University of Strathclyde Glasgow

Safety Performance in the Offshore Wind Industry: Key Challenges and System Safety Solutions

David Rowell

WAMESS CDT

Electrical and Electronic Engineering

University of Strathclyde, Glasgow

November 22, 2025

This report is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Abstract

The offshore wind industry is expanding rapidly, playing a vital role in global renewable energy strategies. However, its unique operational challenges, remote locations, harsh weather conditions, and complex systems pose a significant safety risks to workers.

This research investigates safety performance in offshore wind, comparing it to similar sectors such as offshore oil and gas, and identifies key challenges in managing health and safety (H&S). It highlights limitations in the current reporting of H&S performance data which lack statistical validity and fail to predict emerging risks. To address these gaps, the study develops leading indicators tailored to offshore wind, using precursor and barrier element methodologies. Systems safety theory (STAMP) is applied to an industry wide risk analysis. STAMP theory methods are used to map control structures, identify unsafe control actions, and recommend improvements to legislation, design, and emergency response to improve safety management across the industry.

Recommendations include the adoption of leading indicators and development of an industry wide risk levels report, improving safety performance measurement, updating legislation, and adopting "safe by design" principles into the supply chain and maintenance activities. These strategies aim to proactively manage risk, improve worker safety, and support sustainable growth in offshore wind.

Contents

List of Figures

List of Figures

Acknowledgements

I'd like to start by thanking my supervisors, David McMillan and James Carrol, for their guidance and support throughout this thesis. Your advice and expertise have been crucial in helping me get to this point.

A big thank you to my wife, Tomoko, for always being there and supporting me. To my kids, Ami and Shogo, your hard work and dedication to your own goals have been a constant source of motivation for me.

I'm also grateful to the University of Strathclyde for providing a great academic environment and to EPSRC for funding this research through the Wind and Marine Energy Systems Centre for Doctoral Training (grant number EP/S023801/1). This work wouldn't have been possible without your support.

Finally, thanks to Sky, our dog, for keeping me sane with daily walks along the Kelvin.

Chapter 1

Introduction

This is the thesis of the PhD titled "Safety Performance in the Offshore Wind Industry: Key Challenges and System Safety Solutions". This thesis sets out the findings of three years of research work as part of a four year study with the Wind and Marine Energy Centre for Doctoral Training at the University of Strathclyde. The project began as a study on the challenges of accessibility of offshore wind farms as it related to operations & maintenance but has naturally evolved following on from findings from the literature review and the interests and experiences of the researcher. Offshore wind is a rapidly growing and high risk industry and the nature of the work poses unique challenges in making sure that the installation, operation and maintenance of this infrastructure can be completed safely without harming those who work within it or come into contact with it. The literature review phase of this work identified that there was little research on the safety performance of the industry and that it faced challenges to continue developing while keeping workers safe. Thus operational safety of the offshore wind industry became the focus of this work.

The work is set out in Chapters beginning with this introduction setting out the background to the topic, the research question and methodology. Chapter 2 comprises a literature review, this covers existing research in offshore wind and draws on key safety research from comparable industries and the wider safety science body of knowledge. Chapter 3 then begins with a high level assessment of where the industry stands today in terms of its performance, this includes a discussion of the risk profile, a cross industry comparison of accident statistics and a review and analysis of the legislation that governs safety for the sector. Chapter 4 then looks in detail at the available accident statistics for the industry and how the industry measures its performance and risk levels and whether these methods are effective. Chapter 5 then looks at how leading indicators of safety performance can be developed for offshore wind. Chapter 6 introduces systems safety methods and applies them to a risk analysis of the industry and the development of safety indicators. Chapter 7 then assesses how systems safety methods could be applied to the emerging floating wind industry. Finally, Chapter 8 summarises the research with a discussion of key points, conclusions and opportunities for further research in this area.

Each Chapter will set out its own research objectives that form part of the answer to the primary research question, it will also highlight the novelty of the research, discuss any specific theory relevant to that area and finally set out the methodology, results and conclusions.

1.1 Background

Offshore wind energy production has experienced significant growth over the past decade and become an important part of the electricity generation industry. Figure 1.1 shows the increase in installed capacity each year since 2010, and the forecast capacity to be installed up to 2030 [1].The capacity being commissioned each year has been steadily increasing, while 2021 saw a huge jump with over 20 GW installed globally, bringing total global installed capacity to around 57 GW. For context, the UK total installed electricity generation capacity was around 76 GW in 2021 [2]. Growth has been limited in recent years due to global challenges to the economy and supply chains, however this is predicted to improve with renewed growth in the coming years. IRENA predict that for the world to achieve carbon reduction targets to limit global temperature increases to 1.5 C, 380 GW of offshore wind installation will be required by 2030 [3].

Figure 1.2 shows the global shares of installed offshore wind capacity. Northern European countries such as the UK and Denmark were early leaders in the market and

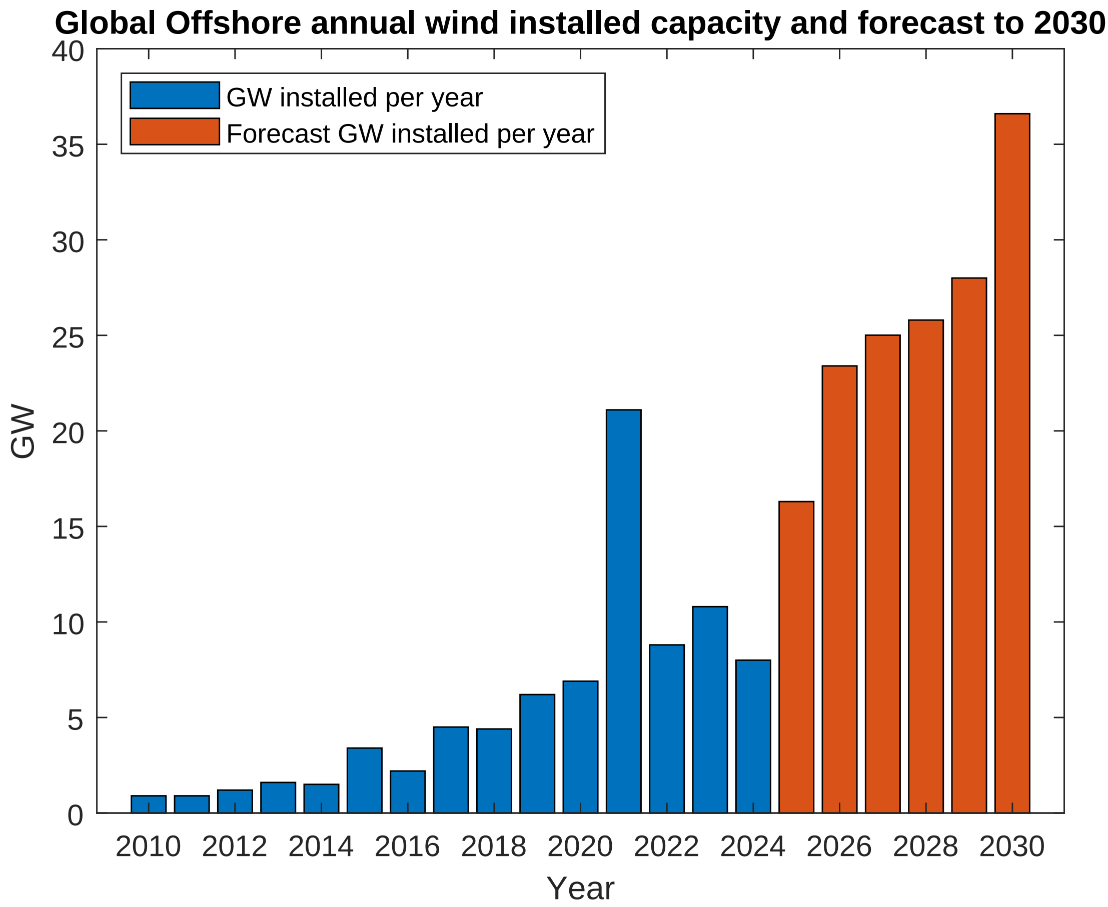


Figure 1.1: Offshore wind global annual installed capacity [1]

still hold significant market share. China has seen huge growth in recent years and now has installed 50% of total global capacity of offshore wind turbines.

Countries around the world including the UK have made offshore wind key pieces of their future energy strategy. The UK alone has set targets of 40 GW of installed offshore wind capacity by 2030, and called offshore wind *"a critical source of renewable energy for our growing economy"* [4]. Other countries have set similarly ambitious goals, for example, Germany is targeting 30 GW and the Netherlands 22 GW by 2030 [5]. The low carbon nature of offshore wind energy make it an important part of the net zero strategy for many countries. The international renewable energy agency (IRENA) have identified that to limit climate change, global carbon emissions need to be reduced by 39.6Gt by 2050, and that 25% of this reduction would come from the adoption of renewable energy technology [3]. For this to be achieved offshore wind will need to

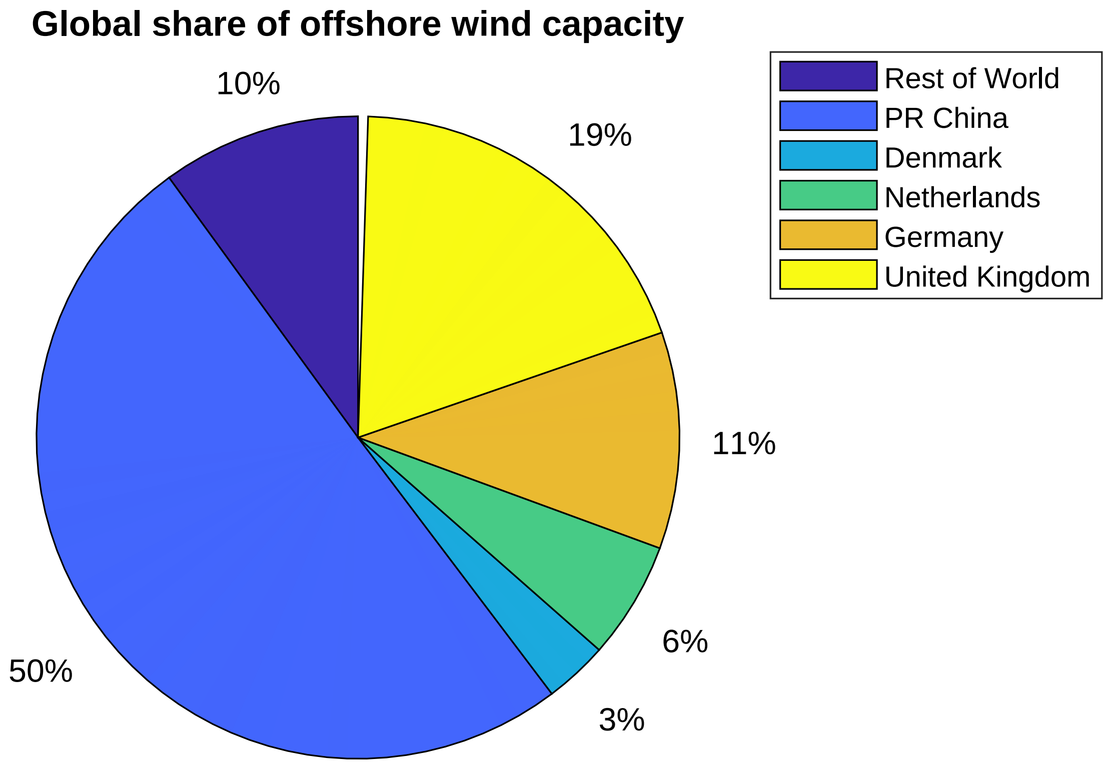


Figure 1.2: Global share of offshore wind installed capacity 2025

increase globally to over 2000 GW of installed capacity by 2050.

IRENA estimate that the cost of offshore wind fell around 48% between 2010 and 2020 [6]. This has now put the cost of new offshore wind power in the same range as traditional thermal fossil fuel powered energy generation methods. As available onshore wind sites have been developed and wind turbine technology has improved, offshore wind farm sites have become more attractive. The increasing size of turbines, falling costs and improved reliability have all made offshore wind economically competitive with other forms of energy. Offshore wind opens up locations out of view of the general public and sites that have higher and more consistent wind speeds than onshore sites [7] [8] [9].

As offshore wind grows in importance wind farm sites are moving to deeper waters, WindEurope have reported that the average water depth for European offshore wind farms was around 20 m in 2010, by 2019 this had increased to over 30 m. Over the same time period the distance to shore increased from around 15 km to 60 km [10]. In

2021 the average water depth of wind farms under construction was 42 m [5].

It is clear that offshore wind is becoming a key part of the World's energy generation industry and also has an important part to play in future de-carbonisation targets. In order for the offshore wind industry to successfully meet growth targets and contribute to net zero, development must be completed in a sustainable way, this includes not only environmental sustainability but also developing as a safe and healthy workplace for all of those involved in the development and operations. The focus of this PhD is to improve operational safety in the industry. Making the industry a safer place to work will also make it a more attractive employment opportunity for future workers and ultimately improve the efficiency of the industry thereby reducing costs.

The installation, operations and maintenance of offshore wind farms are particularly challenging compared to other pieces of infrastructure. To install, operate or maintain an offshore wind turbine, personnel and materials must be transported by sea and safely loaded onboard a turbine. Completing inspections of wind turbines is challenging and relatively expensive, this places more importance on maintenance planning and prediction than would be needed for an onshore turbine for example.

This research began on the particular problem of accessibility. That is how to efficiently and safely make sure that materials and personnel are able to access turbines, when they are needed. As the research developed it became clear that safety was a particularly important part of this challenge that had received less attention in the literature. The accessibility challenges, remoteness and dispersed nature of wind farms all create hazards that are not found in the same way in comparable industries such as offshore oil & gas, fossil power generation or onshore construction.

The offshore wind industry can be considered as a high risk industry for offshore workers. Offshore wind technicians work in challenging conditions, with a typical day involving transport to a work location by a vessel or helicopter that could be 40 or 50 km offshore. Once at the work location they need to complete a safe transfer onto a turbine and carry out maintenance activities that will involve climbing ladders, moving through confined spaces and completing physically demanding work activities. All of this is done inside a complex machine situated far from land and emergency support services. In recent years there have been calls from industry observers warning that the safety performance of the industry needs to improve and noting that the risks are serious and increasing as the industry develops. An article from Ponting in the Health and Safety Bulletin argues that while the industry is experiencing rapid growth, safety performance is not improving and may be declining [11]. Key challenges were cited as including, skills shortages, the introduction of new technologies and the development of projects in more challenging sites with deeper water and harsher meteorological conditions.

The UK has one of the most developed offshore wind markets but has faced recent criticism. In July 2020, Trevor Johnson of the Health and Safety Executive wrote to industry to express concerns over safety performance [12]. The letter commented that improvements in wind industry safety performance have *"at best stalled, if not reversed"*. He highlighted several incidents that have occurred in 2020 and called upon the industry to renew efforts to improve performance. Sectors beyond the UK have also raised concerns, the European agency for health and safety at work commissioned a report on the safety challenges associated with new *'green jobs'* [13]. The report identified that the risks related to offshore wind were significantly greater than onshore wind. They identified challenges including remote worksites, accessibility issues and lower profit margins as all being risks to safety performance. The United Nations sustainable development goals number 7 and 8 identify both the need for development of clean access to energy and also the promotion of *"safe and secure working environments"* to be important elements of global sustainable development [14]. It is important that offshore wind contributes to both goals. While there is an ethical responsibility of the industry to ensure its employees are not harmed, the economic benefits of a safety industry are also clear. The UK Health and Safety Executive estimates that workplace injuries cost employers £3.5 billion annually, furthermore a recent study on the economic benefits of investing in safety found a return in investment of around 1.3 for construction workers [15] [16].

Offshore wind includes challenges relating to personnel safety and process safety. While the process elements of offshore wind do not include the major hazards seen in petrochemical industries, there are still a number of significant process related hazards. Offshore workers are dealing with large complex rotating machines generating electricity. Works in the nacelle can pose hazards from high voltage electrical equipment and high pressure hydraulic systems. Serious process related failures such as the loss of a blade or even the entire rotor due to a shaft failure are not unheard of. There are also fire risks associated with the machinery and electrical equipment in the nacelle. Complex operations are also involved in operating an offshore wind farm, such as personnel transfer from vessels to the turbine, and major component exchanges offshore.

In order to understand the safety challenges related to work in the offshore wind sector, it is important to understand relevant parts of the industry which make it unique as compared to other areas such as oil & gas or onshore construction. These are set out in the following sections.

