. Dissemination of experiences has received less attention in the scientific literature compared to other activities of the learning process [6,30].

The literature on learning from incidents is to a large degree dominated by traditional organizational learning, not largely considering learning between projects and organizations. Le Coze [70] suggests more cross-disciplinary research on learning from accidents. This study adds to this through information sharing in an inter-organizational learning perspective.

To move towards collective information sharing, and thus better utilize the available safety information and through it improve safety at construction sites given the framework conditions of the industry, present obstacles related to information sharing need to be investigated further and resolved. These include limited availability of good data to share, lack of standardization, need for interdisciplinary competence in safety and technology, blame and trust issues, and the ability to customize information to users' needs. Several possible technologies and solutions are described in the literature, but there is a gap between research and practice for such sharing on Norwegian construction sites. Finally, this study proposes a roadmap towards collective safety information.

More studies on practical applications for sharing within the industry and evaluations on how these applications affect inter-organizational learning are needed to further improve safety of the construction industry. Based on the roadmap, a pilot for collective safety information can be established.

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Data availability statement

Data supporting the findings are available within the article. Additional data are not publicly available due to the nature of this research.

Informed consent statement

The Norwegian Centre for Research Data (NSD) was notified about the project, and informed consent was obtained from all interviewees.

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ARTICLE 2

Why Is the Construction Industry Killing More Workers Than the Offshore Petroleum Industry in Occupational Accidents?

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Article

Why Is the Construction Industry Killing More Workers Than the Offshore Petroleum Industry in Occupational Accidents?

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Abstract: In Norway, the fatal accident frequency per year is discernibly higher in the construction industry than in the petroleum industry. To probe the difference between the occupational safety levels in the two industries in Norway, semi-structured interviews with regulators, employer and employee organisations, company management, and safety personnel were conducted. This qualitative approach, together with factual industry information, offer invaluable insight on various elements influencing occupational safety. Rasmussen's socio-technical model is used to sort the information and compare framework conditions, characteristics and aspects of the two industries influencing safety. Though the construction industry's safety level has improved over the years, the results indicate that the petroleum industry's safety level is still considered superior to its counterpart. The interviews point to major accidents and regulations as important for safety development in the petroleum industry. Thorough planning of operations, stricter rules, more standardised procedures and requirements, and fewer actors in the petroleum industry are also highlighted. The results of this study further reveal that safety in the construction industry has benefitted from safety developments in the petroleum industry. There is potential for more learning across the industries, in particular from petroleum to construction with regard to standardisation, barrier-thinking, and knowledge-sharing.

Keywords: framework conditions; construction; petroleum; fatalities; occupational safety; Norway

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1. Introduction

Between 2000 and 2020, 160 occupational fatal accidents occurred in the Norwegian construction industry, against only eight in the Norwegian petroleum industry [1]. However, looking back at the first two decades of operation of the offshore petroleum industry in Norway; i.e., the 1960s and 1970s, statistics show that the injury and fatality numbers were much higher, decreasing significantly over the years [2,3]. In the construction industry, injury and fatality numbers also have decreased greatly since the 1960s and 1970s, but not nearly as much as in the petroleum industry (see Figures 1 and 2) [1,2,4,5]. The two industries operate in different environments and with different risks; nevertheless, a fatality is as unwanted in one industry as in the other. These developments, the fact that the petroleum industry is a locomotive for safety in Norway, and the two industries often being compared without a structured or scientific approach are motives for a comparison of the occupational safety between the two.

Figure 1 shows the occurrence of fatal accidents between 1970 and 2020 for both the industries, and the average number of fatalities over a 10-year period [1,4]. The petroleum industry has only had a few fatal accidents since the 1990s, as compared to the construction industry, in which the number of fatalities is still high. Figure 2 shows the yearly fatality rate per 100 million working hours in the two industries with 10-year averages [1,5,6]. Although there are uncertainties related to the numbers, such as reporting quality and coincidence regarding the outcomes of accidents, they give a pointer to the safety levels in the two industries.

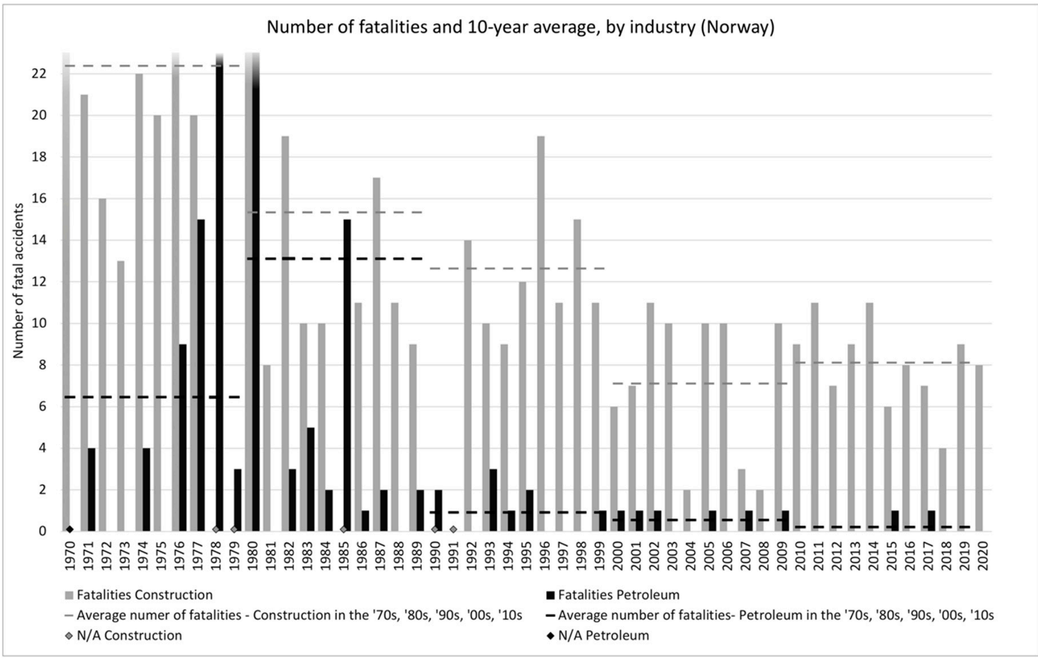

Figure 1. Number of fatalities in the Norwegian construction and petroleum industries and 10-year averages for 1970–2020 (excluding helicopter accidents) based on total hours worked for employees and self-employed in construction and oil and gas extraction, excluding services (from Statistics Norway (SSB)) [4–6]. The rhombus points indicate missing values, N/A—not available (1970 for petroleum, and 1978, 1979, 1985, 1990, and 1991 for construction). The values for 1970, 1976, and 1980 for construction, and 1978 and 1980 for petroleum, are beyond the range of the graph.

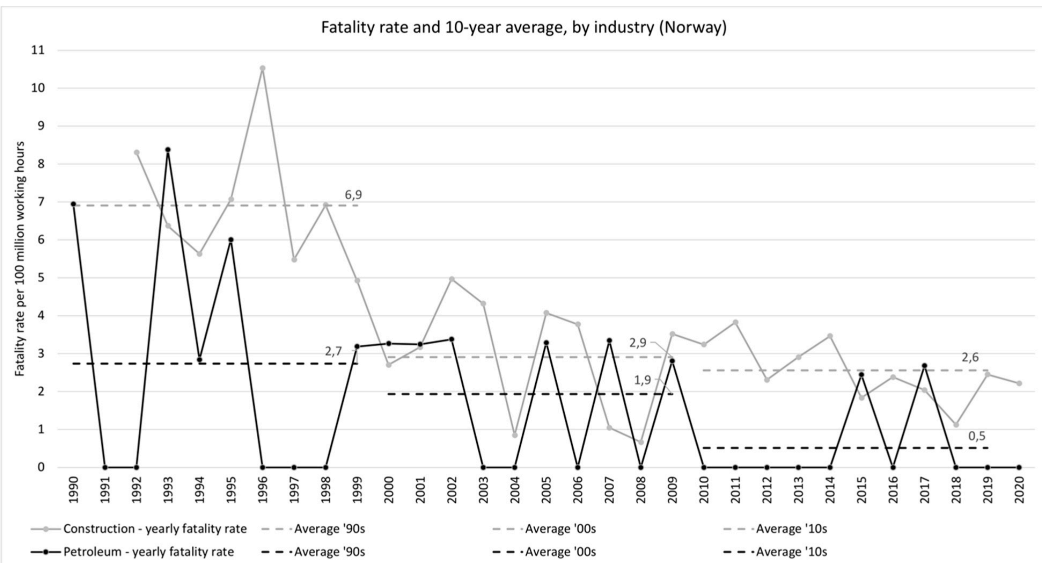

Figure 2. Fatality rates per 100 million working hours for the Norwegian construction and petroleum industries for 1990–2020 (excluding helicopter accidents). Values for 1990 and 1991 for the construction industry are missing. The graph is based on fatality numbers and working hours from SSB [1,5,6].

Many of the occupational accidents that occur in the two industries are of similar types. Among the most frequent accident types leading to injuries in the Norwegian construction industry are fall accidents, contact with a falling object, and contact with moving machinery parts [7], of which, being struck by a falling object, being in/on a vehicle that has lost control, and falls from height led to most fatalities between 2011 and 2017 [8]. Since 2000, fatalities in offshore petroleum have been related to a person being struck by an object, falls from height, and a facility being struck by a wave [9–13]. Data from the UK show that between 2012 and 2018, offshore accidents related to slips, trips, and falls (from same levels and height) and being struck by moving object accounted for more than half of all reported injuries with major or fatal severity [14]. In Norway, the Petroleum Safety Authority Norway (PSA) focuses largely on accidents related to crane and lifting operations and on falling objects through their defined situations of hazards and accidents [15].

An analysis of construction accidents in Norway in 2019 points to actions and behaviour, operative management, and risk management as the most frequent and important contributing factors to the accidents [16]. Barrier-control approaches similar to those in offshore petroleum, implementing multiple physical barriers to control a specific hazard, is identified as a potential approach for accident prevention in construction activities [7]. In petroleum, failures in operational barriers contribute to a large number of accidents [15]. In addition, management styles and trust in management have been found to be important for personal injuries in the petroleum industry [17]. A focus on factors related to work systems, project management, and higher management, as well as framework conditions, can give further insight into root causes influencing accidents and safety [18].

Though a direct comparison of fatality numbers between the two industries can be misleading, similarities in the nature of occupational accidents, and differences in improvement over the years between the industries, are interesting to note. The objective of this study is to explore how the petroleum industry has manged to improve on safety, and what it can mean for the construction industry. Understanding how different factors have affected and currently affect safety in each of the industries can help to identify what limits construction from improving safety and operating sustainably without harm to people. The United Nations emphasises the importance of promoting safe and secure working environments in their sustainability goals (No. 8) [19]. Furthermore, accidents not only result in human, environmental, and material losses, but they can also influence progress and the economy [20]. A good safety performance also is likely to contribute to success in other operational aspects [21], and thus lead to sustainable value creation.

The purpose of this paper is to explain factors behind the differences in the number of occupational fatalities of the two identified Norwegian industries by answering the following two research questions: (1) What effects do industry characteristics and framework conditions have on the level of safety in the two industries? (2) What learning points from the petroleum industry can contribute to improvement of safety in the construction industry?

Characteristics, framework conditions, and safety developments of the two industries were explored through qualitative interviews, supporting literature, and reports. A total of 36 interviewees distributed equally between the Norwegian offshore petroleum industry and the Norwegian construction industry provided their valuable inputs for this research. Several of the interviewees currently in construction had experience in both industries.

The differences between the two industries were studied using a systems perspective, giving insights on each industry's generic underlying conditions and their influence on safety. Rasmussen's socio-technical model involved in risk management [22] (Figure 3) was applied as a starting point to systematically structure the influences on safety from policymakers down to the sharp end. To the authors' best knowledge, no previous studies have compared the occupational safety of these two industries in a Norwegian context.

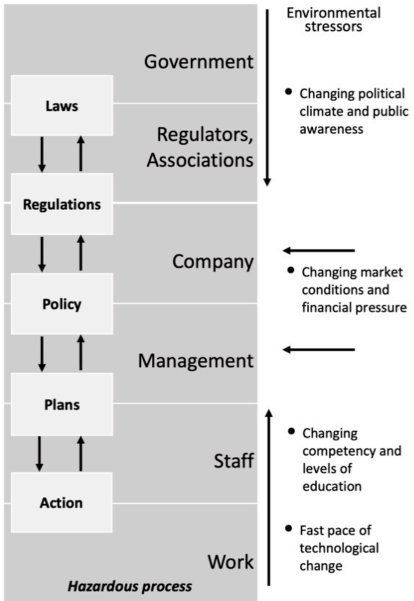

Figure 3. Simplified model of Rasmussen's socio-technical system involved in risk management [22].

Theoretical Framework

Rasmussen's aim of the model was to demonstrate how levels, disciplines, and factors, both external and internal, can influence and control or trigger accidents in a work process [22]. The model has been frequently cited, and its popularity can be attributed to its generic and holistic perspective, which makes it relevant and applicable for most industries. The simplified version of the model in Figure 3 shows how the different stakeholders are arranged according to their distance from the hazardous process—with government at the highest level and farthest from the hazardous process, and the staff closest to the work process and to the hazard. At the top, society seeks control of hazardous processes through the legal system, while on the next level, the legislation is interpreted and implemented by rules to control activities by regulators, industrial associations, and workers' unions. Next, the regulations are interpreted and implemented in company-specific policies. Within the company, the company policy frames management plans and actions by managers and workers to control hazardous processes. Different environmental stressors are shown to the right in the figure. From a safety perspective, such stressors, also called environmental conditions, can be defined as *"conditions that influence the opportunities an organisation, organisational unit, group or an individual has to control the risk of major accidents and working environment risk"* [23] (p. 1967). Rasmussen especially had a focus on organisational and managerial aspects in his model [24]. By this, the model shows the importance of a wider approach across disciplines, including feedback loops running upwards in the hierarchy, being a key to ensure that the levels have knowledge about the safety performances at lower levels as input to modifications of control mechanisms. These are factors that contribute to risk management in a dynamic society.

One of the merits of the model is that it identifies the different actors' contribution and links to safety at the sharp end, which makes it suitable as a framework to compare the construction and petroleum industries. Although it is popular, Le Coze [25] has pointed out some weaknesses in the model, such as linear and hierarchical connections between the levels, which in reality do not need to follow the level structure. However, the model adds depth to the comparison by including a wide range of aspects, and gives a visual overview of the different elements affecting safety in the two industries. It also places safety in a macro perspective and embraces cross-disciplinary research [24].