1.1.1 Offshore wind turbine configurations

Workers in the offshore wind sector are engaged on a daily basis in the installation, operations and maintenance of wind turbines and the associated infrastructure. Figure 1.3 shows typical horizontal axis wind turbine with different foundation configurations. From left to right these are:

- Monopile fixed bottom foundation,
- Jacket fixed bottom foundation,
- Tension legged platform floating foundation,
- Spar buoy floating foundation,
- Raft floating foundation.

The primary choice of foundation is based on water depths, with monopiles and jackets used in water depths less than 60m. Floating foundations are used in deeper waters. The industry has yet to converge on a foundation design of choice yet for floating wind turbines. The choice of foundation design can impact operational safety as it influences the access methods as well as the working methods for installation and maintenance. Platform designs with greater working space at the entry points such as the jacket type of floating raft could be beneficial in offering more flexibility in how workers access the turbine and are able to move equipment and materials around. Floating foundations create challenges around the access for workers moving between two moving structures and also working in moving platforms. These issues are not a primary focus of this research but should be addressed as part of a technical safety or "safe by design process" during the development stages of any project. The implementation of these processes will be considered in Chapter 6 while looking at the management structures that the industry uses to manage wind farm design, installation and operation.

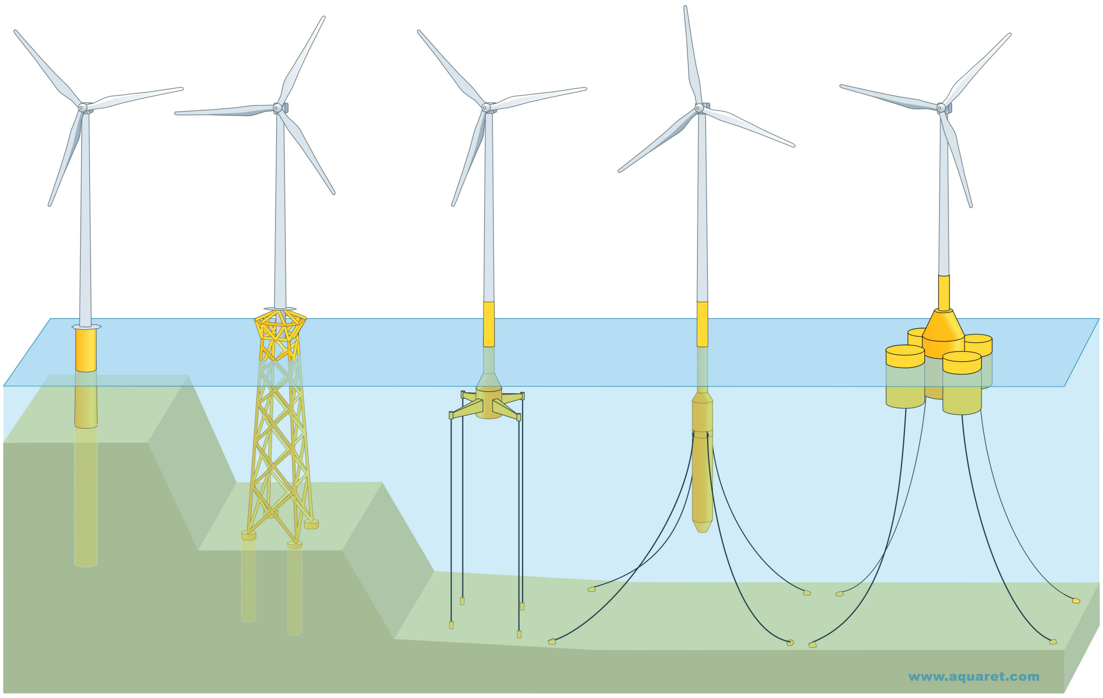


Figure 1.3: Sketch showing fixed bottom and floating foundation types

1.1.2 Wind farm access

One aspect which makes work in the offshore wind sector unique is the challenge in actually getting workers to and back from the work locations. The factors around this are called "accessibility". Accessibility at its simplest is the amount of time that offshore wind turbines can be safely accessed for maintenance or other activities required for the operation of a wind farm. Accessibility is a key challenge for offshore wind farms, for wind turbines to continue operating consistently they must be accessible on a regular basis by personnel, plant and equipment to carry out necessary maintenance activities.

Accessibility is dependent on several factors, these include, the type of transportation systems being used, weather conditions, distances to be travelled and the method of accessing from the vessel on to the turbine. The type of work to be done is also important as it defines the time needed for the work to be completed. Accessibility can be calculated by simple mathematical calculations and is represented as a percentage of time that the turbine can be accessed safely. Research has shown that for an availability of 90% to be achieved an accessibility of 80% is required [17].For higher availabilities then even higher accessibility will be required.

Periods in which works can be carried out are called weather windows, the complication of having to plan and complete all works within available weather windows hugely increases the difficulty of building and maintaining the offshore wind infrastructure.

1.1.3 Access systems

Once workers have been able to reach an offshore turbine they must gain access to the structure to carry out their works. Access to turbines can be typically be achieved at three different locations. These are from a boat landing point at sea level, from a platform at the top of the transition piece and from a helicopter landing platform at the top of turbine [18]. Examples of each access point are shown in figure 1.4

Access to wind turbines can take place from helicopter or boat, with the majority of access transfers being made by boat via boat landing [18]. The main types of boat used are Crew Transfer Vessels (CTVs) and Service operation Vessels (SOVs) [18]

CTVs access turbines by pushing on to a fender attached to the turbine. The CTV will have an egress point at the front of the vessel, the CTV approaches the turbine and pushes onto the fender, the friction created between the boat and the fender stabilises the CTV while technicians can step across onto a ladder. Figure 1.5 shows a CTV at an offshore wind turbine in calm seas.

(a) Gangway access to top of transition piece

(b) Helicopter accessing top of turbine

(c) CTV accessing boat landing point

Figure 1.4: Typical offshore wind turbine access points

CTVs have been the most common method of access to turbines at offshore wind farms constructed to date, as these have typically been located less then 30 km from shore. CTVs are relatively fast and inexpensive compared to other access methods, however they are more limited in the conditions in which they can work. CTVs can usually transfer crew onto a turbine only in wave heights less than around 1.5 m [18].

SOVs typically use motion compensated gangways that provide a stable walkway across to the turbine. Figure 1.6 shows an example of an Ampelmann motion compensated gangway.

SOVs are much larger vessels than CTVs and can carry more technicians and more equipment. They are also able to transfer technicians in much larger wave heights. Modern motion compensation systems are able to operate in wave heights up to 3 m or more [18].

Figure 1.5: Photograph of a CTV at a turbine in calm seas

1.1.4 Helicopter access

Transfers can also take place from helicopters, in which case the limiting weather conditions are wind speeds and visibility. Helicopters typically allow access up to wind speeds of 20 m/s and technicians and materials can be dropped off on a helideck at a substation or the hoisting platform of an offshore turbine [19]. Helicopters offer obvious advantages in speed of access while have limitations due to the high expense and limits on carrying capacity. Payloads for helicopter access are around three to six technicians with around 100 kg of tools or parts per technician [19]. Helicopters form a key part of offshore wind emergency response plans and will generally be the fastest method for evacuating seriously injured workers. The use of helicopters for emergency response will be discussed further in later chapters.

The development of innovative access solutions is ongoing. One of these is the "get up safe" system developed by Pict Offshore which uses a winch system to lift a technician from the deck of a vessel onto the turbine [20].

Other access systems being developed include the "L-Bow" which can be deployed from a shipping container and uses an articulated arm to lift equipment or personnel [21]. The containerised system could be quickly fitted to existing vessels.

The Z-bridge system uses an extending arm with a travelling cage that rides along

Figure 1.6: Photograph of an Ampelmann motion compensated gangway

the arm and delivers personnel or material onto the turbine platform [21].

1.1.5 Automation and drones

The use of automation and drones have the potential to reduce the requirements for workers to be exposed to risk offshore. The reduction in work hours spent offshore will generally have a positive impact on safety performance, however unexpected interactions of autonomous systems can also create new unforeseen hazards [22]. The primary development use of drones for offshore wind work has been for the inspection of wind turbine blades to assess damage and maintenance requirements [23] [24]. This has the potential to reduce work at height activities which will have obvious benefits. A recent review found that unmanned aerial vehicles (UAVs), climbing robots and underwater robots all have potential applications for offshore damage assessments [25]. This review found that the current technologies are limited by a lack of training data for machine learning, motion control capabilities and weather conditions. The use of these technologies is not in scope of this work, however they have clear potential to reduce exposure to offshore workers and thereby improve safety performance.

The use of unmanned rescue vessels for persons who have fallen overboard are also being trialled. Zelim have developed an autonomous system which can rescue a survivor from the water autonomously. This has the potential to improve emergency response solutions for the industry [26]. Emergency response as a key part of the safety performance of the industry will be discussed further in later chapters.

1.1.6 Meteorological conditions

The accessibility of turbines is heavily influenced by the meteorological conditions at the turbines. Transfers are only able to take place when wave heights and wind speeds are low enough. Other weather factors such as visibility due to fog, or rain and lightning, will also limit the ability to work safely.

When planning maintenance missions it is not only the weather conditions at the time of transport that need to be considered, but also the short term forecast. It is important that weather conditions will remain favourable long enough for the maintenance task to be completed and for workers to return to base safely. The required time to carry out the works is called a weather window. The length of window required will depend on the length of the maintenance task to be carried out.

Wave conditions can be characterised by wave height, direction and period. Wave heights are usually classified by the significant wave height H_s.Where H_s is the mean height of the highest one-third of the waves. H_s is the factor typically used in offshore wind maintenance contracts to determine when it is possible for a contractor to carry out maintenance works. If the H_s is below a given safe level than the contractor would be expected to be able to complete it's works during that time period.

There are limitations to using H_s as other attributes of the wave conditions will also effect the ability of vessels to complete missions, for example wave period and direction, sea currents, and also wind speed and direction [18].

Offshore wind operations and maintenance (O&M) is different to O&M in other industries due to it's dependency on the weather conditions. Onshore wind O&M will be carried out by land vehicles and will be far less impacted by the weather. Even in offshore oil & gas, maintenance teams and equipment can be permanently based onboard oil rigs and carry out maintenance tasks and inspections on the equipment all year round. Due to this weather restricted environment, weather forecasting is an extremely important part of offshore wind operations and maintenance planning.

1.1.7 Safety Science background

There is an extensive amount of research in the safety science body of knowledge covering all kinds of industries from nuclear to medical and aviation. This thesis has drawn on some of the key research from other areas and it is useful to set the context of where the academic study of safety lies today and how this research fits into that landscape. Relevant aspects of the safety literature will be discussed in more detail in the literature review and the relevant Chapters. A key concept is the definition of what is safety? Table 1.1 sets out important definitions as they will be used in this work. The Oxford English Dictionary defines it as "The state of being protected or guarded against hurt or injury; freedom from danger". This work uses the definition found in the systems safety literature which is "an absence of losses", where a loss would be an injury or loss of human life in this context.

The safety science research has recently seen the emergence of new ways of thinking around safety, dubbed as "Safety II". This is as opposed to "Safety I" which is made up of the commonly used and accepted ways of managing and analysing risk and safety in industrial systems. Safety I would include risk assessments, accident statistics, and safety management systems that would be found in almost all workplaces and are generally required by legislation in most jurisdictions. Critics of safety I methods argue that safety performance in many industries has stagnated or regressed. Safety I methods are also criticised as being unequipped to deal with modern systems which include automation and human machine interaction [27].

Safety II proposes new approaches to thinking about safety and believes that a focus on what goes right rather than what goes wrong should be the focus of how we manage safety. Safety II includes methods such as resilience engineering (Hollnagel) [28], human and organisational performance (HOP) from Conklin [29] , and safety differently (Dekker) [30]. Key concepts of Safety II are that it rejects human failure as a cause of accidents, and believes that focusing on an absence of danger is insufficient. Critics of the Safety II methodologies argue that Safety II has to date only produced theories with very little in the way of methodologies for improving safety or of validated studies showing its effectiveness [31]. Systems based safety methodologies developed by Leveson can also be considered as part of the Safety II way of thinking however, these methods have been shown to have useful impacts such as discovering previously unseen failure modes [32]. Systems safety methods have also seen adoption by advanced industries such as avation and aerospace.

This focus of this thesis is not to debate the merits of the various safety science philosophies as they are currently defined in the literature. However, it would seem that there are truths in the criticisms of both Safety I and Safety II methodologies. The most promising of the new safety methodologies is systems based safety or STAMP as developed by Leveson. This has demonstrated proven outcomes in other industries and so this methodology was selected for further analysis into potential applications to the offshore wind industry. This work sets out to assess how safety is currently managed in the offshore wind industry and investigate how these methods could be improved or methods from safety research literature may improve performance. In this way it draws on methods used in both Safety I and Safety II. Further discussion of the safety literature is set out in Chapter 2.

1.2 Research question and approach

Based on the challenges set out in this introduction, the objective of this thesis is to answer the following research question:

"How can we understand, measure, predict and address the safety challenges of the offshore wind industry to allow for the reduction of injuries, and the avoidance of major accidents in the future?"

To answer this overall question this project went through several stages which are set out in Chapters 4 to 7. The overall methodology is described here, but each Chapter includes its own detailed methodology section as necessary.

The initial phase of the PhD research was the literature review. This was completed in two parallel streams. The first exercise was to perform a mind mapping exercise around the general topic of accessibility. The second part was a traditional literature review using keywords and research databases. A mind mapping exercise was completed around the keyword "accessibility", this generated a number of topics, which then generated further layers of sub topics. This exercise was completed together with the PhD Supervisors. The high level summary mind map is shown in figure 2.1, and the full mind map is included in Appendix A. At the initial stage key research papers were identified around topics for initial reading. As the literature review was progressed further sub topics were identified, with some branches expanding down to 8 levels. The mind map was then used as a visual aid to identify areas around the topic that have received less attention from the research community and where gaps in the literature may be found. In parallel with the mind mapping exercise a traditional literature review search was also completed. An initial literature search plan was developed using keywords generated from the PhD research question. Keywords such as data analysis, wind turbine, accessibility and synonyms were then used in search engines to find related papers. Online search engine Compendex was the main search engine used. Search plans were also developed based on the work package scopes keywords. Suitable papers were then exported to Endnote and organised in groups based on topic. The results from each search were recorded in a search log including, keywords used, databases searched, papers returned and papers selected for export. Additional papers of interest were also discovered through the reviews of references in key papers and these were also downloaded to Endnote for future reading. The research mind map and research library exported to Endnote then generated the reading and route map for continuing with the literature review. As research papers were reviewed notes were then collected in a word file to document key findings and relevant pieces of information from each paper.

The literature review write up was then completed following the initial structure that was developed by the mind map. The full literature review is included in section 2.

Tackling the problem of safety is complex as their are so many interrelated components that work together to determine if the industry operates safely. It was decided that the research should begin at the highest level, first identifying what research had been done, and what available performance reports indicated about current performance, this is set out in Chapter 3. The research then moved to a more detailed in depth analysis of industry accident statistics and drew on statistical analysis methods that have been applied in other industries, these methods are discussed in 4. In order to improve how the industry measures safety performance and risk, methods in developing leading indicators of safety performance were set out in Chapter 5. Finally the methods used in systems safety were applied see how these can be used to improve how the industry manages safety and also how floating wind operations could benefit, this is set out in Chapters 6 and 7.

In line with the overall aim of the research, the thesis can also be viewed as progressing through three interrelated themes: *understand*, *measure and predict*, and *address*. Chapters 2 and 3 focus on *understanding* the context and current state of safety in the offshore wind industry, through a review of relevant literature, accident statistics and regulatory arrangements. Chapters 4 and 5 then *measure and predict* safety performance by critically evaluating existing performance indicators, applying statistical methods to industry data and proposing a framework for leading indicators tailored to offshore wind. Finally, Chapters 6 and 7 *address* system-level risks and opportunities for improvement by applying systems safety methods to the development, operation and future evolution of offshore wind and floating wind projects. Chapter 8 draws these strands together, revisiting the three themes and summarising how the work contributes to understanding, measuring and addressing safety performance in the offshore wind industry.

1.3 Novelty and contribution

From the initial literature review carried out it was determined that novel research would be valuable in the following areas as little to no research had been done in these areas:

1. The current state of safety performance in the offshore wind industry and how it compares to similar industries.

2. The measurement and understanding of safety performance in the offshore wind industry

3. The development of safety leading indicators for offshore wind

4. The application of systems safety theory to the offshore wind industry

The following Chapters of this thesis address these knowledge gaps and make novel contributions to the literature in this area. Chapter 3 addresses gap one by making an analysis of the current safety performance in the industry, it makes a cross industry analysis of safety performance, reviews how safety legislation manages performance and proposes a new metric for risk exposure measurement to consider how risk levels will grow in the future.

Chapter 4 tackles knowledge gap 2 by making a detailed assessment of safety performance measurement methods used in the industry, completing a statistical analysis of accident statistics by work activity and finally by proposing improvements to existing performance measurement methods.

Chapter 5 addresses knowledge gap three by developing a framework for leading indicators of risk specific to the offshore wind industry, reviewing current work in the area and finally proposing a set of leading indicators of risk specific to offshore wind.

Finally, Chapters 6 and 7 apply methodologies from the safety science body of knowledge to the offshore wind industry where they have either not been applied or applied in a very limited way. Chapter 6 applies systems safety methodologies to the industry to make an industry level risk assessment of the development and operation of offshore wind. This reinforces the work done in Chapters 3 to 5, by highlighting new risks, mapping the control structures of the industry and expanding the development of leading indicators of risk. Finally, Chapter 7 looks at the application of systems safety methodologies to the floating wind sector and how it can be used to address novel risks from the interactions of new technologies.

Phrase	Definition
Safety	An absence of losses
Hazard	A system state that will lead to a loss in worst case environmental conditions
Loss	Loss of human life or injury
Accident	Any undesired and unplanned event that results in a loss
Risk	Severity of an event combined with probability of occurrence
Leading indicator	an event that indicates a change in risk level or change in the performance of the safety management system.
Lagging indicator	a measure that records events that have cause injury, loss or property damage, such as an incident rate like TRIR.

Table 1.1: Key Definitions

1.4 Important definitions and scope

This research thesis sets out to push forward the research that can help solve some of the challenges around safety in the installation, operation and maintenance of the offshore wind industry. The scope of the research includes offshore operations and does not look at the onshore fabrication and staging activities associated with offshore wind.

It is important to set out the key terms and definitions around safety, to avoid any confusion, key terms and definitions will be set out here and used consistently throughout this research. The definitions used in research generally align with those used in the systems safety literature [27].

1.5 Research output

Peer reviewed journals and conference papers published, submitted or in draft are listed below as are conference presentations which have been completed.

Published:

1. Offshore wind H&S: A review and analysis. Renewable and Sustainable Energy Reviews, 2024. (Includes contributions of Chapters 2 & 3)

2. Development of a framework for a systems-based risk analysis of the offshore wind industry. Advances in Reliability, Safety and Security, 2024.(Includes contributions of Chapter 6)

3. Application of systems safety principles for O&M of floating offshore wind, Journal of Physics, 2024. (Includes contributions of Chapter 7)

In draft:

1. Safety Performance Measurement in the Offshore Wind Industry: Progress, Challenges, and Opportunities.(Includes contributions of Chapter 4)

1. Systems theory based analysis of the UK offshore wind industry (Includes contributions of Chapter 6)

Invited presentations:

1. Application of systems safety principles for O&M of floating offshore wind, Deepwind 2024

2. Development of a framework for a systems based risk analysis of the offshore wind industry, European Safety and Reliability Conference 2024

Chapter 2

Literature Review

Figure 2.1 shows the mindmap developed as the starting point of this literature review. This was used as a tool to structure the review and develop the following section of this report. While the overall research theme began as accessibility, during the literature review it became clear that safety in offshore wind was a key challenge and this became the focus of the research project.

The review begins with a discussion of the available literature in offshore wind H&S, and then delves into the wider body of safety science research. The review then touches on other aspects of offshore wind operational research which can have an impact on safety outcomes.

These include accessibility and weather windows, vessel strategies, weather forecasting and O&M modelling. The fully expanded mindmap including all levels is included for reference in Appendix A

2.1 Health & safety (H&S) in offshore wind

As the offshore wind industry (OWI) is still in its relatively early stages of development there is a small amount of research on the specific H&S challenges it faces. However, there is a significant body of research on all aspects of H&S from other industries and much of this can be drawn upon to help the OWI. This section reviews the literature specific to the OWI and draws on key areas of research from other industries that are

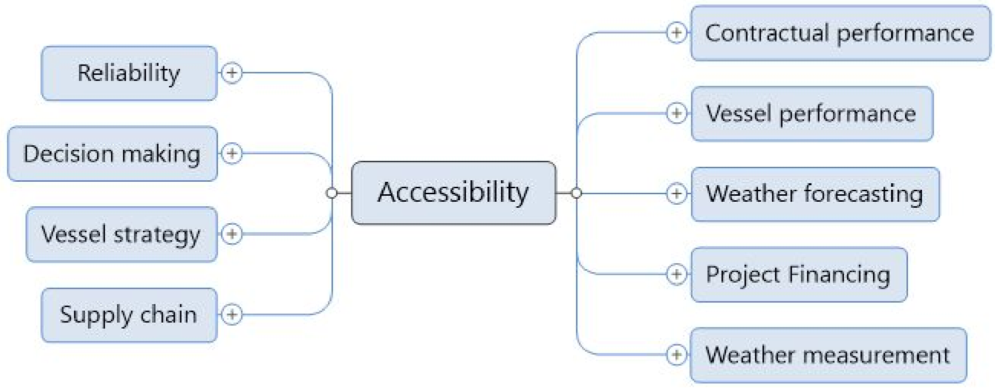


Figure 2.1: Level 1 Research Mind Map

applicable to offshore wind.

2.1.1 Safety Key Performance Indicators

In order begin to understand the challenges of safety in the industry then exploring how it can be measured is an important starting point. H&S Key Performance Indicator (KPI) research is far more widespread in other industries such as construction, nuclear energy or oil & gas and much of this research is applicable to offshore wind H&S. Several debates in the research literature have received significant attention over the past several decades. The key topics of discussion have been around, the validity and usefulness of lagging safety indicators such as TRIR, the potential for the development of leading safety indicators and how to define concepts such as leading indicators and develop frameworks for their implementation.

The industry with the most overlap to offshore wind and with a significant amount of research in the area is offshore oil & gas, and there is great potential for the OWI to learn from work that has been done there.

Part of the debate in academic research on the development and use of safety indicators has been around key definitions, so those that are used here are summarised below for clarity.

Key definitions
Safety indicators - any indicator or measurement used to measure an aspect of safety performance.
Leading indicators - a measure that aims to predict H&S performance or show a change in risk level before an incident occurs.
Lagging indicators - a measure of incidents that have occurred, that aims to provide information about safety performance.
LTIR - Total number of lost time injuries (incl fatalities) per million hours worked.
TRIR - Total number of recordable injuries per million hours worked.
Recordable injuries - Include: fatalities, lost workday cases, restricted workday cases and medical treatment cases.
Process hazard – a hazard arising directly from the operation of plant or equipment i.e a turbine blade failure
Personnel hazard – a hazard arising around human activity i.e a fall from height hazard.

OWI incident data & indicators

Available sources of H&S data from the offshore wind industry are quite limited. Annual reports from G+ contain incident data from its members. Statistics reported for 2021 showed there were 50 lost work day injuries, indicating that there is huge room for improvement regarding safety in the industry. Injuries on CTVs were one of the most common incidents with 79 occurring in 2020 and 85 in 2021 [33]. The related work processes with the largest number of incidents were, 'transit by vessel', 'vessel operations' and 'transfer from/to vessel'. Aside from G+ reports, sources of specific offshore wind incident data are not widely available.

Asian et al completed a data mining study of media sources in an attempt to analyse the frequency and causes of accidents involving wind turbines [34] [35]. They used a data mining approach due to a lack of available incident data from the wind industry. The study analysed 240 incidents between 1980 and 2013 which occurred both onshore and offshore. The nature of the data collection posed obvious limitations to the study as the authors could only find incidents that had been prominent enough to be reported in the media. The paper found 240 incidents between 1980 and 2003, which includes on and offshore wind farms. The key finding of the paper was that accidents involving humans were mostly related to transportation activities during wind farm construction or operation.

A similar study by Sovacool et al. looked at the safety performance of all low carbon energy technologies [36]. This used a database from 1950 to 2014 and only considered incidents involving a fatality, data for offshore and onshore wind were not separated. The study found that wind had the worst fatal incident rate when normalised by energy output. Wind energy was characterised by lower impact but high frequency events, as opposed to nuclear energy which has a small number of events but which can have a very high impact. Common causes of incidents were fire, blade failure and transportation failures.

Most jurisdictions also have legislation that require employers to report all H&S incidents. Within the UK, all employers have a duty to report H&S incidents, under legislation known as RIDDOR [37]. The data is reported on an industry sector basis and does not include a category specifically for offshore wind or renewable energy. Instead, the statistics are included in the category of electricity generation. As such, a specific analysis of this data to look at offshore wind performance is not possible.

Within industry it is common to manage and report business performance by the use of Key Performance Indicators (KPIs) [38] . Reporting of safety performance can also be included in KPI reporting. There has been some research regarding the best use of KPIs within the OWI, although not always with a strong focus on health and safety. The following section reviews the latest literature on KPIs or safety indicators and H&S performance measurement.

Gonzalez et al reviewed the use of KPIs in the wind industry, they found that their use was not widespread and that there was little literature available on the subject [38]. The paper focused on energy generation performance, reliability, maintenance and finance but did not consider H&S KPIs. A set of KPIs for use in wind farm O&M

were proposed but did not consider H&S measures. Pfaffel has also studied the use of KPIs in offshore wind farms through an industrial survey [39]. The study found that while 20 out of 28 respondents used performance KPIs to monitor turbine operation, only 5 respondents used any H&S KPIs. The H&S KPIs found to be in use were:

- Total accident rate,
- Total lost time occupational illness frequency,
- Fatal accident rate,
- Recordable injury rate.

Torres et al have proposed safety and security KPIs that incorporate quantification to demonstrate safety and security levels on an offshore wind farm [40]. The paper proposes the concept of a key risk indicator (KRI). A KRI is defined as 'a measure for possible exposure or loss'. These consider security threats such as cyber-attacks or piracy, as well as safety threats to personnel. One proposed KRI tracks the risk of personnel being stuck on a wind turbine, it would take into consideration metrics such as time of day, wave heights and light levels. The paper proposes that there should be occupational health and safety goals as part of an operational wind farm set of KPIs.

Seyr and Muskulus looked at KPIs and drew on knowledge from the oil and gas industry to propose safety KPIs for use in offshore wind [41]. The paper reviewed incident data from the OWI and identified a set of safety indicators that could be implemented to monitor safety performance. They proposed lagging indicators were split into four categories [41] including technical failure, work environment and training, transport, and external factors.

Organisational safety indicators were also proposed directly from research related to the oil and gas industry [41]. The indicators from these papers include KPIs to measure the state of the O&M planning system, such as no. of work orders where material is fully received in the plant and time to response after a failure [42] [43]. They also include measures of the cost and schedule performance of the project or facility, as these could give an indication if there is a risk of shortcuts being taken due to time and cost pressures [43]. The oil and gas research drawn on by Seyr and Muskulus highlights that the oil industry has recognised that safety indicators must be more diverse than traditional lagging indicators recording the frequency of incidents.

Research has also been undertaken to assess the inter-dependencies of KPIs and 'safety and security goals' [44]. This study by Kopke identified nine safety and security goals for an OWF, which were modelled to assess how they relate to each other and effect the overall state of the wind farm This research was further developed to include a Bayesian Network to improve the modeling of the wind farm [45]. These models all relate to the system or process safety of the windfarm and how they interact with personnel safety, rather than safety risks to personnel due to their work activities or behaviours.

Torres et al proposed a method for the development of safety and security KPIs that incorporate quantification to demonstrate safety and security levels on an offshore wind farm [40]. The paper proposes using key risk indicators (KRI). A KRI is defined as 'a measure for possible exposure or loss' [40]. These consider security threats such as cyber-attacks or piracy, as well as safety threats to personnel. One proposed KRI tracks the risk of personnel being stuck on a wind turbine, it would take into consideration metrics such as time of day, wave heights and light levels. The paper proposes that there should be occupational health and safety goals as part of an operational wind farm set of KPIs. KRIs as proposed by this method would be considered as leading indicators as they are attempting to measure the risk of future negative events.

Research has also been undertaken to model the safety and security status of a wind farm. A study by Kopke identified 9 safety and security goals for an OWF, which were modelled to assess how they relate to each other and effect the overall state of the wind farm [44]. This research was further developed to include a Bayesian Network to improve the modelling of the wind farm [45]. These models generally relate to the system or process safety of the windfarm and how they interact with personnel safety, rather than safety risks to personnel due to their work activities or behaviours. The authors argue that safety and security of the wind farm system need to be considered together, as failures in one area will impact the other.

Lagging indicator research

Construction industry research has looked at the statistical significance of lagging indicators such as TRIR to measure H&S performance [46]. The effectiveness of measures such as TRIR have been questioned, with warnings that they should only be used in certain situations such as cross industry comparisons where there are very large datasets to use for the calculations [46].

A global multi-industry survey from ERM in 2018 found that 70% of respondents were using lagging indicators to manage their safety performance and only 26% were using leading indicators. The survey was conducted by interviews with over 140 senior safety functional leaders from a variety of organisations and was not specific to wind or the energy industry.

Lagging indicators appear to still be the most common method of measuring H&S performance and industry risk levels, however the limitations of lagging indicators have been well documented in the literature. Lagging indicators focus on recording incidents that have occurred in the past. It is obviously important to record and investigate injuries, lessons can be learned to prevent similar incidents in the future and information can be collected that may help to improve safety management in the future.

It is often said that lagging indicators are not interpreted correctly. Striccoff pointed out that a stable safety management system will produce incidents with unpredictable frequencies [47].

If a project suffers zero incidents one month and two the next, it does not necessarily mean the risk levels on the project have changed, but depending on the number of hours worked large changes in the injury rates might be seen. A recent report by the Construction Safety Research Alliance explored these issues in depth. The report looked at the statistical significance of TRIR to measure H&S performance and concluded that it is rarely correctly used [46]. The research questions the effectiveness of measures such as TRIR, the main concern raised is that they are used without consideration of their statistical validity. TRIR is often reported to two decimal places, however, when the statistical distribution underlying the related process is considered this level of accuracy is not realistic. They also highlight that most variation in TRIR is due to randomness, and does not correlate with fatal incidents. The study placed a call to action on industry and researchers to find improved methods of measuring safety performance and using incident data.

The incident triangle, or Heinrich's triangle has often been used as a guide for the relationship between the number of minor incidents and major incidents such as fatalities. Heinrich's triangle was developed in the 1930s and was believed to describe the relationship between minor injuries and serious injuries as resembling a triangle. Minor injuries occur frequently and represent the base of the triangle, as the triangle is ascended incidents become more severe with low frequency major incidents such as fatalities representing the top of the triangle.

Henrich's study was based on research from 5000 occupational injuries, it found that for every major injury there were around 29 minor injuries. A more recent study re-examined this ratio and found that it is now around 1,000 OSHA recordable cases for one fatality [48]. It would make sense that over time as safety management and industrial practices have changed that the relationship would change. The ratios would also be dependent on the accuracy and reliability of the incident reporting. The relationship has a logical appeal, as a useful heuristic, it makes sense that an organisation with lots of minor injuries because workers don't use the proper equipment, are badly trained and have poor management are likely to end up having a serious incident after some time.

However, as per Hopkins, it is also important to remember the other side to the relationship [49]. Just because an operation is generally well organised and has a low number of minor incidents, it doesn't mean that they are managing major risks properly, such as fire or explosion risk related to process safety. A further study on the Heinrich accident triangle analysed an incident database from the oil & gas contractor Schlumberger, this also found that the ratio between minor and major incidents has changed [50]. They concluded that focusing on minor incidents to reduce the risk of major incidents creates the risk of low probability high severity events being overlooked.

In an early paper from the oil & gas industry Toellner highlighted many of the drawbacks of relying on lagging data [51]. These include issues of under reporting and the use of case management to classify incidents as less severe than they actually are [52] [53]. One study from Australia found that only 19% of incidents treated by the insurance providers as recordable and work related were recorded with the same classification by the employer [54]. It was found that it was common to classify incidents as non work related or to downgrade incident severity by case management. The researchers in the study felt that this was as a result of pressure to reduce injury rates and over emphasis on rates, as opposed to companies purposefully trying to hide incidents.