2. Characteristics and Framework Conditions of the Two Norwegian Industries

2.1. Accident Numbers

The first fatality in the offshore petroleum industry in Norway was reported in 1967, and the largest accident on the Norwegian Continental Shelf (NCS) happened in 1980, when the semi-submersible Alexander Kielland platform, a flotel, capsized and claimed 123 lives [26]. Since 1981, occupational accidents have dominated as a cause of fatalities, rather than major accidents (such as the Kielland accident) [15]. In the industry's early years, the fatal accident rate per 100 million working hours for fixed facilities was around 230, and from the mid-1980s through the 1990s, stabilised at around three [2]. For mobile fatalities, the value was around 100 in the mid-1970s, and fell to 14 in the mid-1980s and remained around that level until 1998, when it started decreasing further [2]. For both types, fatal accident rates, from an average of above 100 per 100 million working hours, greatly improved to 3.3 in the 1990s, and further to 0.5 in the period of 2016–2020 [15].

The petroleum industry has experienced more fatal accidents related to transportation, with one recent example being the Turøy helicopter accident in 2016, which claimed 13 lives. However, in this comparison, transportation accidents were excluded, as the focus was on occupational accidents during work activities with the PSA and the Norwegian Labour Inspection Authority (NLIA) as regulators.

There has also been a reduction in the number of injuries occurring since reporting started in 1978 and 1990 for production and mobile facilities, respectively [2]. The number of personal injuries per million working hours for production facilities decreased from around 30 to 40 in the 1980s to 25 in the 1990s [2], and further to around 7.3 in 2010 and to 5.0 in 2020 [15]. For floating facilities, the number of injuries per million working hours was between 31 and 35 in the 1990s [2], and declined to 5.8 in 2010 and 3.9 in 2020 [15].

For the construction industry, the average number of fatalities per year between 1967 and 1976 was around 25 (ranging from 13 to 43 fatalities per year), which translates to around 11.7 fatalities per 100 million working hours [4–6]. In the years 2000–2019, there were, on average, eight fatalities per year (between two and 11 per year), with around 2.6 fatal accidents per 100 million working hours [1,27]. The reported number of injuries in the period 1967–1977 was, on average, 18.5 per million working hours (around 3500–4500 reports per year) [4,5], whereas the average between 2014 and 2019 was more than halved, to around 7.9 per million working hours (around 2600–2800 reports per year) [27]. The construction industry has seen a great improvement in occupational safety. However, there is still a large scope for improvement.

2.2. Work Characteristics

The petroleum and construction industries are different in many ways, including in terms of age, size, and value creation. While the construction industry has nearly always existed, the first production licences on the NCS were given out in the mid-1960s, the first exploration well on the shelf was drilled in 1966, and the first production started in 1971 [28]. The difference in size between the two industries is significant with the construction industry in Norway employing around 10 times more persons than the petroleum industry (based on employees and self-employed, excluding services)—246,400 and 24,500 persons, respectively, in 2020 [5]. The exposure in terms of worked hours is important to consider when comparing accident statistics of the two industries. Estimated workforce offshore in 2017 was 25,000 employees (including the service and supply industry) [29]. An even more substantial difference is in the number of establishments. In the petroleum industry in 2020, there were 24 operators and 13 companies with production licenses [30], and additionally over 1100 suppliers and sub-contractors supporting tasks such as service and maintenance (but not all offshore) [31]. In the construction industry, most of the almost 69,000 (per 2020) establishments were small, with 91% having less than 10 employees each. Close to two-thirds of all the registered companies were one-person firms, and only around 1% had more than 50 employees [32].

The construction industry is project-based, and there are many variations within projects that affect daily operations, including project size, company size, contract practices, and private versus public clients. Having a complex project organisation is found to create significant health, safety, and environment (HSE) challenges [33]. When it comes to safety, the petroleum industry is exposed to major accident risks (i.e., accidents killing more than five people) in addition to occupational accident risks, which affects how all activities are carried out. In the construction industry, the risks are closely related to specific work activities and are mainly occupational. In this paper, safety is compared in two different project phases: for construction, it is during building, and for petroleum, mainly during offshore operations.

2.3. Regulators and Regulations

Different authorities supervise safety in the two industries, the PSA and the NLIA. These two authorities have very different fields of operations, regulations, and resources. The PSA, in 2020, with 180 employees, was responsible for supervising 80 permanent installations and around 60 mobile units at the NCS, eight major land-based plants, and several subsea installations and petroleum pipelines [34]. The PSA primarily uses dialogue as a means of supervision, although they also make use of other strategies such as notification of order and, in more severe cases, requiring a shutdown of operations until the safety issue is resolved. The PSA's regulatory performance-based approach encourages the adoption of industry standards and best practices [35]. PSA is also responsible for the monitoring program known as the "RNNP" (trends in risk level in the petroleum industry), which is a collaborative effort that results in yearly reports measuring the impact of HSE work in the industry [36].

The NLIA is the supervising authority for all other land-based enterprises in Norway, spanning large international firms to one-person businesses. It is important to highlight that safety-related supervision is just one of the areas of responsibility within NLIA's jurisdiction. The NLIA comprised around 650 employees (580 person-years) in 2020, and in the years 2016–2020, performed on average almost 10,500 inspections yearly of preventive work environments, work health and safety, and good working conditions, of which more than one in three targeted the construction industry [37]. Many of the inspections in the construction industry are unannounced and can result in improvement orders, stoppage of work, or even fines for serious violations [37]. In the period of 2013–2016, the NLIA had a campaign regarding the prevention of injuries and health problems related to work at construction sites [38].

In the 1960s, safety and working-environment regulations in the petroleum industry in Norway were mostly based on existing regulations from other industries and started with "a Wild West Texan approach" [39], with fragmented regulations and responsibilities. Over the years, the petroleum industry has experienced several large-scale accidents that had profound effects on the regulation of safety on the NCS. The Ekofisk Alpha fire and lifeboat accident in 1975 and the Bravo blowout in 1977 were events that paved the way for Norway's Work Environment Act of 1977 [40]. The safety regulations also provided the workers' unions with a strong platform for collective bargaining and the right to stop work when working conditions offshore were deemed unsafe [41]. Another event that had a massive impact on the industry was the Aleksander Kielland accident in 1980 [26]. Following that disaster, the Principles of Internal Control (1981), which required the responsible party to comply with the regulations through systematic and documented HSE work [36], and the Petroleum Act (1985) were introduced [40].

A new regulatory regime and administrative model were established in 1985 [36]. Regulations after this time became risk-based, with performance-based (functional) requirements; clear responsibilities, transparency, and collaboration between actors of major importance in the government-supervised self-regulation regime [35,36]. Enforced self-regulation in the petroleum industry transferred the responsibilities of managing risks to the companies and required them to develop their own safety-management system or internal control [42]. The Petroleum Act [43] and the Working Environment Act [44] specify, respectively, overall safety requirements and requirements for the working environment. A further five sets of regulations, among them the Framework Regulations [45], provide more detailed requirements for HSE [46]. In 2002, following the government's concern for HSE in the industry [47], the PSA introduced the requirement of having a "sound HSE culture" in the Framework Regulations. This introduction signalled the regulator's desire to explore various ways of looking at and dealing with risks in the industry [48]. Following the Deepwater Horizon disaster in the Gulf of Mexico in 2010, the PSA introduced the principles for barrier management in the petroleum industry, calling for a more proactive safety approach that underlined the need for a sound HSE culture, improved management systems, and robust solutions [49].

Like the petroleum industry, the regulatory approach in the construction industry is functional, but the development of regulations was not related to specific accidents. There are three main laws and regulations that, to a large degree, set preconditions on safety: The Working Environment Act [44]; the Internal Control Regulations [50], following the internal control principle from the petroleum industry; and the Construction Client Regulations [51], which were based on a European Council Directive and aim to protect workers from risks, giving responsibility for safety to clients and designers. In addition, there is a set of regulations that elaborates the Working Environment Act. Some of these are detailed regulations; e.g., concerning assembly and use of scaffolds. All the regulations are minimum requirements, and some actors have more stringent requirements.

The tripartite collaboration and cooperation between the government, employers, and labour unions stands firm in Norwegian working life. In the petroleum industry, this collaboration is exercised in arenas such as the Regulatory Forum (RF), the Safety Forum (SF), Working Together for Safety (SfS), and the HSE Managers Forum (HMF), which also organises the network for safety and emergency response training [52–54]. Concerted efforts have resulted in the development of uniform rules for issuing work permits and performing Job Safety Analysis (JSA) of installations. Similarly, and in part inspired by the petroleum industry, the construction industry signalled its intentions to improve safety in 2014 through the "Charter for an injury-free building and construction sector", later called "Working Together for Safety in the construction industry" (SfS BA) [55].

2.4. Environmental Stressors and Trends

These two industries and the safety of the workers are affected by numerous factors in their environment outside of their control. Hovden [39] highlights the threats to safety from changing market conditions and technological change, such as economic optimisations that have reduced safety margins, and a more robust infrastructure in the industry, which might reduce motivations to keep safety up to the same level. The price of oil strongly influences the operating margins in the petroleum industry. In the 1990s, as a consequence of the decline in oil prices and reduced revenue, the Norwegian Offshore Cost-Effective Initiative (NORSOK) was introduced with an aim of reducing costs while maintaining HSE, initiating technological developments, and making changes in organising the industry and the development of standards [39]. However, this also altered market conditions and challenged power balances in the tripartite collaboration through changed relations between actors [56]. The financial downturn in 2009 affected both industries, with a decrease in employment and output of goods and services [57]. In 2013, the petroleum industry experienced a fall in oil prices and production, resulting in cost cuts and decreased employment, activities, and investments [3,57]. The 2015 RNNP report revealed that NCS workers experienced that production considerations came before HSE, and inadequate maintenance affected safety negatively [58]. Whether or not a regulatory regime succeeds depends more on the political climate and public awareness than the scientific basis for enforcing alternate administrative principles of regulation and control [39]. In the construction industry, the largest value creation is during the construction phase, when the operating margins are at their lowest, on average being around 3.6% [59].

The changing conditions in the market and available resources have also affected these two industries. Since early 2000, several small and medium-sized companies entered the NCS, contributing to changes in the petroleum industry's composition [30]. A prequalification system was established to cope with this change. In the construction industry, a substantial change occurred after the opening of EU borders in 2004, when the number of migrant workers from Eastern Europe started increasing [60]. In the years 2012–2018, more than one-third of the fatal accidents in the industry involved foreign citizens [8]. Furthermore, several of the fatal accidents (around 25% in the years 2012–2018) in the construction industry occurred to persons not employed directly in the construction industry, but through a temporary work agency or in another industry [8], which highlights an additional factor affecting the industry: hired labour.

New trends such as competition from shale-oil production, lower production prices in the global market, lower production costs of renewable energy, and decreasing resources on the NCS further pressure the petroleum industry [61]. Although recent trends are not necessarily negative for accident risk, the lack of knowledge about the interactions of these trends is problematic [39]. Fast-paced technological developments in the petroleum industry can contribute to improved safety, but also bring in new challenges [62]. In the construction industry, technological developments, regulations, and improvements in emergency treatment have contributed to safer sites in recent years. The developments also involved a change of perception; what was earlier perceived as safe enough is today considered unsafe. However, dangerous work tasks and risks due to increased complexity still influence safety. The industry remains bedevilled by challenges related to hired labour, social dumping, and fragmentation of responsibilities [63].

2.5. Summing Up Characteristics of the Two Industries

Figure 4 summarises and compares characteristics of work and framework conditions in the two industries by using Rasmussen's model [22] based on the descriptions in Sections 2.1–2.4. Inside the boxes, divided by actor groups, industry facts and framework conditions that can affect safety are listed. Additionally, outside the boxes, examples of environmental stressors are summed up.

An examination of Figure 4 reveals the significant differences between the nature of the two industries across all levels from Rasmussen's perspective. Government influence at the top is greater and clearer for the petroleum industry, where there is a recurring and explicit ambition of the Norwegian Government for the industry to be a world leader on HSE [36,64]. The scope and resources for the two regulatory authorities again are drastically different, with the PSA focussing mainly on safety in just the petroleum industry, and the NLIA having its focus on safety in multiple industries. Furthermore, in the petroleum industry, major accidents have changed the political climate and public awareness, which have in turn changed regulations.

In both industries, there are several levels of actors that, through their actions, produce important framework conditions for other actors. Decisions, budgets, and plans from one actor can become framework conditions for other actors [23]. The number of operating companies is also significantly different. While cost-cutting has affected the petroleum industry in the past years, small operating margins have traditionally been a characteristic of the construction industry. This plays a significant role as an external stressor in the way companies and management work with safety. Structural conditions in the company affect how accident risks are managed—for example, size affects the communication patterns and the need for advanced safety management system, or resources in terms of affording safety solutions and safety personnel [18].

Differences between the industries in social climate, such as trust in regulatory institutions and political and regulatory culture (or style), might affect how risk is governed within the two industries [65].

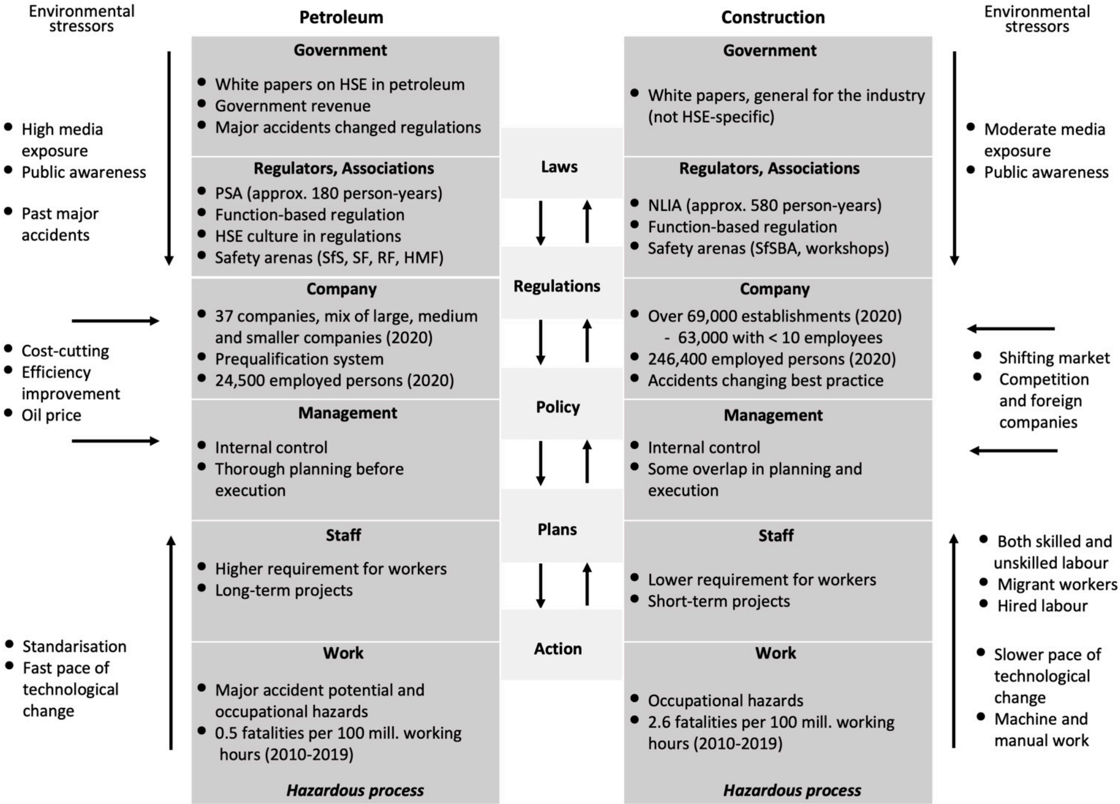

Figure 4. A generic perspective on the petroleum and construction industries. Based on Rasmussen's model [22].