Oswald has highlighted that it is possible to become too focused on the use of quantitative measures only to try to measure safety performance or risk levels and that qualitative measures should also be used [53].

Leading indicator research

Key issues around the use of KPIs for H&S performance management are the statistical validity of indicators and the distinction between different indicators such as leadings vs lagging and process vs personnel [46] [55]. Research from the construction industry is pushing for a move away from lagging indicator KPIs such as total recordable injury rate (TRIR) and into the use of leading indicators [56]. Leading indicators are measurements such as, frequency of pre-task planning meetings conducted, or number of site inductions completed. These indicators are intended to predict the future performance of a H&S programme, as opposed to a lagging indicator such as LTI rate that records past performance only. Hopkins has also identified the importance of discerning between leading and lagging indicators, stating that both are required for an effective system [49]. The concept of using leading and lagging indicators in conjuctuon is described as "dual assurance" by the UK HSEx (Health & Safety Executive) [57]. Hopkins identified that leading indicators are required for managing process safety, and stated that the likely frequency of events must be considered when looking at lagging indicators [49]. Hopkins also highlighted that lagging indicators are unlikely to be suitable for low frequency but high consequence events.

Hinze proposed the adoption of leading indicators into the construction industry, summarising the drawbacks of relying on lagging data. Including that incidents need to occur before anything is learned from lagging data, and that the accuracy and consistency of reporting lagging data is questionable [58]. Challenges highlighted in developing leading indicators were raised, including, organisational resistance, a lack of shared definitions and the complex challenge of implementation.

A review of leading indicators in the construction industry identified that there are a number of studies indicating that the use of leading indicators can have a positive impact on safety performance, however results of the correlations between indicators and performance are not consistent [56]. Definitions of leading and lagging indicators and of the concepts of passive and active indicators were also proposed. Through a meta analysis of the research nine leading indicators that were correlated with injury rates were found. Correlations between leading indicators and outcomes are calculated using incident rates such as the TRIR, so given the shortcomings of TRIR highlighted by the CSRA, it is less clear whether these correlations are significant [46].

Xu et al. completed a recent review of the use of leading indicators in the construction industry, the study developed a framework for classification of leading indicators and identified 16 that were found to be in use in the construction industry [59]. They proposed that while implementing leading indicators will likely have positive effects, there are many pitfalls. Recommendations from this study including using both qualitative and quantitative measures, considering temporal effects in the use of indicators and ensuring that an "ecosystem approach" is used in their implementation.

Grabowski et al proposed a process for developing leading indicators using real world data from oil tanker operations [60]. The motivations for developing leading indicators were that lagging data did not give warning of low frequency, high impact events, and that once data was available it was too late to prevent the incident.

One paper outlined a process developed by Scottish Power to implement leading indicators across its business. This was developed to manage process safety in the aftermath of the 2005 Buncefield fire depot and subsequent recommendations made by the UK HSEx on the development of leading indicators for process safety [61]. The project identified eight risk control areas across the business and developed combinations of leading and lagging indicators for these. A key challenge highlighted was the difficulty in transferring an ideal project on paper into real world implementation, with recommendations for similar projects to focus on automation and a minimisation of paperwork burden.

The UK HSEx also set out a six point process for the development of process safety indicators, this was developed in the aftermath of the BP Grangemouth incident. The HSEx highlighted that while the process was developed for developing safety indicators to manage major hazards involved with handling chemicals and hydrocarbons, it could also be applied to industries with a need to manage process related hazards [57].

A paper by Skogdalen et al. looks in detail at the BP deepwater horizon disaster of 2010 and considers whether the risk measurement scheme used in the Norwegian oil industry may have helped to prevent that incident occuring in the drilling industry [43].

The RNNP is an annual report on the trends in risk level in the Norwegian Oil and Gas industry [62] . It publishes data every year on the health, safety and environmental performance of the industry. It was setup in 1999 with a goal of measuring safety risk in the Norwegian industry following major changes that occurred throughout the 90s. A key principle of the report is using a triangulation method to measure trends in risk, and not focusing on a single metric such as lost time incidents. The report also aims to use social science methods in addition to statistical reporting. The report collects data which includes measures such as, major incidents, occupational injuries, injuries with high severity and near misses. Data is also collected on the performance of barrier indicators, which are used as a form of leading indicator for major incidents. Barrier indicators include elements such as the performance from testing of fire & gas detection systems. The report also includes data from questionnaires with diving personnel that aim to take a measure of safety culture in the industry. When statistics are reported they are presented with a confidence interval based on previous years, this aims to indicate whether annual fluctuations are statistically significant. The research behind the methods used in the RNNP report has been set out in several papers [63] [64] [65].

Vinnem et al. set out a proposed process for developing indicators for major risks based on their research and lessons from the Norwegian risk level project.

The process for developing the indicators began with analysis of lagging data and selecting incident indicators based on historical incidents. Events were identified that can lead to loss of life or property, such as gas leaks. Data for these events is collected and barrier elements that prevent these events were identified. This led to the selection of tracking indicators to measure the performance of barrier elements such as the testing performance of gas leak detection systems [64].

The RNNP also uses innovative methods to present the lagging data it collects, these methods were developed based on research by Kvaloy & Aven [66]. This research proposed that classical statistical methods are designed to detect strong trends and are not useful for incident data, as by the time a strong trend has appeared a significant problem has occurred. They use a Bayesian approach to fit a probability distribution to the lagging data. This allows a confidence interval to be applied and give an indication of the expected range of future values. This range can then be compared to the actual value to indicate whether a trend is statistically significant.

More recent research has proposed that there are three methods for the development of leading indicators [67]. This is presented in the context of major accident prevention in the oil & gas sector and proposes that event chain, systems engineering and resilience engineering are three potential methodologies. While the most commonly used method to date has been the event chain other methodologies have the potential to improve work in this area.

Drawbacks of developing leading indicators include that once you start measuring an item people can become incentivised to manipulate the outcome of the indicator. Complaints can also be heard that leading indicators are used, just because the data is available, but there may not be any value added [68].

Leading vs lagging debate

There has been debate around the definitions of leading and lagging indicators, much of those arose from a special issue from Safety Science on the topic arising following a paper from Hopkins [69]. This originally arose into debates sparked by the publication of the Baker report into the Texas City oil refinery disaster with caused 15 fatalities and over 170 injuries [70]. The Baker report identified that BP were using indicators of personnel safety, such as recordable incident rates to measure their safety performance. However, this meant they were only measuring personnel safety performance and their was little focus on safety performance. The report identified that a strong process safety management system should include a combination of leading and lagging indicators.

Hopkins pointed out the confusion around leading and lagging indicators, and also pointed out the definitions can vary depending on whether we are looking at a process safety or personnel safety issue. As defined in section 1, for the purposes of this research, lagging indicators are those that record events that have occurred and caused injury or property damage. A leading indicator is generally, something that indicates a change in the risk level of performance of the management system before an incident has occurred. However, lagging indicators can also be used as leading indicators depending in the context. For example, small fires in a process plant can be leading indicators of a larger more serious event [55]. The usefulness of any indicator can be described by the "zoom effect", for example a fatality rate could be a useful industry wide performance indicator, however for a single organisation where fatal incidents would be very rare, the lack of a fatal incident in a given year, would not necessarily tell us about the performance of the safety management system [55]. So as we zoom in the indicator becomes less useful. More recently, there have been calls to more beyond the debate on safety indicators definitions and focus on the implementation of indicators to improve industry performance [67].

A further differentiator of safety indicators are the terms active monitoring and reactive monitoring, where active monitoring provides information before an incident occurs and reactive monitoring relies on incidents that have already occurred to provide information about the safety performance [57].

Process safety vs personnel safety

A key debate that has taken place in the literature is that of the distinction between process safety and personnel safety. A special issue of the journal Safety Science included this and similar topics and generated a significant amount of debate and follow on research [69]. The special issue was instigated by a paper from Hopkins which reviewed key documents related to the development of process safety indicators [55]. These were the Baker report on the Texas City Oil refinery and a UK HSEx document on the development of leading indicators for process safety [57] [70].

Process safety hazards are those which concern operation of the plant and hazards that arise from a fault in the plant operation. For example, in the case of oil and gas, the unintended release of gas or chemicals [55]. In a wind turbine, this could be an electrical fire in the nacelle or a blade failure. Personnel hazards don't relate to the operation of the plant but impact people working there. For example this could be a worker falling from height while working on a wind turbine tower. The confusion between personnel and process safety was found to be a factor in the 1998 explosion at a gas plant at Longford in Australia [49]. The plant had a very low lost time injury record, with zero LTIs in the previous year. The low injury rate gives an impression of a safe plant; however, this is only a measure of personnel safety, not process safety. Hopkins well known quote to explain this phenomenon was that, "An airline, for instance, would not make the mistake of measuring air safety by looking at the number of routine injuries occurring to its staff" [49].

Hopkins set out a clear definition of the differences between process safety and personnel safety [55]. Process safety originates from the US and is generally concerned with process involved in the extraction and processing of hydrocarbons and other chemical processes. Process safety hazards are those which arise from the process itself. In the context of oil & gas a process safety hazard would be a gas leak and potential for fire and explosion. While offshore wind does not have the same potential for major incidents, there are process related hazards. For example, a blade failure resulting in materials being thrown into the environment, or an electrical fire. Personnel hazards are those which arise directly from the interaction of personnel, such as slips, trips and falls that could occur during the activities of a wind turbine maintenance technician [71].

Safety indicators in the oil & gas industry

Research in the oil industry has focused on the development of process safety indicators to prevent major incidents. There is the potential to learn from this research and use aspects in the development of safety improvements for the offshore wind industry, so key aspects are reviewed here.

Skogdalen et al. looked in detail at the BP deepwater horizon disaster of 2010 and considered whether the risk measurement scheme used in the Norwegian oil industry may have helped to prevent that incident [43].

Hopkins looked into how terms leading and lagging indicators are used in different contexts [55]. They highlighted that the definitions of leading indicators are not consistent, but this is often because the definition can vary depending on the context in which they are used. They concluded that using leading and lagging indicators is important, particularly when managing process safety. The international association of oil & gas producers publich an annual report on safety performance indicators for the oil and gas industry [72]. The report publishes incident rates such as thr TRIR and LTIF from across the global oil industry including the offshore sector. It includes data from 48 member companies with over 2.5 billion hours worked in 2020.

2.1.2 Safety science theory

There are a range of accident models that attempt to understand why accidents occur and these have evolved over time as industry has changed and become more complex. Accident models are important to help understand why accidents have occurred, to help prevent future accidents and to help quantify the probabilities of future accidents. Rausand classifies accident models into six groups [73], these are:

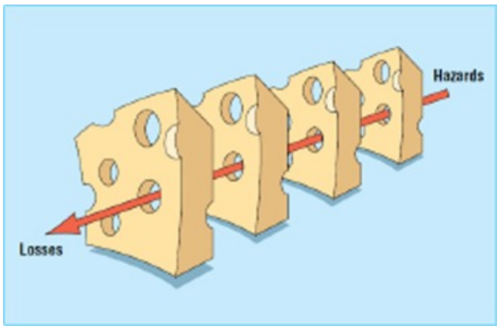
1. Energy and barrier models
2. Event sequence models
3. Event causation and sequencing models
4. Epidemiological models

5. Systemic accident models

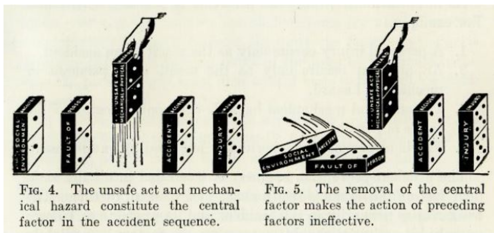
6. Accident reconstruction methods

A full discussion of all types of accidents models is beyond the scope of this work, however it is important to understand how these models have developed over time to explain accidents in ever more complex industries.

One of the earliest and best know accident models is Heinrich's domino model. Heinrich identified five causal factors and events that are present in most accidents, one of these events triggers the others in a domino chain. The Heinrich model was simplistic and focused on people as being the main cause of accidents [73]. This was probably reflective of the simple industrial systems in place at the time of development. Reason's Swiss cheese model is classified as an epidemiological model and has been highly influential since its inception. This uses slices of Swiss cheese as barriers to the occurrence of accidents. Holes in the slices represent latent conditions or failures, if there are sufficient holes aligning through the barriers accidents occur. Systemic accident models were developed as a result of a belief that existing accident models were insufficient to explain accidents occurring in modern complex socio-technical organisations [27]. This research set out in Chapter 6 uses methods from STAMP theory which is part of the group of systemic accident models.



(a) Reason's swiss cheese model [74]



(b) Heinrich's domino model [75]

Figure 2.2: Famous accident causation models

Competing safety science theories have recently been categorised into the concepts of Safety I and Safety II. Safety II as a concept arose in the mid-2010s as a reaction to flat-lining improvements in accident rates. Key proponents are Hollnagel and Dekker [76] [30]. Hollnagel defines safety as a state when as many possible things go right, and that a safe system will be resilient to perturbations. This is as opposed to the traditional Safety-I approach to focus on what goes wrong and reacting to events and preventing recurrences. Hollnagel proposed that safety is created by allowing for performance variability, meaning that people or the system can adjust to events without failing. It is also defined as a proactive approach where humans are viewed as a resource rather than as a source of failures. Dekker proposed the concept of "Safety Differently", this also emphasies a focus on humans being a resource rather than a cause of accidents. Dekker states that traditional safety methods focus on linear cause and effect and a compliance with bureaucracy [30].

A recent paper by Cooper made a comparison of the two groups of safety theories (Safety I and Safety II) [31] . They found that Safety I includes most of the traditional safety management methods used in industry today, such as safety management systems, safety policies, accident data collection, risk assessment and a focus on accident prevention and the prevention of harm. More recent initiatives within safety science theory would also include safety culture, safety climate and behaviour based safety. Safety II includes more recent theories such as Resilience Engineering by Hollnagel, Safety Differently by Dekker and Human and Organisational Performance by Conklin. These theories have been called the new view and some of the key features are a belief that focusing on the absence of danger is insufficient and that there is a need to study what goes right to create to create a safe environment. They also reject the idea that humans are always the cause of accidents and believe workers should have more influence over managing safety. Coopers critique of these theories is that they have yet to produce any validated results to prove they can improve safety performance, and that they actually still rely on on the methods used in Safety I [31].

High reliability organisation (HRO) theory proposes that even in highly complex socio-technical systems accidents can be prevented through effective management and control. HRO theory grew out of Perrow's normal accident theory which proposed that in tightly coupled, complex systems accidents are inevitable [77]. HRO theory was based on the successful operations in complex operational systems such as aircraft carrier flight operations, nuclear power plants and air traffic control [78].High reliability organisations were identified as those that exhibit certain key attributes, including, hyper complexity and tight coupling, large numbers of decision makers in complex communication networks and more than one critical outcome [78].In a recent scoping study by Dyer they found that while HRO has become an important safety paradigm and has had influence on industry, there are few studies showing empirical evidence of its benefits in reducing accidents [79].

2.1.3 Systems theory

The use of systems engineering theory to manage safety has been developed successfully in some complex industries. Proposals to use systems theory to improve safety outcomes were developed by Leveson [27] [80]. Systems engineering theory was developed after World War 2 to manage the development of complex engineering systems such as intercontinental ballistic missiles. It was recognised that existing methodologies were not adequate to understand complex systems such as those required for missile systems. A systems based safety management program was developed and implemented by the US Navy to manage the design and operations of nuclear submarines. It has also been proposed by Leveson and others that systems engineering techniques can and should be used to manage operational and managerial aspects of safety management. While these tools have been implemented in places such as nuclear submarines, there is potential for lessons to be learned for other industries such as offshore wind, which have less complexity or potential for major incidents, but could still use these processes to manage their own challenges [81].

The systems developed by Leveson are collectively known as STAMP and represent a new framework for accident causality, however they have now begun to be used for broader applications. A joint project between NASA and MIT was one of the first to apply the STAMP methodology to organisational safety [82] [83] [84]. STAMP recognises that accident causation includes social and organisational factors not just technical factors and therefore can be successful in analysing how organisations contribute to safety. The NASA/MIT project also applied dynamic systems theory to create a model of the factors that contribute to safety performance of an organisation and to determine what impact organisational changes may have. They found that generation of a dynamic model gave insights into how risk levels can migrate over time as varying factors change such as budgets, time pressures etc. [82]. The process to build a dynamic model of an organisation was set out in a thesis by Dulac [85].