3. Materials and Methods

3.1. Data Collection and Analysis

This qualitative study was based on semi-structured interviews with stakeholders in the construction and petroleum industries to give insight into aspects influencing safety performance and development in the two industries. The nature of qualitative studies is to gain insight, rather than to generalise to facts. The practices and opinions from the interviews contribute to nuances, which without the interviews are difficult to capture. A semi-structured approach was chosen as it offers flexibility and room for elaboration and clarification during the interview [66]. The interviews were conducted in 2017 and 2019. Documents, reports, and statistical data were used as background information. The factual and empirical data complement each other in shedding light on safety related aspects.

Rasmussen's model was used as a starting point for the research design to ensure that all important levels influencing occupational safety at the sharp end, as well as important framework conditions, were included. The interviewees were from four different levels—supervisory authorities, employer and employee organisation representatives, company management, and company safety personnel. This spread of viewpoints and experiences made the data comprehensive and contributed to a broad understanding of safety practices in the two industries.

The selection of interviewees was based on purposive sampling, which is suitable for in-depth studies, as it aims to provide rich information through participants with required status, experience, or knowledge [66,67]. The selection criteria of the respondents were organisation type (i.e., safety authorities, employer and employee organisations, and petroleum and construction companies), employment position (for companies—top management, safety manger/coordinator), and a focus on hands on experience in the industry. Further, participants within the criteria with experience from both industries were especially targeted. Snowball sampling, in which new contacts were recommended by other interviewees [66], was used to some extent to recruit participants.

The interviewees had from 3 to over 20 years' experience in the petroleum industry, with the majority between 10–30, and between 3 and 15 years in the construction industry, with the majority being around 5–10 years.

An interview guide was made with adapted questions for the four different types of interviewees. The interview guide included (but was not limited to) the following topics: perceived level of safety in the industry; challenges in the industry that may affect safety; influences from different levels of actors; relationship between the safety authority, industry, and the workforce (tripartite collaboration); views on the respective safety authorities; and where relevant, a comparison of safety management across the two. During the last interviews, a saturation point for the main questions in the interview guide was reached, with no more new, relevant data emerging [68], indicating a sufficient sample size.

Table 1 shows the number of interviewees from each industry and the four categories covered. In total, there were 36 interviewees in the study, of which 33 were interviewed and 3 answered questions by e-mail. Some interviews were in person, while most were conducted via phone and lasted between 0.5 to 1 h. Of the interviewees, 18 had experience in both industries. All of the interviews were conducted in Norwegian. Most of the interviews were recorded and transcribed, except for a few. These interviews were conducted by two interviewers and detailed notes were written during the interview.

Table 1. Number of interviews for each industry.

	Petroleum Industry	**Construction Industry**
Safety authorities	3	2
Employer and employee organisations	7	3
Top management	3	4
Safety personnel	5	9
Total	18	18

The transcribed data were coded based on categories from the interview guide and through open coding, in which new categories were found. The coding of the data was performed in parallel by two researchers to ensure a correct basis for the analysis. The data used for quotations were translated by the authors from Norwegian to English. The transcribed and coded data were analysed systematically by categories with the research questions in mind, which resulted in state-of-the-art descriptions of the safety in the two industries, a comparison between them, framework conditions affecting safety in the two industries, and the learning potential.

In summary, the comparison of the industries was based on information from workers in each industry, comparison by the workers who had experience in both industries, as well as factual information from statistics and documents about the industries. This allowed for triangulation of the analysed data, in which findings could be crosschecked [67].

3.2. Delimitations and Limitations

To compare the two industries, this paper is limited to looking at framework conditions that were comparable between the two industries related to factors that affected the level of safety, such as the economy, authorities, and management. Factors specific to each of the industries, such as contracting models in construction and how they affect safety, were beyond the scope of this study.

A comparison of safety in the construction industry during the building phase and the petroleum industry in the operating phase is not straightforward. The aim was to look at safety from a generic perspective in both industries. However, there were large variations within the industries that needed to be taken into consideration when interpreting the results. As there are, in practice, many influences from one industry to the other, a comparison between the two industries was rationalised.

4. Results

The empirical results indicate aspects affecting safety. The results are divided into the general safety level of the two industries, influences on safety from different actors, and influences between the two industries.

4.1. The Safety Level in the Norwegian Petroleum and Construction Industries

The interviewees from both industries perceived the petroleum industry to have a higher level of safety than the construction industry. The interviewees varied in their perception of the construction industry's general safety level. One interviewee compared the safety in the construction industry to the safety in the petroleum industry in the 1970s and 1980s. Overall, the safety level in the construction industry has improved in recent decades. However, several interviewees agreed that the industry still has potential for improvement. As one interviewee from an employer organisation in construction said: "*Actually it is quite good, but not good enough*".

Many attributed the high safety focus in the petroleum industry to major accidents. In contrast, the focus in construction is primarily on occupational safety, as the industry evaluated the risk of major accidents as being relatively lower. Fatal accidents in construction usually result in improvements within a project in a company, rather than impacting the whole industry. However, a few examples of accidents impacting the entire industry were found, such as a bridge collapse in Trondheim in 2013, which was said to have ended the practice of keeping roads open for public traffic below concrete work. Another example mentioned was large contractors demanding machinery re-design after accidents.

Many interviewees also attributed the higher safety level in petroleum to a better economy that allowed for more resources to be allocated to safety. Several interviewees noted that due to low oil prices, cost-cutting has resulted in a backlog of facilities maintenance. The interviewees also underlined that many offshore facilities are reaching their life expectancies, and modifications to extend their operations could impact safety.

4.2. Safety Influences from Different Actors

This subsection presents the findings on how different levels of actors and related factors influence occupational safety in the two industries, structured according to Rasmussen's socio-technical model [22], starting from the government at the top, moving down towards staff and the work itself.

4.2.1. Government

The top level of the framework involves control of safety through the legal system. Legislation and the use of standards were identified as important factors influencing safety in the petroleum industry. The regulations in the petroleum industry are trust-based and were perceived as good by the interviewees, providing a common goal for the industry. However, some claimed that trust-based regulations do not work well during financial downturns.

In the construction industry, some argued that not all of the regulations were beneficial for safety. Others found the regulations to be too bureaucratic. It was also mentioned that the formulations should be stated more clearly to avoid varying interpretations of the regulations. Some interviewees argued that the regulations already were good, and the problem lay in using them in practice.

Changes in the regulations allowing the use of temporary workers have resulted in an influx of foreign, contingent workers in both industries.

4.2.2. Regulators and Associations

There was no common agreement among the interviewees on how the regulators influenced safety in their respective industries. Although both regulators utilised similar sanctions and measures, the interviews indicated a difference in the degree to which different sanctions and measures were used and in the way they conducted audits. The NLIA conducted both announced and unannounced inspections (sometimes referred to as "actions"), while the PSA operated under announced audits. Offshore constraints (in terms of transport scheduling and capacity) necessitated the announcement of when the PSA audits would take place. There was consensus among the interviewees that the NLIA's resources were meagre compared to the PSA's, despite their wider area of responsibility. As a result, there can be long periods between the NLIA's visits to the same construction company. Some added that the NLIA is often limited to supervising large companies that already have good systems in place, instead of focusing on smaller companies. The NLIA was also perceived as being somewhat reluctant to fine companies that do not follow regulations. According to some interviewees, this may be due to the observation that fines are ineffective in getting rid of unscrupulous actors. A large fine could easily break small but serious companies, whereas less-serious actors can simply start over by declaring bankruptcy.

The development of the NLIA's safety work was perceived as adequate by several interviewees. Workshops that the NLIA holds together with the industry were perceived as very positive. It was highlighted that the PSA's reports from inspections are made public, which puts a high focus on sharing and learning between companies in the petroleum industry. One interviewee emphasised the active role that PSA plays in the safety level of the industry:

> *"They [PSA] are professionally good. [. . .] They always come with some improvement points. We do not always agree with each other, but I find that the PSA helps to keep up the standard. They help to make us good. They are important to the industry, I think."*
>
> *(Manager, Petroleum)*

Not everyone shared this view of the PSA. Some interviewees found the PSA to be weaker than the NLIA, pointing to the PSA's inadequate supervision and restrictive use of sanctions on oil companies. Others stated that the PSA had lost the unions' trust, as they seem to accommodate the companies too much. Others again experienced the PSA as not clear enough when it comes to their safety requirements.

> *"If you look at the NLIA, they have stopped 50 workplaces in one year. The PSA has in the last 20 years barely stopped anything."*
>
> *(Employee and employer organisation, Petroleum)*

Traditionally, the trade unions have been influential in the petroleum industry. While some mentioned that the collaboration between employer and employee associations and organisations is positive for HSE, others pointed out that the financial downturn has affected the position of the trade unions, decreasing their capacity to influence.

> *"It is the mainstay of the Norwegian industry—it [the tripartite collaboration] is seen as a success factor. But the truth is that we feel it has become more and more challenged. They want us not to have so much influence."*
>
> *(Employer and employee organisation, Petroleum)*

For the construction industry, no notable aspects or opinions were presented regarding trade unions, except the role of safety deputies. Some perceived the role of safety deputies in construction as having less influence and a lower reputation than in the petroleum industry. The higher level of risks offshore and the higher costs in petroleum if something goes wrong were given as potential reasons for this by the interviewees.

4.2.3. Company Level

The oil companies and clients in the construction industry are influenced by actors above them and are in a position to influence actors on lower levels, such as operators, contractors, and sub-contractors. In the petroleum industry, the safety procedures are set from the top, by the oil company and the operators. Procedures and requirements were described by the interviewees to be, overall, similar within the industry, often based on standards such as NORSOK, which are stricter than the Working Environment Act. In the construction industry, the companies primarily aspired to achieve the minimum standards set by the regulations. It was also stated that a client could operate with internal HSE rules for their own employees and external HSE rules for contractors. One reason for this was not to intrude into the contractor's work methods and procedures. Looking at the construction industry as a whole, procedures and rules therefore vary somewhat between companies, although they fulfil regulatory requirements. One interviewee mentioned that the larger contractors in construction have systems that are similar to that in the petroleum industry. However, there are large variations in the construction industry—for example, between small and large companies, public and private clients, and even between different projects in the same company. It was mentioned that, in construction, both the reporting system and the reporting culture are not as well developed as in the petroleum industry. Others mentioned leniency in terms of local choices and adaptations and less severe sanctions for HSE rules not being followed than in the petroleum industry.

> *"In the petroleum industry similar rules and procedures generally apply. In the construction industry, on the other hand, in my company we have an external HSE towards the contractor and so on, and an internal towards our own employees."*
>
> *(Safety-responsible, Construction)*

Prequalification of companies (e.g., contractors and sub-contractors) is the norm in the petroleum industry, including assessment of HSE results from earlier projects. In the construction industry, large clients and contractors use similar systems, but they are not as widespread as in the petroleum industry. Some interviewees pointed out that the smaller number of companies operating in petroleum enabled them to have more straightforward control of aspects such as worker competence, qualifications, and experience.

Continuity in the organisation was also identified as a factor influencing safety. While construction is generally project-based in its organisation, petroleum facilities usually comprise the same operative organisation for many years. Some also pointed to the dependencies between actors at construction sites and the possible resulting delays as having consequences for safety.

4.2.4. Management

The interviewees identified thorough planning of operations and highly controlled activities as factors promoting safety in the petroleum industry. Any change was regarded as a potential contributing factor to unwanted events.

Further, management was regarded by the interviewees as having an influential role for safety. All interviewees agreed that managers are role models and need to communicate clearly and insist that safety comes first. Leadership was indicated by many of the interviewees as an essential condition for safety. Several aspects of leadership were pointed out: making managers accountable rather than just responsible, stable relations between managers and workers, loyalty to safety systems by mangers, "anchoring" of safety systems in managers, and consequences for both workers and leaders if attitudes and actions are not correct.

> *"Something that characterises the construction industry is that there are no stable manger-employee relations."*
>
> *(Manager, Construction)*

4.2.5. Staff and Work

In comparison to the construction industry, many interviewees described the petroleum industry as having stricter rules and a greater focus on understanding risks and emphasis on barrier thinking. In construction, attitudes towards safety and understanding of risk were described to be challenging, and the understanding of safety concepts was perceived as weaker than in the petroleum industry.

The significant number of contingent labourers that lack competence and equipment to perform the work safely in construction was indicated as another reason for the higher number of injuries and fatalities than in the petroleum industry. Such work practices were described as potentially affecting the establishment of relations and continuity in organisations, such as between managers and workers or between workers. In addition, in the petroleum industry, the use of hired labour is also becoming more common, especially in land facilities. Some noted that these two industries are becoming more similar in terms of increased hired labour. Related to hired labour in construction, it was mentioned that it could be challenging to know who works on the site and with what competence. The randomness of temporary-worker composition was said to affect the possibility of incorporating these workers in the safety culture at the site. Proper training of workers, being familiar with the organisation, the importance of knowing each other, and continuity were highlighted in both industries as critical to safety.

> *"I see a development where more and more unskilled workers are coming from Eastern Europe who are willing to do the job on conditions which Norwegians cannot live off. […] If we can't turn this around and change this, then we will end up in a few years with the same conditions as they have in the construction industry."*
>
> *(Employee, Petroleum)*

4.3. Influences between the Industries

According to several interviewees, oil companies have influenced contractors in the construction industry through contract requirements. Large contractors that have previously worked for petroleum companies, for example in building onshore facilities or doing maintenance offshore, had incorporated some systems related to safety from the petroleum industry.

> *"At the end of the 1980s I would say a clear improvement happened, more systematising and routines for HSE. This happened in the contracting companies, and the reason was that the large contractors were getting building orders from the oil companies. The oil companies had requirements for systems and routines, which the construction contractors did not really have. So, the part of the construction industry that worked with the petroleum industry developed and improved HSE in construction."*
>
> *(Employer and employee organisation, Construction)*

The petroleum industry has experienced several oil-price crises that led to workforce reductions. During these periods, many workers and managers moved to other industries, such as construction. The petroleum industry has thus influenced the construction industry. Many tools, practices, and even regulations from the petroleum industry have been copied and adapted by the construction industry. It was, however, pointed out that framework conditions are different in the two industries, and not everything is directly transferable between them. Room for adaptations and an understanding of the circumstances and situations to comprehend the risks were also highlighted. It was also pointed out that sometimes the vocabulary in the two industries is different, meaning that the same safety words can in practice mean different things.