STAMP has also been applied to an industry wide analysis to assess risks in the US drug industry by modelling the industry control structures (static modelling) and using a dynamic model to test policy changes [86] [87]. The systems based approach has also been proposed as a methodology to develop leading indicators of risk, this is an area of leading indicators that has not been explored significantly [81]. STPA is a new hazard analysis methodology that uses the principles of STAMP to identify hazards associated with complex systems [88], this methodology was used by Puisa to analyse SOV operations in offshore wind and found that it had potential to identify emergent hazards that arise as a result of the interaction between parts of a complex system. In this case an SOV operation was a complex system made up of multiple systems operating together, such as a walk to work gangway, an SOV with complex positioning systems and lifting equipment carrying out maintenance tasks [22]. They highlighted that a complex system could have emergent properties that may pose unexpected risks. An example was an SOV with multiple systems that all have associated risk assessments and method statements for their operation. Traditional risk assessments will not pickup interactions between the different systems, a systemic hazard analysis is proposed to assess the interaction of multiple systems in an environment such as an SOV.

Recent literature reviews have found that while STAMP has become an established methodology in the literature, it has not yet become mainstream enough to be included in common textbooks [89] [90] [91]. Industry use is not easy to gauge but industry engagement in research has been limited and would be of use. STAMP research papers have been published in many industries, the most common being aviation, process, automotive and medical [90]. STAMP has not been used extensively in renewable energy research and could be of benefit to that sector [90].

2.1.4 Human impacts in the OWI

This section discusses research into the specific stresses and health effects that offshore wind workers are faced with. A study into a job task analysis for a typical offshore wind worker highlights the challenging activities workers face. These include, transferring from vessels to turbines, ladder climbing, moving through hatches, mechanical torquing and hauling a casualty in an emergency [71]. Other research has shown that the most common physical strains to workers are caused by climbing, and that workers are also challenged by increased exposure to noise, vibrations, humidity, cold and heat [92]. Studies have also been completed specifically looking at health effects impacting workers in the wind industry in general [93] [94]. Onshore there are some known health risks around turbine manufacturing, particularly around the use of epoxies for blade manufacturing. There are also challenges around noise exposure for onshore wind workers. However for offshore wind more research is needed on challenges around ladder climbing and confined space working [94]. In particular for offshore workers the issues of accessibility and weather exposure are of concern. These studies all highlight that the work of offshore wind workers is challenging with 12 hour shifts and 14 day work rotations being normal [95]. Workers are normally hired for offshore work subject to the passing of pre-employment screening tests, as a result the workforce is generally of an above average fitness level and typically report themselves to be in good health [95] [96]. The SPOWTT initiative looked at improving the safety and productivity of offshore wind technician transit [97]. The project has completed a study looking at the effects of CTV sailing on worker mental and physical wellbeing. The overall goal was to provide better advice to make the go/no go decisions prior to maintenance missions. A model was developed to understand and predict the impacts of motion sickness on workers.

There has also been research on the effects of floating wind turbine motion on workers carrying out tasks inside the nacelle and the potential impacts of motion on their health and performance. This has suggested that the motions of floating wind turbines which are likely to be in the low frequency range (less than 0.5Hs) may cause motion sickness and create difficulties for technicians to complete maintenance activities

[98].

2.1.5 HSE Management and Emergency Response

Ahsan et al have looked at HSE management systems in the Danish offshore wind industry and proposed that more standardised systems are needed [99]. Their study interviewed offshore wind farm technicians and managers, they found that although most systems were developed under OHSAS 18001, there was a lot of variability in systems between companies. The study recommended that more emergency response standardisation across the industry would make it easier for technicians or subcontractors that work across multiple projects and overall improve standards. Research has also looked into emergency preparedness at Danish wind farms [100]. The study interviewed 18 parties from across the Danish offshore wind industry. They found that operators have varying emergency response systems, and the response system is fragmented across the industry. It was also noted that operators don't share resources such as helicopters, in some instances workers were reported to have non-life threatening but painful injuries and due to non-availability of helicopters must endure uncomfortable sea journeys back to shore for medical attention. The Global Wind Organisation (GWO) have developed training standards for the offshore wind industry [101][69]. Their goal is to make H&S training standardised across the industry to raise standards and to make it easier for companies to ensure their employees have been adequately trained. If workers have been trained to GWO standards then they would be able to move between projects or employers without needing to be re-trained each time. The GWO has developed standards that cover training in areas including basic safety, advanced rescue and first aid. Over 200,000 people have completed training to GWO standards [101].

Renewable UK published the Offshore Wind and Marine Energy Health and Safety Guidelines in 2014 [102]. The guidelines do not set specific standards for H&S in the industry, but they act as a guide to the existing H&S legislation and industry requirements and how they relate to the specific risks in the industry. They are written from a UK perspective and include an overview of legislation that applies to the UK offshore industry.

2.1.6 H&S legislation

Health and safety legislation has an important influence over the operation of wind farms, legislation influences strategic aspects of development through rules influencing wind farm design, and operational aspects through legislation controlling issues such as the use of lifting equipment or vessel safety. Wifa has called for reform to the health and safety legislation governing the offshore wind industry [103]. Wifa's paper proposed that the Australian offshore wind industry should learn from issues faced by the UK industry and consider adopting a safety case regime such as used in the oil and gas industry. The safety case regulations that the oil and gas industry use were brought in following serious incidents such as the Piper Alpha disaster in the UK, it has been discussed that the issues faced by the UK oil industry were at least partly due to the rapid growth of the industry in the 1970s and 80s [104]. Comparisons have been made between the oil and gas industry at that time and the present day offshore wind industry. There is little research into the legislation governing the offshore wind industry and how it impacts operations or health and safety.

2.2 Supporting determinants of offshore safety

The following subsections set out the literature in areas which while not directly impacting safety can have an indirect effect on safety outcomes in the industry.

2.2.1 Accessibility

Offshore wind farms can be remote from shore and are also dispersed in their nature. This creates one of the key challenges in the installation, operations and maintenance of a wind farm. Factors such as distance to shore, wind speeds, visibility, wave height all impact the ability of workers to be able to install or maintain these assets. As such, a huge amount of research had gone into understanding the optimum ways to plan offshore wind farm works. These challenges are all directly related to the challenge of working in offshore wind safely. The accessibility challenge for offshore wind is a unique one not faced by comparable industries such as offshore oil & gas and therefore required consideration.

There is a significant amount of literature on the topic of accessibility. This primarily deals with methods of calculating or forecasting the accessibility of a wind farm. Research indicates that to achieve wind farm availability of 90% then an accessibility of at least 80% is required [17]. Modern offshore wind farms aim to achieve energy based availability of 95% or greater. An annual report (SPARTA) from UK offshore wind farm operators is published which includes availability, transfer and reliability data [105] [106]. The latest SPARTA reports show that the average availability of UK offshore wind farms was close to 95% between 2017 and 2021.

The accessibility of offshore sites is a critical factor that allows operators to maintain high availability and maximise the revenue generated by an offshore wind farm. Information about the accessibility of potential sites is important in establishing costs of future offshore wind developments. Operations and maintenance costs are around 20 to 30% of the lifetime costs of a wind farm, and accessibility is a significant driver of this cost [18].

The recent SPARTA reports have highlighted that the number of crew transfers per month per turbine have been decreasing over the past 5 years. A transfer is defined as one technician transferring on to, and then off a turbine. Monthly transfers per turbine have decreased from around 11 in 2014 to 6 in 2020. The latest SPARTA report highlights that there has been a decrease in total record-able injury rate (TRIR) over the same time period [106]. Every technician trip to an offshore turbine increases exposure to risk, so reducing the number of trips offshore could be an important part of making the industry safer.

The lower site accessibility is, there is a potential for greater pressure to be placed on available weather windows, this could lead to increased work pressure leading to poorer safety performance. It is important to understand the accessibility of sites to be developed so that works can be effectively planned. Studies have used different methods to calculate accessibility. Martini and Guanche applied set theory to create a mathematical definition of accessibility and completed a study of the North Sea using hindcast data [107]. There have also been accessibility studies on specific sites in

Portugal, the Irish West Coast and the Netherlands using similar methodologies [108] [109] [17].

Feuchtang and Infield proposed a closed form probabilistic method of calculating accessibility that only requires limited data about a site to perform quick calculations [110]. Walker and van Nieuwkoop-McCall also used a probabilistic method applying Weibull distributions to calculate weather windows with a case study on the Devonshire coastline in England [111]. Scheu and Matha have used Markov simulations to generate wave time series data to simulate conditions at a wind farm and model operational aspects of a wind farm including accessibility [112]. Paterson and Thies used a Markov switching autoregressive model to generate stochastic wind speed and wave height time series to calculate accessibility and weather windows [113]. Langevin models are another method that can be used to simulate environmental conditions at a site and generate wind and weather time series data when there is not enough available [114]. Analysis of the FINO1 bouy data in the North Sea off the coast of Germany has also been completed to assess weather windows and waiting times to complete maintenance activities at that location [115]. Rinaldi et al modelled O&M strategies to compare a fixed bottom wind farm with a floating wind farm, however that study considered that the two farms were at the same site with the same meteorological conditions for input [116]. Other studies have showing that comparing fixed bottom wind farm sites to floating sites, the floating sites will tend to have lower accessibility levels [117].

2.2.2 Forecasting accessibility

In order to be able to predict accessibility levels and plan operations it is necessary to introduce forecasting tools into accessibility calculations. While there is already a significant body of research on accessibility calculations, accessibility combined with probabilistic forecasting is a newer area of research that is still expanding. The ability to better forecast accessibility could help improve operational safety by reducing the risk of works taking place in marginal weather conditions and also by reducing time pressure on workers through better planning.

Statistical and AI methods have been used to improve predictions of future wave heights for access calculations [118]. Forecasting accessibility can also potentially improve the safety of transfers as it is less likely workers will be forced to make a transfer in marginal conditions. Recent incidents have been reported where workers were injured during crew transfers due to deteriorating weather conditions during transfers off a turbine. Zhang et al noted that the uncertain nature of weather forecasting is often missed from O&M models, they investigated the use of multi-step probabilistic wave height forecasting (MPWHF) to improve accessibility calculations [119]. They found that accessibility increases non-linearly with wave height limit increase. Gilbert et al proposed a probabilistic forecast of accessibility, it combines weather forecasting with a vessel motion model to predict accessibility levels at a given location up to five days ahead [120]. This paper also proposed a visualisation methodology to create a simple tool for maintenance planners to make decisions before a work activity is commenced. Similar research has combined probabilistic wave height forecasting with a Monte Carlo model to calculate the uncertainty of accessibility at an offshore wind farm [119]. Forecasting and decision making for better crew transfer safety has been investigated by Gilbert et al [120]. The study recognises that pressure to increase access to offshore turbines while cutting maintenance costs will increase the risk of crew transfers taking place in marginal conditions. A key aspect in safe and successful transfers is making a decision about the weather forecast for the day and deciding whether a maintenance task should go ahead. The study developed a model based on probabilistic weather forecasts to predict the likelihood of successful crew transfers. It then developed a visualisation to represent that data in as simple a method as possible to operations managers can make informed decisions.

Real time sea state monitoring is another tool available to increase accessibility. Research on dry sea state monitoring has shown the potential to increase weather windows by as much as 15% [121]. This is done by using a vertical radar attached to the bow of the vessel which measures the air gap from the bow to the sea surface. This data is then used to increase the “alpha factor” which sets the operation limits of the vessel. The alpha factor is the ratio between the operational limit of the vessel and the maximum limit. So the higher the alpha factor that can be safely used the closer to the maximum limits operations can continue.

2.2.3 Vessel performance

Studying vessel motions can help improve the understanding of accessibility and crew transfer safety by predicting how vessels react under given meteorological conditions.

Access to turbines is usually defined by a limiting H_s, however understanding how a vessel actually behaves in wave conditions can allow better decisions to be made about crew transfers. Studies have attempted to create mathematical models of vessel motions during push on transfers. The development of mathematical models to simulate these interactions are complex as they must consider the behaviour of the vessels in response to wave conditions, the interaction between the vessel and the fender as well as the interaction of the turbine structure and the waves [122]. One study used scale model testing to verify the numerical model with some success [123].

Gilbert et al. used vessel telemetry data available from a wind farm construction phase, together with wave bouy data to build a data driven vessel model to predict actual vessel movements under wave conditions [124]. More sophisticated vessel performance models could allow access decisions to be made using all the available data such as wave peak periods or wave direction, rather than H_s only. Using only H_s as the limiting factor in crew transfers could cause abortive maintenance missions, where a vessel is launched as the H_s is below the limiting factor, but the wave direction or period may influence the vessel and not allow a safe transfer to be completed.

Wu developed a numerical analysis in the frequency domain to assess the performance of motion compensated access systems in comparison to push on transfers [125]. The frequency domain calculation was proposed to be computationally cheaper than a time series analysis. Other research has used a "monte-carlo based method" to generate bi-variate wave statistics combined with a finite element model of the vessel to determine extreme motions during a fender push on crew transfer [126]. This can be combined with forecasting to create more advance models.

The move to floating turbines increases the complexity of the problem with the motion of the foundation, nacelle and vessel all having an impact on crew transfer.

Research on accessibility of floating wind turbines is less developed due to the young age of the technology. Research has been done into floating turbine motions, Guanche developed a model in the frequency domain to compare the performance of a CTV pushing onto a fender with an SOV using a walk to work gangway. For floating turbines the wave direction was very important, when the transfer took place in a head sea with the turbine sheltering the vessel the transfer was more likely to be successful [127]. Martini calculated that if CTVs and fender push on are used for floating turbines then accessibility levels could be as low as 24% due to the relative motions of the two bodies [128]. Jenkins et al looked at the motions of a nacelle on a floating wind turbine to determine the levels of movement that would be experienced during maintenance activities [129]. This showed that accelerations should be within normal limits during expected wave conditions.

2.2.4 Contractual performance

Contracts are at the core of any successful project or commercial enterprise and an offshore wind farm is no different. In an offshore wind operation the contract is a key governing document which could have a significant impact of safety. The contract will set out key safety requirements for suppliers to follow and also define the weather limits within which contractors are expected to complete operations.

A good O&M contracting strategy will incentivize the parties to work together and properly allocate risks. A key issue regarding the wind farm operations that needs to be addressed are the conditions in which maintenance contractors are expected to be able to access the turbines. The contract must stipulate under what conditions a vessel is expected to access the wind farm considering issues such as significant wave height, the contract must also make allowances for weather days when no work will be able to be carried out due to extreme weather. There is a limited amount of research in this area publicly available. Contracts related research is often restricted due to the confidential nature of much of the information. The existing publicly available literature is summarized in this section. Commercial pressures to complete maintenance works is a factor that could have an adverse impact on safety if not carefully managed.

Hawker and McMillan have written about the impact that choice of O&M contract can have on the availability of a wind farm [130]. This paper highlighted that while most O&M modelling assumes that the owner controls maintenance resources, these are often actually constrained by commercial issues. Wind farms will often be competing for the same maintenance resources and this will be impacted by the choice of maintenance contract strategy. A paper from Wang et al studied the potential benefits of using performance based contracts in O&M and used a model to show that it would outperform a standard contract [131]. Liang et al has also proposed that O&M contracts with profit sharing mechanisms can improve wind turbine availability by aligning the incentives of the O&M contractor with the wind farm owner [132].

Adopting standard forms of contract for the offshore wind industry has been considered for some time but little progress has been made. In 2009, the adoption of standard forms of contract was proposed, using the success of the oil and gas industry as an example [133]. Experiences from the oil and gas industry have been that standard contracts speed up negotiations, reduce disputes, are easier to manage, and are better at properly allocating risk. A more recent report from BVG associates in 2021 commissioned by the Scottish Government reviewed the contracts commonly used in offshore wind and also proposed that a standard form of contract should be developed [134].

Busch has reviewed the key aspects of contracts for the construction of offshore wind farms [135]. Busch also highlighted that the adoption of a standard form of contract would be beneficial for wind farm construction. The FIDIC Yellow Book contract is commonly used for wind farm construction, but usually in a heavily modified form. One of the areas the Yellow Book contract struggles to deal with is extreme weather, as Busch noted, extreme weather is often the norm rather than the exception in offshore wind farms. Weather is currently dealt with in wind farm construction contracts by allocating a number of weather days that would be expected each month, based upon statistical data. A contractor would not be able to claim for any delays unless extreme weather conditions persist for longer than the number of specified weather days. Busch highlighted one successful case of standard contracts as being the BIMCO standard contracts for vessel charter. BIMCO publish the Windtime contract, which is described as a 'standard offshore windfarm personnel transfer and support vessel charter party' contract [136]. Clause 15(d) of the contract states that the Charterer bears the risk of weather causing the vessel to return to port. Force Majeure events are covered by Clause 32 and it states that neither party shall be liable for 'any loss, damage, liquidated damages or delay' due to any force majeure events including 'extraordinary weather conditions'. The contract does not deal with any specific limits regarding meteorological conditions during crew transfer.