> *"After the oil crisis we got many persons from petroleum. […] They may have many good systems for reporting, but they have never been in construction. […] Some think you can transfer everything one to one, but that does not work. We need to think what to do differently, not just copy."*
>
> *(Manager, Construction)*

When it comes to arenas for knowledge sharing, the petroleum industry has long had networks promoting safety, such as the SfS. With inspiration from the petroleum industry, the construction industry in Norway has now established the SfS BA. Many of the interviewees believed that this arena would improve safety in the construction industry.

Systematic work and standardisation were mentioned as key areas where the construction industry should continue to adopt practices from the petroleum industry. The use of JSA, for instance, was regarded as coming from the petroleum industry. Here, some interviewees mentioned a striking difference in the adoption of this practice. While JSA is used selectively in petroleum, there seems to be an excessive use of JSA in construction. Better planning was mentioned as another area where construction could learn from petroleum. The example given was that many aspects need to be in place and risk assessed before a work package is sent to offshore for execution, whereas in construction, a worker sometimes gets some necessary information only just before the worker is sent to work, and the job might not be sufficiently well planned.

All of the points mentioned about learning from each other were related to what the construction industry can learn from the petroleum industry. When asked what the petroleum industry could learn from the construction industry, the interviewees did not have anything to say or offer.

5. Discussion

The empirical findings indicated aspects that, according to the interviewees, influenced safety positively or negatively; these are summarised in Figure 5. In this section, important results that contribute to explaining the different evolvement of safety in the two industries and point on improvement potential are discussed.

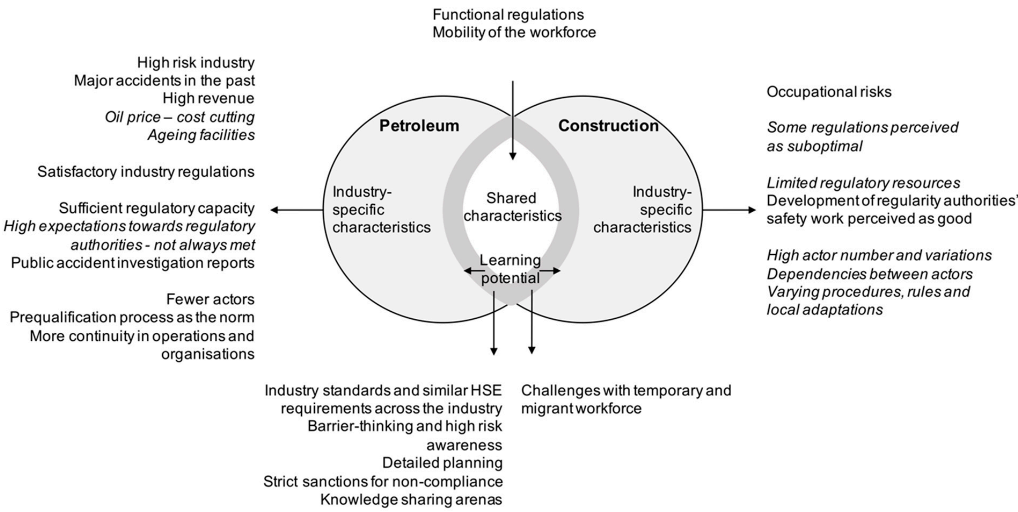

Figure 5. Aspects influencing safety and learning potential between petroleum and construction (aspects that can have a negative influence on safety are marked in italic).

5.1. Development of Safety Work in the Two Industries

Construction was a developed industry long before the petroleum industry began its operations in Norway. Safety in the two industries has been and is still under development. Worker protection to regulate safety began playing a role in Norway and in Europe in the 1890s, and the central Working Environment Act came into force in 1977 [63]. The approach to safety at the start of the petroleum industry in Norway in the early 1970s has, over the decades, changed and developed [39,69], contributing to the industry becoming a leader in

Norway on safety today. Explicit expectations from the government towards HSE [64] put pressure on the petroleum industry and contributed to this development.

The petroleum industry is perceived by the interviewees as being more mature in terms of safety than the construction industry. To a large degree the focus on safety and the culture for prioritising safety are shared across all levels in the petroleum industry. The results indicate that the organisations in the petroleum industry have strict procedures for activities, substantial changes to planned operations require new risk assessments and procedures are revised according to the management of change procedures. Ad-hoc solutions have no place in their operations, in contrast to the construction industry, where workers may feel compelled to devise local adaptations as situations arise.

5.1.1. Major Accident Risk Prevention as a Driving Factor

Major accidents have affected the level of safety in the petroleum industry and are a constant reminder of the inherent hazards associated with petroleum-related activities. These hard-earned lessons led to many safety developments [70], and have engendered a profound change in the regulations and safety-management systems of companies, as well as propelled technical innovations that help control risks in the industry [69]. The risk of major accidents might be perceived as larger than the risk of occupational accidents, and thus could give rise to new safety measures to prevent future accidents. Perceived consequences, such as those of major accidents, play a role in the demand for risk mitigation [71]. The changes in regulations have also influenced other industries, such as through the regulation on internal control of safety, which today in the construction industry—together with the Working Environment Act and the Construction Client Regulations—are among the laws and regulations affecting workers' safety the most. The results indicated that accidents in the Norwegian construction industry have not had a direct influence on regulations as in the petroleum industry, and the regulations in the construction industry are perceived as suboptimal. However, a few larger accidents have received more media and public attention, which influenced awareness within the industry and led to a change in best practices.

5.1.2. Regulatory Resources and Tripartite Collaboration

While regulations of both industries are functional, the results indicate variations in how they are enforced by regulators, such as in the use of sanctions, and how often inspections and audits are conducted. The disparity between the ideal regulatory activities and the actual resource at hand has repercussions on the performance of the safety regulators, making one regulator (PSA) more fortunate than the other (NLIA). The regulatory authorities are important for safety, but the interviewees' opinions fluctuated as to the degree to which the authorities actually influence safety. According to findings from the Office of the Auditor General, the PSA's supervisory practices had a limited impact on companies' follow-up of HSE in the petroleum industry [64]. In the interviews, some perceived the PSA as being better in earlier days. It was also mentioned in the interviews that the PSA and NLIA have different resources available and different supervision styles, and that the PSA is only responsible for the petroleum industry, while the NLIA has many industries to oversee, which could influence safety in the industry. Tripartite collaboration also seemed to differ between the industries. In general, it has an important role in the Norwegian working life, but the development and degree of influence from associations were indicated by the interviewees to be higher in the petroleum industry. The weaker impact of the associations could contribute to the explanation of the different safety levels in the two industries, through the impact on safety at the sharp end.

5.1.3. Wide Range of Actors

The petroleum industry consists of a modest number of companies and a few global actors, which pales in comparison to the number of companies in the construction industry, which consists of everything from individual enterprises to large, international enterprises.

The large number of small companies in the construction industry was indicated to challenge the overall development of safety in the industry, as common attitudes, norms, and values are needed. It was pointed out that the large companies lift the small companies to a certain degree, but the variations within the industry are large. Although there are differences between companies offshore, the interviews indicate that requirements, systems, and organisational structures are more standardised in the petroleum industry than within the construction industry, which promotes a more similar safety level across the industry. Antonsen et al. found in a case study that an implemented standardised operation model for offshore installations positively influenced planning of tasks and compliance with procedures [72].