Further development of standardised contracts that contain clauses specifically written to deal with challenges such as accessibility and safety could have significant potential to help the industry grow successfully. Contracts are the key method with which a developer or operator can enforce safety performance on their supply chain, so the development of suitable contract mechanisms for the industry is important.

2.2.5 Decision making / O&M Modelling

An important aspect of managing accessibility safely is the decision-making process during operations and maintenance of wind turbines. One goal of research in this area is to make it easier for human operators to make decisions regarding maintenance mission planning. Incorrect decisions can lead to maintenance trips starting and being aborted due to weather conditions or other factors stopping the successful completion of an activity. This could lead to unnecessary missions leading to increased risk exposure, or also to a backlog of maintenance work, increasing pressure on the workforce to complete tasks in challenging conditions.

Decision support models are often used to assist operators and developers in understanding how decisions will effect the operations of a wind farm. Detailed operations and maintenance models are used in the development of wind farms to aid in prediction of costs and yields and also in the daily operation of wind farms to support operators in decision making [137] [138].

Decision making can be considered at different levels and stages of the life of a wind farm from initial design decisions about the farm design to choice of maintenance contract. Shafiee et al proposed that maintenance logistics research can be divided into strategic, tactical and operational categories of decision making [139].

Strategic decisions are made at the design stage, such as wind farm layout, tactical decisions are medium term decisions including choice of maintenance contractor and tactical decisions are those made on a daily basis such as the launching of a vessel on a maintenance task. Decisions at all of these levels have the potential to influence the accessibility levels of a wind farm, the safety of workers and the cost to maintain the plant and equipment.

Clem Stock Williams has researched the potential for operational decisions to be automated [140]. A method was developed using a meta heuristic and genetic algorithm to automate the daily planning of maintenance activities. This can be advantageous as maintenance planning can quickly become too complex to be done by hand, a case study showed potential for a 1% saving on O&M costs using automated methods, although it was noted that further research and validation were needed in this area. Chaterjee completed a review of literature regarding artificial intelligence in offshore wind operations and maintenance[141]. They proposed that artificial intelligence had huge potential for providing real time decision support in the coming years.

There is a significant amount of research on decision support models and how they can be used to assist in the operations and maintenance of a wind farm. A comprehensive review of decision support models by Seyr can be found in [142]. Seyr identified that there are three broad categories of model types based upon the methods used to develop the mathematical model, these are:

- Discrete event simulation
- Markov models
- Differential equations (including Monte Carlo models)

The most common planning and cost factors found to be included in O&M models were:

- occurrence of failures

- crew availability
- parts availability
- vessel availability
- weather
- external factors
- chosen maintenance strategy
- electricity prices and subsidies

Monte Carlo models appear to be the most common methods used to develop decision support models [143]. Markov decision processes have been proposed as an alternative with one advantage being that they require less computational power.

The list of common factors included in decision support models show that accessibility is a key influence. The accessibility in this case will be defined by the weather and vessel availability. It can be noted that the literature on decision support models does not talk extensively about safety as an aspect of the modelling. However, decisions made on planning maintenance missions will have an influence on safety outcomes. The following section discusses the relevant safety literature in detail.

2.2.6 Reliability

Offshore wind farm reliability, accessibility ans safety are closely related, without access to the turbines, checks and maintenance cannot be completed, components will fail and the energy yield of the turbine will drop. This will in turn increase pressure on the operational teams to complete maintenance tasks and could have a negative influence on safety. OWF O&M models need to include aspects of accessibility along with component reliability in order to fully model the wind farm performance. A study from Koukoura et al develop a wind farm operations model to understand the relationships between component reliability, accessibility and wind farm availability [144]. It found that if a condition monitoring system can provide more advanced warning of component failure there will be more opportunity to schedule maintenance within a suitable weather window. Similarly, if accessibility can be increased by improved weather forecasting or by increasing transfer wave height limits then repairs can be scheduled more efficiently, and reliability and availability will also improve.

These issues can also be related to H&S challenges, as unexpected failures and unplanned maintenance can put more pressure on maintenance crews to complete tasks in a shorter timescale. Better prediction of failures will allow longer planning timescales and allow work to be completed under less pressure and in more favourable weather conditions.

2.2.7 Floating wind

To date the majority of offshore wind farms are constructed in relatively shallow waters (less than 50m depth) and are constructed as fixed bottom foundations. In the coming years it is expected that floating wind turbines will begin to comprise a large part of offshore wind generation fleets. Floating wind turbines introduce new challenges to the development of offshore wind.

A summary of the latest floating wind operations and maintenance research identified some of the key challenges to the future of floating wind [145]. This included development of foundation designs. As the industry is in very early stages of development an industry consensus on the preferred type of floating foundation has not yet been reached. The selection of a preferred foundation will have implications on access strategies and technician safety. The potential for shortages in port infrastructure is also highlighted. The paper concludes that more O&M research on floating wind is needed including wider case studies, towing procedures and limits for worker safety. The changing risk profile of floating wind including increased distances from shore, crew transfers on and motion sickness while working on floating platforms are all highlighted.

Earlier in this section some of the the specific challenges of floating wind related to accessibility and human factors such as sea-sickness have been discussed. As the offshore wind industry grows and floating wind deployment begins at commercial scale further research in all of these areas is very important.

A recent report from the carbon trust looked at some of the latest challenges related to floating wind and accessibility [21]. These included determination of the optimum strategy to be used such as using SOVs, CTVs or a mixed strategy using daughter craft. It highlighted that further research on vessel strategies will be important to answer these questions. Other challenges reported were the development of strategies for major repairs and tow to shore procedures. Potential opportunities were highlighted including the use of novel walk to work systems and the use of automation to decrease human involvement in maintenance activities.

2.3 The Literature gap

While there is a significant amount of research literature across the safety science body of knowledge, there is very little application of this work to understand the challenges of the offshore wind industry. The actual safety performance of the industry is not well understood, this includes its performance relative to similar industries and also how to effectively use the data that is available. These challenges will be addressed in Chapters 3 and 4. The literature review has identified that the development of leading indicators of risk for offshore wind has only been explored in a limited way, this will be addressed in Chapter 5. Finally, Chapter 6 will look at how novel methodologies such as safety systems theory could be used to understand and address the wider safety challenges facing the industry.

Chapter 3

Current status of H&S in the OWI, challenges and risk profile

3.1 Chapter contribution

Understanding the safety challenges of developing offshore wind is important for industry to ensure that the sector can grow sustainably without negative impacts on the workforce. Regulators also need to understand the unique challenges associated with offshore wind to make informed decisions regarding the need for implementation of regulation to manage the industry. This Chapter sets out to establish a benchmark of the current safety performance of the offshore wind industry and the outlook for the future. This is not an easy question to answer, relying solely on traditional performance statistics is not a reliable method. It was decided to use statistics to complete a cross industry analysis and offshore oil and gas was selected as the industry with the most in common to offshore wind. The second part of this Chapter looks to understand how safety is governed by legislation, and the UK as a mature sector of the industry was selected for this analysis. Safety legislation is a primary level of control that sits at the top of the hierarchy of all other controls. Understanding the strengths and weaknesses of legislation in offshore wind can also provide information about how the industry is performing. Finally, this Chapter looks to see how risk levels in the industry might change in the coming years. Again, the UK was used as an example for this, and crew transfer rates were selected as a useful proxy for worker to exposure to risk. This gives one indicator as to how risk levels might change in coming years. Looking at these three aspects of safety; statistics, legislation and risk exposure allow an overall picture of the performance to be built. Finally, it also allows for critique on the state of the industry and identify where challenges lie in ensuring the industry grows safely in the future.

This Chapter aims to answer the following research question:

"How does the performance and safety legislation of offshore wind currently compare to a similar industry, and how is the risk profile likely to change in the coming years?

The contributions of the chapter are as follows:

- Cross industry comparison of accident statistics.
- Cross industry comparative analysis of the legislative framework which governs safety.
- Introduction of crew transfers as a measure of risk levels, and a forecast for the UK industry.

This section focuses on the UK for the legislative analysis and the growth estimates for technician transfer. As the UK industry is one of the global leaders in offshore wind, lessons from this jurisdiction can be applied to other countries with less developed offshore wind markets.

3.2 Accident rate comparative analysis

This section will look at the available accident data from the offshore wind industry to gain insights on the industry's performance. To make a performance comparison, data was collected from the offshore oil and gas industry. Offshore oil and gas was selected as it is an industry that deals with similar challenges such as extreme weather conditions, transfer of materials and personnel to offshore structures and remote work locations. Much of the daily activities of offshore workers are also similar, such as electrical and mechanical maintenance work, managing lifting operations, climbing ladders, and accessing confined spaces. Data used in the comparison are collected from G+ and the international association of oil and gas producers (IOGP). The onshore wind industry was considered as a comparison, however it was felt that the key challenges to safety that offshore wind face are primarily around the work location. Aspects such as marine transfers, accessibility and emergency response are the unique challenges that define offshore wind and these have more in common with the offshore oil & gas industry. The study is limited by the available accident data from the offshore wind industry, of which G+ is the only available source.

Injury rate statistics available for offshore wind include the TRIR and LTIR, the drawbacks of these are outlined in Chapter 2, however this is the data available and is still an industry standard. While injury rates can be unreliable when working with small numbers, cross industry comparisons with large datasets are valid [46]. 95% confidence intervals were calculated for both data sets using the Wilson Confidence Interval method [46] [146].Figure 3.1 shows a comparison of the TRIR for the offshore oil and gas and offshore wind industries. Figure 3.2 shows the same comparison but using the LTIR.

In Figure 3.1 and 3.2 the size of confidence interval for the oil and gas industry data is an order of magnitude smaller than that of the offshore wind industry. This is due to the much larger number of hours worked in the oil and gas data, this increases the confidence in the validity of the statistics. For example, in 2020 the recorded hours worked from IOGP were over 650 million, whereas just 25 million hours were recorded by G+. Both industries have shown a decline in incident rates since 2015, however the offshore wind industry incident rates are significantly higher. Over the past 5 years the wind industry TRIR has been over 3 times higher and the LTIR 4 times higher than the offshore oil and gas industry. Due to the greater volatility in the offshore wind statistics and the lower personnel hours it is harder to draw a conclusion that the decline in numbers represents a significant improvement in performance. Factors that govern injury rates are extremely complex and have been much debated in the research, some factors that are commonly agreed to be important are safety culture, worker competence

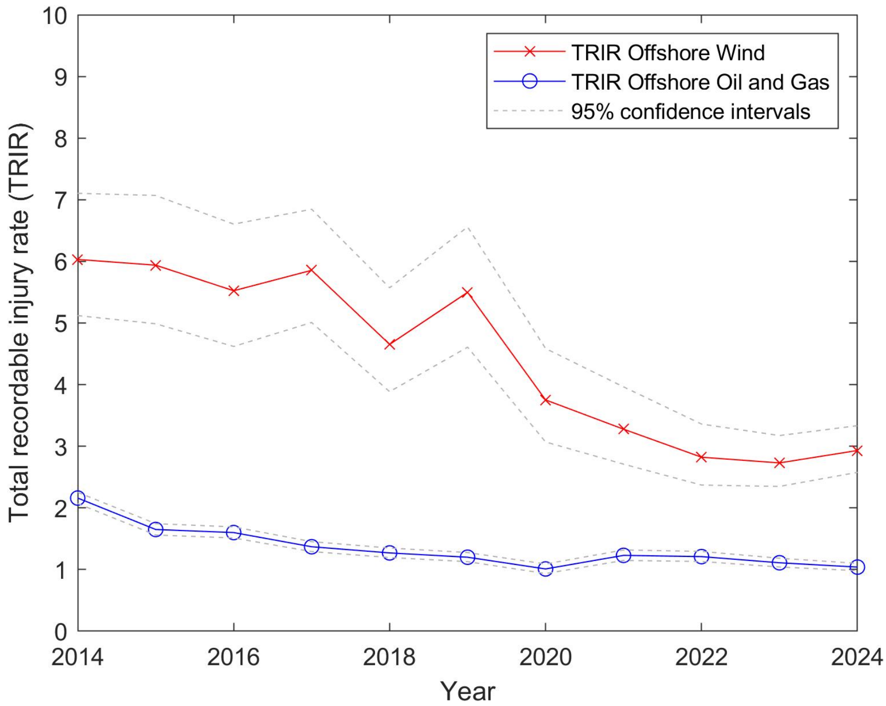


Figure 3.1: Comparison of TRIR for offshore wind and offshore oil and gas industries [147] [148]

and training standards, stakeholder engagement, supply chain capabilities, design and planning and hazard identification and control. As a reference point the onshore wind TRIR statistics for the UK were an average of 0.56 from 2020 until 2022 [149]. These are the only available statistics for onshore wind, however, the significantly lower rates add weight to the argument that the unique factors of working offshore are the key challenges for safety in the offshore wind industry.

Reporting from the IOGP on historical trends in oil & gas data shows a downward trend in fatality rates (FAR) from 1985 were the FAR was around 16 to the past decade where the rate has averaged between 1 and 2 [148]. The introduction of the safety case regulations is regarded as one of the greatest contributors to the decrease in the fatality rate in the oil & gas industry [104].

G+ also publish the incident rates for the offshore wind industry broken down between the operations and the construction phases of projects.

Figure 3.3 shows the comparison of the two datasets. The data is only available

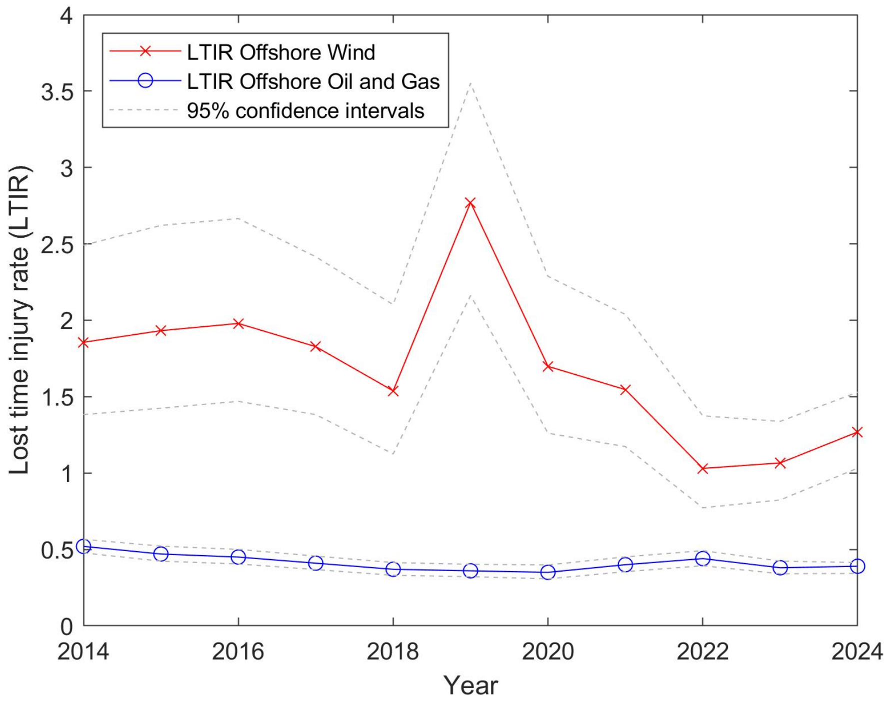


Figure 3.2: Comparison of the LTIR for offshore wind and oil and gas industries [147] [148]

for 4 years but shows a clear difference between the two project phases. The TRIR for operational sites is on average 3 to 4 times that of construction sites. The reasons for this discrepancy are not clear. It might be expected that construction would have a worse injury rate, wind farm construction will include more high-risk activities such as heavy lift operations and working conditions will be changing every day, however this may mean wind farm construction sites receive more attention from senior management and safety inspectors. Differences in injury reporting may also be a factor, research has shown that temporary workers are less likely to report injuries due to job security concerns [150]. The nature of construction work will mean that more workers are on temporary contracts compared to O&M contracts which are likely to be longer term, so this could mean there is more under-reporting on construction projects.