However, since the beginning of the 2000s, the composition of companies in the petroleum industry has changed, with new, less-experienced companies and smaller companies entering the NCS. The interviews indicated that collaboration and communication could vary from project to project, and may become more challenging as the number of firms increases. This diversity can challenge the industry's overall safety level, as more actors need to adapt, comply, and develop a similar HSE culture, and authorities have to adjust and follow up with the new actors as well. Ambiguities in roles and responsibilities between personnel from different companies have been found to be a factor contributing to occupational accidents and major near-accidents in the petroleum industry [73]. Regulations that demand a good HSE culture through continuous HSE work might support this [45]. In addition, the characteristics of the construction industry, being project-based, multi-tiered and with changing worker compositions, can result in short-lived interactions and lack of continuity. Since the workers are at each construction site for a limited time, this can reduce the opportunity for developing shared norms and practices.

Aspects such as employment condition also play an important role for safety, and the use of hired workers or non-standard forms of employment make it even more complicated. The interviews indicated that it is common to use hired labour in the construction industry, and it was also mentioned that foreign workers pose a challenge not only in terms of lingual issues, but also in terms of employment arrangements. The working arrangements are also changing in the petroleum industry. As stated in the interviews, more and more of the workers in the petroleum industry have temporary contracts, as in the construction industry. A review of earlier studies showed that temporary agency workers have a higher occupational health and safety risk, including higher injury rates [74].

5.1.4. Ensuring Continuous Improvement

Although the safety level has improved over the years in both industries, they continuously strive to improve. In the construction industry, this can be seen in the eagerness to learn from the petroleum industry; e.g., adopting tools and practices, and creating SfS BA. For the petroleum industry, however, trends such as unstable oil prices, organisational change (e.g., hired labour), and already operating at a high safety level might make it harder to develop safety further at the same pace. This could lead to an "attention withdrawal" by the top management, in which attention to safety and safety performance can gradually decrease [75]. Furthermore, some of the interviewees argued that the apparent economic differences in revenue can no longer be used as a reason or excuse for less-developed safety in the construction industry, as the petroleum industry currently does not have the same economic resources as previously.

5.2. Transferable Experiences and Knowledge

The petroleum and construction industries in Norway are distinct, but these two industries can potentially learn from each other. For the construction industry, an opportunity to learn from the safety-management systems in the petroleum industry was previously identified, especially related to knowledge management, in an earlier study [76]. Broadly speaking, the construction industry is looking up to the safety level and practices of the petroleum industry.

5.2.1. Petroleum as a Role Model

Analysis of the empirical data points to several influences from the petroleum industry on the construction industry's safety. The construction industry has benefitted from the experiences and knowledge developed for and in the petroleum industry, including safety-management tools such as incident-reporting systems, risk-assessment tools (e.g., JSA) or frequent meetings at the sharp end. Several arenas have been established to share safety knowledge and experience in the construction industry, such as conferences, workshops, and forums. For example, inspired by the SfS network in the petroleum industry, the construction industry established a similar network—SfS BA.

5.2.2. Adoption of Practices

Regarding standardisation, it seems that the construction industry is moving towards practices from the petroleum industry related to more uniform safety tools, methods, and practices across companies, and more uniform requirements across large clients and contractors. The fact that some construction companies have been working for oil companies has helped them adapt parts of their safety practices to the stricter practices in the petroleum industry, which slowly seem to be becoming an industry standard. These similar characteristics may be created through various institutional pressures, resulting in isomorphism [77]. Movement of petroleum workers to the construction industry, coupled with the transfer of practices and tools, such as toolbox talks, barrier-oriented thinking, and standardisation, may have resulted in the diffusion of ideas.

There is, however, reason to believe that the outright transfer of knowledge from one industry to another is not straightforward. The indiscriminate use of JSA in the construction industry, for example, has reached a point where its adoption runs the risk of losing value and function [78]. All measures are not necessarily suitable, and practices need to be translated and adapted to the industry and prevalent conditions. It was pointed out by several interviewees that not everything could be directly copied and expected to work in the same way in the two industries. First, the understanding and perception of safety and the industry itself is in some cases different between the two industries. It was also seen from the interviews that not all framework conditions necessarily behave the same way in the two industries. This was also observed in the varying trends between the two industries, perhaps attributable to their distinct safety levels. The risk picture in the two industries is different, and thus the need for measures will also differ. It is therefore crucial to adapt different measures, concepts, tools, and policies and the like to the industry's framework condition, needs, requirements, and competence, rather than directly transferring them and taking for granted that they are the same in the two industries. The differences between companies within the industries, where the differences are larger within construction than within the petroleum, are another consideration. For the construction industry, it might be wise to mature at the industry's own pace when it comes to safety and not necessarily rush into adopting solutions that have worked in petroleum.

5.2.3. Technological Innovations

From the analysis, it was prominent that there were trends related to the structural systems that can influence safety. Some framework conditions are stable and cannot easily be changed, such as the size of companies, the number of companies, and regulations. Technological developments have been fast in the petroleum industry, and at present also are becoming increasingly rapid in the construction industry, thus requiring constant adaptation. The extensive use of automation and barriers that characterise petroleum activities are features that remain wanting in the construction industry. However, many developments are coming that are related to, for example, digitalisation. The new developments will introduce new possibilities, but also challenges and more complexity. Many of these developments are also somewhat generic for both industries. In terms of safety management, experiences with technological developments and digitalisation could be shared and learned across the two industries.

5.2.4. Experiences from Construction to Petroleum

The already high level of safety in the petroleum industry seems to prevent many from identifying learning opportunities from the construction industry. The interviewees in the petroleum industry had a rather pretentious attitude towards possible learning points from construction. However, the construction industry has a lot of experience, for example with migrant workers and temporary contracts, that could also be of value for the petroleum industry in the future. The caveats that come with a growing population of migrant and temporary workers coupled with ageing facilities and the emerging effects of peak oil should be brought to the petroleum industry's attention and resolved, with the same ambition that brought about the industry's high level of safety.

6. Conclusions

The construction industry has a significantly higher fatal accident rate than the petroleum industry in Norway. Through a systematic, qualitative, interview-based study with actors across both sectors and organisational levels, this paper has elaborated reasons for the different safety levels between the industries. The paper has also identified and discussed further potential for improvement across the two industries. The novelty of the study is the comparison with an inter-industry perspective, and a focus on transferable experiences given the influencing characteristics and conditions.

The petroleum industry is primarily perceived as having a more mature level of safety. In the construction industry, there are large variations in the safety level between companies. The safety developments in the petroleum industry have largely been accelerated by several major accidents, which brought changes in the regulations and increased the focus on safety, which is not the case in the construction industry. The interviews indicate that procedures and requirements in the petroleum industry are more standardised and similar for all actors within the industry, as compared to the construction industry, where the companies primarily aspire to achieve the minimum standards set by the regulations. The interviews further point to structural differences, in particular the large number of actors in the construction industry, as challenging for a general level of safety and having similar practices across the industry. In addition, sharing lessons learned and other relevant safety information between companies in the petroleum industry are more systematic and frequent than in the construction industry.

Furthermore, the construction industry has benefitted from safety improvements in the petroleum industry, such as tools and methods, through interaction between the two industries; e.g., movement of people and contractual requirements. Nevertheless, the interviewees from the construction industry all agreed that better planning, standardisation, and barrier-thinking more similar to those implemented in the petroleum industry could improve the industry's level of safety. Furthermore, the technical developments and knowledge sharing are more developed areas in the petroleum industry. The petroleum industry has to further strive to maintain and evolve its safety levels, given possible changes and new developments, and might also benefit from looking into experiences across sectors; e.g., the construction industry's experience with the temporary and migrant workforce.

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MANUSCRIPT FOR ARTICLE 3

An analysis of the relationship between project management and safety management in the Norwegian construction industry

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