Up until 2022 the G+ statistics had recorded no fatalities however since this research project began there has been one fatality in 2023 and one in 2024. Furthermore, an internet search can find reports of serious incidents that do not appear in the G+ statistics, highlighting that not all offshore wind projects will be included in those

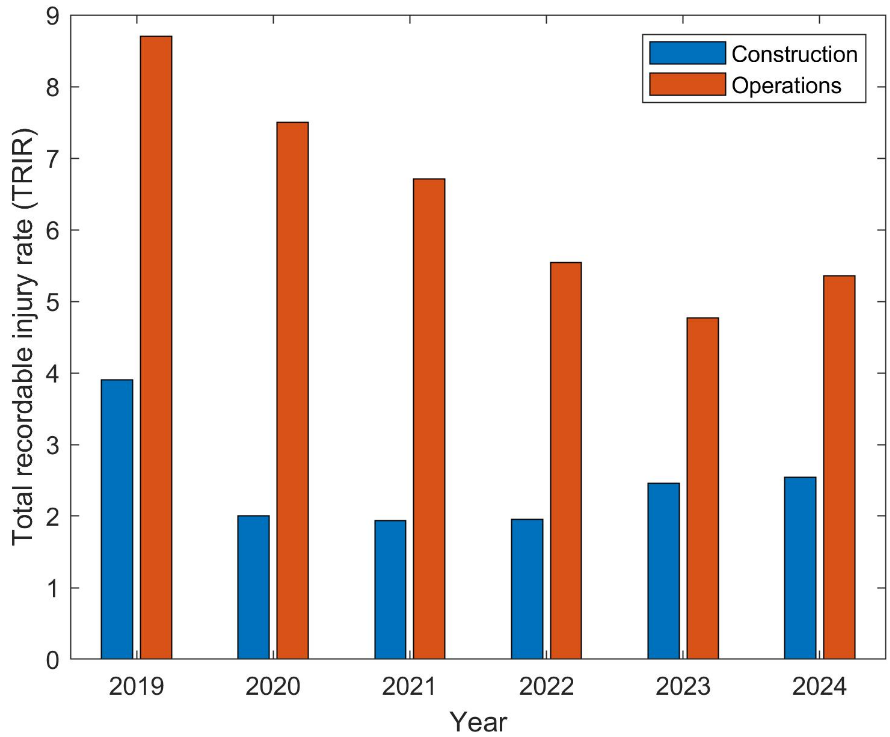


Figure 3.3: Comparison of offshore wind construction and operations injury rates [147]

figures [151]. G+ are the only organisation publishing accident statistics specifically for offshore wind, however it is missing large parts of the industry. Figure 3.4 shows the hours worked by country for all G+ members that reported accident statistics [11]. Figure 3.5 shows the GW of installed capacity of offshore wind farms globally [152].

The differences in the charts highlight that there are large sections of the offshore wind industry which are not included in the G+ data. While China has the largest installed capacity, they do not have any reporting in the G+ data set. This is a key limitation to this study and the availability of more accident data covering the entirety of the offshore wind industry would allow for further research to be completed.

Emergency response incidents are also reported by G+, these indicate when an accident has required response of an emergency team and possible medical evacuation of personnel. These are therefore a good indicator of accidents with higher potential for negative outcomes.

Figure 3.6 shows the number of emergency response events every year reported by G+. There has been an average of 30 emergency response events every year since

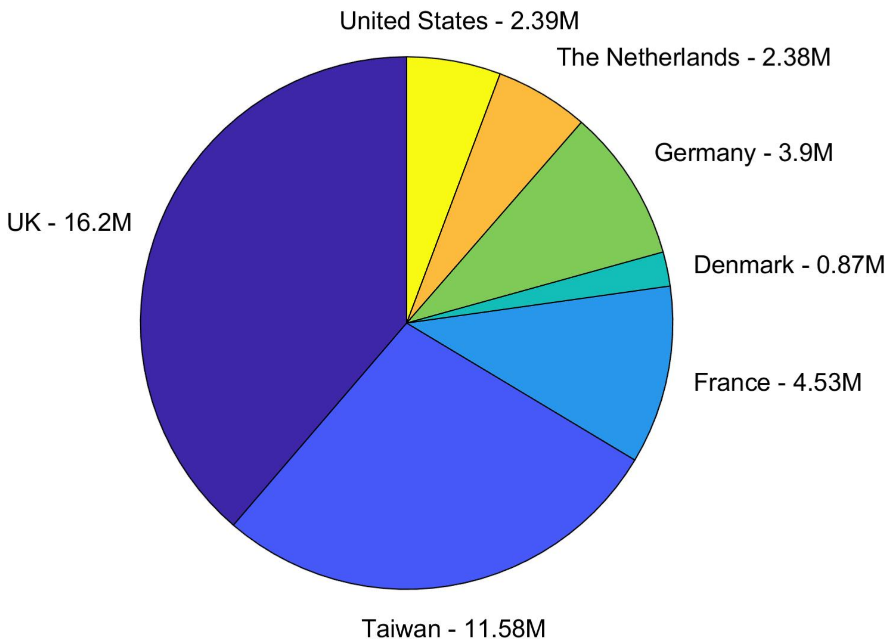


Figure 3.4: Hours worked in G+ member countries [147]

2014. G+ also report that on average 40% of these have been classed as high potential incidents.

This preliminary analysis indicate that the OWI industry injury rates are significantly higher than the offshore oil and gas industry. This suggests that there is scope for large improvements in H&S performance at offshore wind farms. The offshore wind TRIR shows a slight decreasing trend over the past five years, however any improvement in the LTIR is less obvious. The OWI has experienced two fatal incidents reported by G+ in the past two years, the relatively high total recordable injury rate and number of emergency response events could indicate that there is a further risk of serious incidents.

Some research has shown a link between the number of minor safety incidents and how they might relate to more incidents or fatalities [75]. Recent studies have suggested a relationship of 500 lost workday cases to one fatality [48]. As set out in Chapter 2 research from the oil & gas industry has questioned the validity of the relationship between minor incidents and more serious accidents or fatalities. Another level of uncertainty arises from the fact the TRIR and LTIR do not give a measure

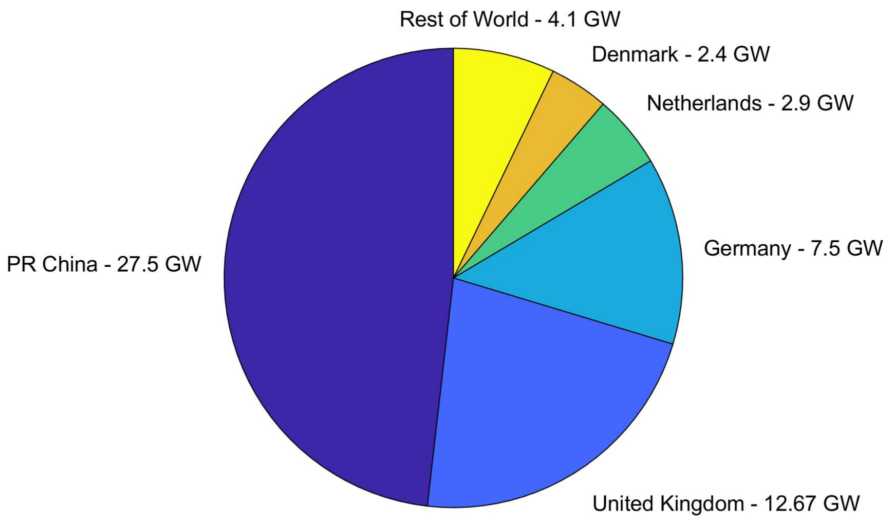


Figure 3.5: Global GW of installed capacity of offshore wind by country [152]

of the severity of the incident. However, considering these uncertainties the relatively high accident rates in the industry raise cause for concern and indicate that significant improvements can be made.

Figures 3.4 and 3.5 show that there is a large section of the industry, primarily in China where accident numbers are not included in the G+ data. This indicates there are potentially many more accidents taking place that are not included in accident data. Media reports that can be found online also indicate some serious accidents have taken place, possibly including fatalities. Furthermore, under-reporting of occupational accidents is known to be an issue across all types of industries. A recent study in Australia found that only 19% of occupational injuries were correctly recorded [54]. The study concluded that case management was being used to reduce injury rates, so for example, recordable injuries were downgraded to first aid injuries. These issues will contribute to error in this type of study; however, this is likely to mean that injury rates are worse than reported and reinforces the need for improvement.

Overall, the comparison of incident statistics shows what there is opportunity to improve H&S performance in offshore wind. The offshore wind industry is still in the early stages of development so it is not surprising that it might not have the same performance level of a mature industry such as oil and gas, however as the industry continues to grow it is important that safety improvements are also made. While

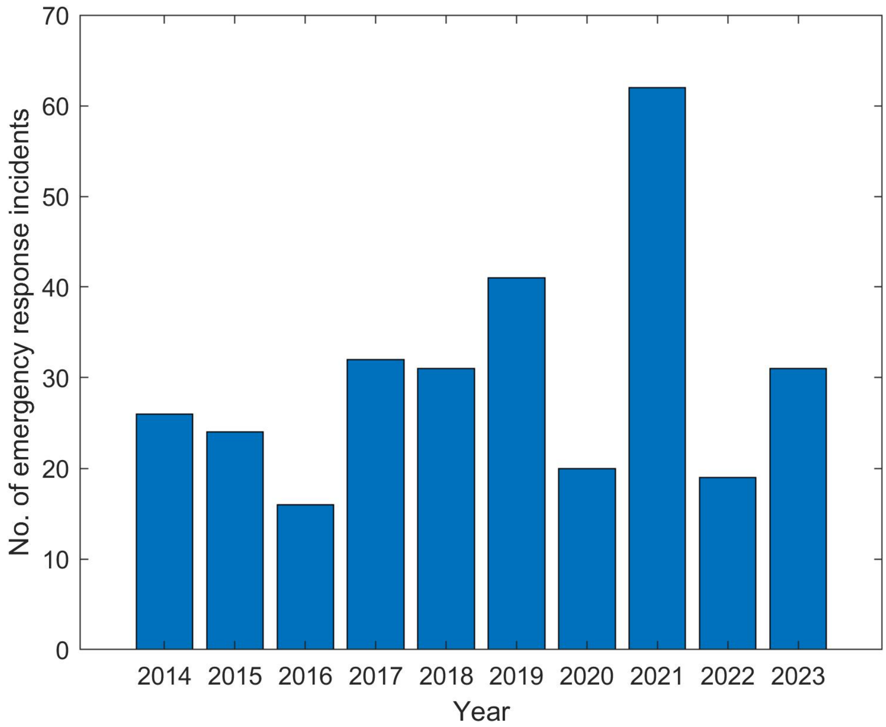


Figure 3.6: No. of emergency response events each year among G+ members [147]

performance can be improved, the industry should also look at innovative methods of risk measurement and reporting as have been developed in other industries. The reliance of the OWI on TRIR and LTIR to measure performance, particularly where they are reported without the use of confidence intervals is a weakness.

3.3 Risk profile and industry growth

Offshore wind continues to grow worldwide, while growth is usually discussed in terms of additional MW of capacity installed, it can be useful to consider other measures when considering risk exposure. To this end, an analysis of the number of technician transfers to turbines expected to occur annually up until 2030 within UK waters has been calculated. Technician transfers to a turbine can be considered a good measure of risk exposure, as it quantifies the number of visits to turbines by personnel who will be exposed to risk in the journey itself, as well as the transfer to the turbine and the subsequent work that they are carrying out on the turbine. UK data is used for the calculation in this section; however the same trends will apply to other offshore wind sectors.

These estimates are necessarily approximate and are based on simplified assumptions about future turbine sizes, project build-out and visit rates. They are intended to provide an order of magnitude indication of how worker exposure to offshore wind operations may grow, rather than precise forecasts of future transfer numbers.

3.3.1 Methodology

To calculate the future number of technician transfers, it is necessary to find the expected number of turbines installed each year and the average number of visits per turbine.

Turbine numbers

Figures from Renewable UK show that in early 2022 there were 2,297 offshore wind turbines installed and commissioned with a cumulative generation capacity of around 10.4GW [153]. There are over 500 turbines currently being installed and a further 687 turbines planned in consented projects. If these projects are completed by 2026, the UK will have a total of 3,507 installed. This represents a 53% increase in the number of installed offshore turbines. The UK government has set a target of 40GW of installed capacity by 2030, to achieve this the total number of turbines will need to increase to over 4,600, roughly double the numbers installed in 2022 [4]. For future projects up to 2030 a turbine size of 15MW was assumed in the calculations.

Technician visits

The increased turbine numbers will, in turn, increase the amount of maintenance work to be done and the number of technician visits to a site. SPARTA is a collaborative project run by the renewable energy catapult in the UK. It collects operational performance data from owners and operators in UK offshore wind industry. According to the SPARTA project the average technician visits to a turbine in their reporting period covering 2019 to 2020 was 6.5 per month [74]. A technician visit is defined as one technician visiting a turbine, including their step on and step off after their work. Other research from an operational offshore wind farm in the UK reported that turbines were visited by a vessel just under 19 times per year [75]. If an average vessel visit involved 4 technicians, then the numbers from the two sources would agree. Based on the numbers outlined here, a forecast of future wind turbine technician transfers has been completed. The forecast is based on the following calculation steps:

$$N_T = 12 \cdot T \cdot R$$

Where:

N_T = No. of technician transfers per year.

T = No. of turbines installed.

R = Technician transfer rate per month.

The technician transfer rate is based on figures from the SPARTA project. The technician transfer rate has shown a trend of decreasing since the SPARTA figures were first published in 2015. It could be expected that there will be some continuation of this trend in decreasing technician visits due to improved O&M management. The forecast technician transfer numbers have therefore, been calculated as a range based upon the transfer rate staying as the current rate and following a similar trend of reduction up to 2030.

Transfer forecast results

Expected transfer numbers have been calculated based on the assumptions stated. Figure 3.7 shows the projected growth in technician visits based on the reported average visits by SPARTA.

Transfers are projected to grow from around 180,000 per year in 2022 to between 300,000 and 350,000 per year in 2030. The upper estimate assumes that the technician transfer rate stays constant from 2020 until 2030. The lower range estimate assumes that the rate decreases following a similar pattern as seen between 2014 and 2020.

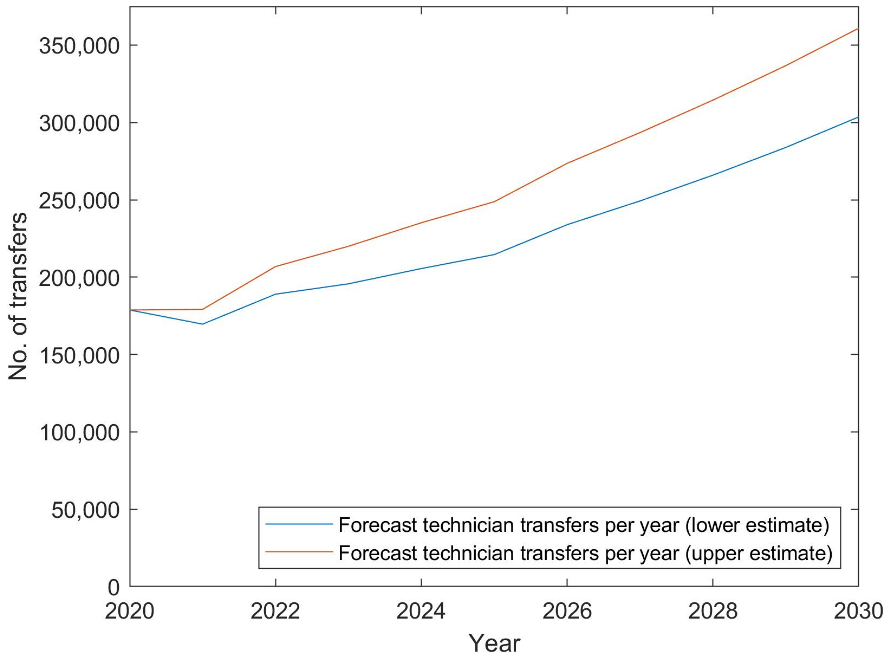


Figure 3.7: Technician transfer numbers UK forecast growth to 2030

Technician transfers gives a quantifiable indicator for the exposure that workers have towards the H&S risks associated with operating and maintaining an offshore wind farm. The more transfers there are indicates more journeys to the wind farm, more transfers to a turbine and more work carried out on turbines, these are all times when workers are exposed to risk. Any changes in the way wind turbines are operated and maintained that can reduce this number has strong potential to reduce the number of safety incidents occurring across the entire industry. With wind farms moving further offshore, technicians will also be travelling further and working in different ways. The latest round of leasing for wind farm sites in Scotland (Scotwind) includes 10 potential floating wind farm sites, the average distance to shore of these sites is greater than 100km, whereas existing fixed bottom sites tend to be around 50km from shore [51]. This shows another factor that is likely to increase the risk exposure to offshore wind workers in the coming years as the industry grows globally.

3.3.2 Health and Safety Legislation

It has been noted that in the early days of offshore wind development the H&S risks were often underestimated [154]. One of the key aspects of success in managing health and safety relates to the governing legislation that sets minimum requirements to which industry must comply. One challenge to effectively manage offshore wind H&S is developing an adequate legislative regime that is suitable for the full range of activities involved in operating and maintaining an offshore wind farm [154]. There has also been commentary that one of the reasons for the relatively poor safety record of the offshore wind industry is due to the lack of a comprehensive safety legislation regime [103]. Comparisons have been made to the offshore oil and gas industry in the 1970s, which went through rapid growth and suffered from poor H&S performance as a result [104]. This led to the introduction of new legislation to manage the industry [104]. This section looks at how the UK applies legislation to the management of safety in offshore wind. As one of the largest existing offshore wind markets, lessons learned in the UK have the potential to be applied to other countries. For this study, a review was completed of the relevant legislation that applies to offshore wind energy operations and maintenance in the UK. Comparison was then made to the legislation applicable to the UK offshore oil and gas industry. It should be noted that while this work refers to UK legislation, there can be differences in applicable legislation across the constituent countries of the UK. For example, Northern Ireland has its own version of the Health and Safety at Work Act. For simplicity, the study refers to UK legislation, but care should be taken to check applicability across the different jurisdictions within the UK. This study also has not considered shipping legislation that is often applicable to vessels involved on offshore wind energy work.

The discussion of legislation often involves arguments over the burden of cost and administration and that there is already too much H&S legislation, recent reviews have found this not to be the case. In 2011, Professor Löfstedt was asked by the UK government to review all UK health and safety legislation to determine if it was fit for purpose and if there was scope to reduce and simplify legislation [155]]. The report found that there wasn't a case to significantly reduce legislation and that it had a net benefit in terms of reducing incidents and costs for industry. However, there were areas where legislation could be simplified and consolidated.

The Health and Safety at Work Act (HASWA) 1974 sits at the top of the H&S legislation hierarchy and is applicable to the UK offshore wind industry and the offshore oil and gas industry [156]. The HASWA consolidated much of the existing H&S legislation and introduced a risk-based philosophy that allowed duty holders to assess risks and implement suitable measures to mitigate them to a level that is 'as low as reasonably practicable'. The HASWA was extended in 2013 by the Health and Safety at Work Acts 1974 (Application outside Great Britain) Order 2013 [157]. This ensured that the act would apply to works outside UK territorial seas and to floating offshore wind turbines [158]. The HASWA also created the Health and Safety Executive and gave it powers to both issue regulations and to enforce the application of regulations and investigate incidents. While it is not possible to directly assess the impact of legislation such as the HASWA, there has been an improvement in H&S performance across industries in the UK since its introduction in 1974. UK construction industry annual deaths were at 276 in 1964 and fell to 100 by 1984, there were many improvements in working practices over this time, but improvements to the legislative regime likely also account for some of this improvement [159]. The HASWA gives power to the Health and Safety Executive to implement further health, safety, or environmental regulations. There are many of these across all industries that regulate all kinds of activities, from the use of personnel protective equipment, to lifting equipment and the control of hazardous substances. Regulations made under the HASWA only specifically apply offshore if there is a clause within them that confirms their application [160].

Below the HASWA the next most significant pieces of legislation that apply to the OWI are the Management of Health and Safety at Work Regulations 1999 (MHSWR) and the Construction (Design and Management) Regulations 2015 (CDM Regulations) [161] [162]. The MHSWR introduced a statutory requirement for duty holders to complete risk assessments for their work activities. This requirement applies to the OWI industry and oil and gas industries. It also includes other requirements such as a duty for employers to provide adequate training and providing information about risks to employees. The CDM regulations are one of the most important requirements that apply to offshore wind, they do not apply to offshore oil and gas. The CDM regulations place duties on certain key stakeholders' in projects. The key duty holders are the Client, the Principal Designer and the Principal Contractor. The CDM regulations define construction work as including activities such as commissioning and maintenance, so wind farm maintenance activities are included within their scope. There are however edge cases where short duration and routine maintenance jobs won't fall under the CDM regulations. The regulations set out responsibilities and processes that must be followed by all parties. These include a requirement for designers to consider risks throughout all stages of the lifecycle of a facility. Designs must consider how a plant will be maintained, and suitable mitigation measures should be built in. For example, handrails at exposed edges where personnel would need access for maintenance. The regulations first came into force in 1994 and so would not have originally expected their extensive use for offshore wind energy works. There are not any aspects that specifically address offshore risks. These include aspects such as development of a construction phase plan and engineering risk assessments. Since the first issue of the regulations in 1994 they have been updated in 2007 and 2015. Updates have attempted to streamline the legislation and take on board criticism from users. It has been questioned if their introduction has led to any improvements, and the safety statistics from the UK construction industry do not show any obvious signs that they have [159]. The CDM regulations do not apply to offshore oil and gas, their closest equivalent would be the Offshore Installations (Safety Case) Regulations 2005. Wifa has claimed that the H&S performance of the OWI lags the oil and gas industry and that a lack of suitable legislation is a cause for this [104]. They proposed that legislation like the safety case regulations should be implemented in offshore wind. Wifa also completed a comprehensive review of the safety case regulations and found that while there have been criticisms the regulations are 'robust and would benefit other offshore industries ' [104]. In terms of legislation, the clear difference between oil and gas and offshore wind are the application of CDM regulations and the safety case regulations. With the safety case regulations applying to oil and gas, but not the OWI and CDM applying to OWI but not oil and gas. It

Feature	Legislation	
	CDM 2015	SCR 2005
Construction phase plan	✓	
Health and Safety file	✓	
Safety and environmental management system		✓
Major accidents prevention policy		✓
Formal review and acceptance		✓
Focus on emergency response		✓
3rd party verification		✓

Table 3.1: Comparison of items included in legislation

is worth comparing the two pieces of legislation to help inform how suitable the CDM regulations are in governing H&S in the OWI. Table 1 shows a summary of the key differences between the two pieces of legislation.

The first point of comparison is considering the background for the implementation of both pieces of legislation. The safety case regulations arose as a direct reaction to the Piper Alpha disaster. They were implemented following the recommendation of the report by Lord Cullen into the disaster [163]. The motivation for developing the CDM regulations were to address the poor performance the construction industry had seen in the 1980s [164]. A key reason for the poor performance was believed to be a lack of coordination between Clients, Designers and Contractors. The strategy of the CDM regulations was to reduce incidents by improving the design and planning processes of construction work [159]. The CDM regulations and Safety Case Regulations, therefore, have a focus that reflects their origins. The CDM regulations are focussed on assigning duties to the various parties to construction projects. These are, the Client, Designers and Contractors. They also emphasise designing out risks and improving planning and management of the construction phase of a project. The Safety Case Regulations have a strong focus on major accident prevention. The key deliverables of the CDM regulations are, the ‘Construction Phase Plan’ and the ‘Health and Safety File’. The construction phase plan is drawn up by the principal contractor in charge of the works. It must cover all aspects of the construction work and will set out how work is carried out while managing risk to health and safety. It is completed prior to setting up site and constantly updated throughout the project. There are no formal requirements for its review and approval by any other parties. The Health and Safety file is a record that contains all the documents that would be required to safely maintain, repair, renovate or demolish a project. So, the Construction Phase Plan is a key document how the H&S of a project is managed, whereas the H&S File is a deliverable that remains with a project after completion and enables future users to have all the necessary information about the project available to them. The key deliverables of the safety case regulations include the documentation of the safety and environmental management system.

This needs to include aspects such as the:

- Organisational structure,
- Identification and evaluation of major hazards,
- Emergency planning and response,
- Management of change,
- Performance monitoring,
- Audit and review arrangement.

The safety case also requires a major accidents prevention policy to be implemented by the duty holder. There are other notable differences between the two sets of legislation. The safety case Regulations require the review and acceptance of the safety case by the competent authority. There is no specific review and approval of the construction phase plan under the CDM regulations. The safety case regulations require the development of a safety and environmental management system. The regulations also require that the implementation of the safety and environmental system and the functioning of safety critical systems are verified by a 3rd party. The operation of which will be checked by an 'independent' and 'competent' verifier. There are also specific penalties for a duty holder if the procedures on the safety case are not followed, these can include fines and up to 12 months imprisonment in Scotland, or 3 months in England and Wales. The safety case regulations also require confidential and anonymous reporting systems that allow workers to raise safety concerns. There is also a requirement for a monitoring system to track and report the H&S performance of the facility. Finally, the safety case regulations have a stronger focus on emergency response. The safety case regulations state that the 'duty holder must perform internal emergency response duties' and includes 14 clauses specifying requirements. Part 4 of the CDM regulations includes milder language such as 'where necessary...suitable and sufficient arrangements for dealing with any foreseeable emergency must be made'. There are some aspects of the safety case regulations that stand out as being superior to what is required under the CDM regulations. These include the safety case itself which requires the operator to develop a comprehensive document that covers the full scope of a project from engineering to decommissioning. In contrast, CDM regulations require the construction phase plan. The construction phase plan is also a comprehensive document that aids in planning a project, however it was not developed specifically for operating and maintaining an offshore wind farm. It was intended for the management of a construction project, although it does apply to maintenance activities. It is unlikely that maintaining a wind farm offshore was ever thought of when the legislation was written. Other advantages of the safety case regulations are, it's focus on emergency response with the specific nature of offshore work in mind, and the requirements for regulator acceptance and 3rd party verification of its systems. Finally, requirements for reporting and worker involvement. The clear difference is that the safety case regulations were specifically written for Offshore Oil and Gas work, but CDM regulations were not written with the offshore wind industry in mind. There are many other important pieces of legislation that apply to both industries. These are often more prescriptive and set standards for specific activities or hazards. These include legislation for lifting operations, the operation of mechanical plant and standards for personal protective equipment. This section has highlighted that they key difference between the legislative regimes of offshore wind and oil and gas are the applicability of the CDM Regulations and the Safety Case Regulations. The UK has opted not to develop specific legislation for the offshore wind industry, but the application of existing legislation may lead to gaps in the legislation that fail to address risks unique to the industry. The offshore oil and gas industry has successfully implemented specific legislation which has a strong focus on elements important to that industry such as emergency response and verification of safety critical systems. Other leading offshore wind markets are taking different strategies in terms of the development of legislation. Norway has put the regulation of offshore wind under the authority of the Petroleum Safety Authority and are currently developing offshore wind specific legislation [22]. The USA went through a reorganisation of the regulatory authorities for offshore energy following the Macondo disaster, and offshore wind is now overseen by the BSEE and it is expected that existing regulations will be updated to address the challenges of offshore wind [87]. As offshore wind continues to grow across the world the development of specific safety legislation for the sector is an important factor in ensuring the industry is managed safely.

3.4 Conclusions

This Chapter set out to gauge safety performance in the offshore wind industry by an analysis of accident statistics, the legislative regime and an analysis of risk profiles through forecasting crew transfer statistics.

This Chapter highlights that offshore wind is a high-risk industry and current injury rates are 3 to 4 times those of the oil & gas industry, indicating there is huge potential for improvement. It also found that existing globally reported injury rates are missing key sectors such as China and do not include some serious incidents due to not being part of the scope of reporting groups. While accident numbers appear to be improving it remains to be seen if this is a significant trend. It should be noted that caution must be applied when looking at performance indicators such as TRIR. Offshore wind is a far younger industry with less work hours in an operational year, so a single injury has a greater impact on the injury rate as the denominator is much smaller. Since this research began G+ has reported two fatal incidents furthermore a high minor incident rate, could indicate the potential for more serious incidents in the future. A simple google search highlights three serious incidents in the offshore industry reported in the media between May 2020 and October 2021, one of which resulted in multiple injuries and one with four persons lost at sea [151] [165] [166]. None of these are found in industry reports. Furthermore, it is important to ensure that injuries are reported and not hidden, research into injury reporting rates show that under reporting appears to be common in many industries, so a danger of over focus on injury rates is that pressure builds to under report. The findings of this Chapter and the literature review both indicate that the development of improved methods of measuring and reporting safety performance for the industry are required.

This chapter has also considered the changing risk profile of the industry and has shown that there will likely be an increased exposure of offshore technicians as the industry grows. In addition, the development of more remote sites and roll out of new technologies, has the potential to increase the risk of more serious incidents. When considered in the context of the high existing injury rates and the numbers of emergency evacuations this highlights the need for further focus on the safety management of the industry.

Finally, the chapter has considered how safety legislation is used to manage the industry with an in depth look at the UK safety legislation considering its place as one of the largest offshore wind markets. It was seen that the UK has so far chosen not to adopt specific legislation for the offshore wind market. This contrasts with the oil and gas sector which developed specific legislation based upon hard lessons learnt following serious accidents. This study has highlighted some of the unique challenges of managing safety in the OWI. The comparison of the CDM regulations and the safety case regulations also highlights that the CDM regulations are weaker in several key areas and weren't written with offshore operations in mind. As the wind industry continues to grow the development of specific legislation tailored to the needs of the industry should be considered. Other developing sectors such as the USA and Norway are both looking at developing specific legislation to address challenges in offshore wind. Other jurisdictions around the world should consider the development of specific legislation that can address the risks faced in offshore wind. Once legislation from Norway or other countries is released this could be of great benefit to other countries in developing their own frameworks.

The analysis in this chapter was limited to the available accident data that is reported in the public realm, primarily that published by G+. If more data became available this would allow the scope of the study to be broadened. Analysis of technician transfer numbers and safety legislation was based on the UK industry, as a leader in the offshore wind market, there is more information available in the UK compared to other countries. Additional analysis including more countries would be beneficial for further studies.

Rapid growth and the changing nature of the industry mean the risk profile of the industry is growing. Worker exposure to hazards is likely to grow due to more offshore work taking place in the coming years. In conjunction with the development of more remote sites and the implementation of new technology this could mean the potential for more serious accidents to occur. A focus from research, industry and regulators on safety is important to ensure these challenges are met before serious accidents take place. Finally, legislation is a key aspect of the management of safety performance, regulators should consider the development of industry specific legislation as has been done in the oil and gas sector to ensure the offshore wind sector can be safely managed.

Chapter 4

Safety performance measurement in the OWI

4.1 Chapter contribution

Safety performance measurement is an important part of effective safety management for organisations and industries alike [167]. The offshore wind industry is an emerging and rapidly growing industry and as it develops it is important that it effectively measures and manages its safety performance. This chapter reviews the performance measurement systems that are in place within the offshore wind industry and makes a detailed analysis of performance data. The chapter then proposes improvements to performance measurement and reporting that could be adopted by industry and regulators to provide better information to help safety based decision making at an industry or organisational level.

There is a huge amount of research on the subject of safety performance measurement within the safety science body of knowledge, including the drawbacks of lagging indicators and the potential for leading indicators [167] [67]. It is also widely regarded that industry lags behind the latest research in terms of actual implementation [167]. As an emerging industry there is almost no research of safety performance in offshore wind.

While traditional safety performance measurement has relied on accident data, there is a growing consensus that effective safety performance measurement should be holistic with a range of measures including accident statistics or lagging indicators, but also utilising leading indicators and assessments for other aspects of safety such as safety culture [167] [168]. Safety performance measurement is an important part of the industry control structure providing performance feedback that allows organisations and regulators to make effective decisions to manage safety [81].

Research specific to offshore wind on the use of key performance indicators has found that they are not in widespread use across the industry [38] [41]. An industrial survey of offshore wind farm operators found that while 20 out of 28 respondents used KPIs to monitor performance, only five used KPIs to measure H&S performance. The indicators in use were all lagging indicators, these included:

- Total accident rate,
- Total lost time occupational illness frequency,
- Fatal accident rate,
- Recordable injury rate [39].

It is critical that an industry such as the OWI develops effective performance measurement systems, specifically suited to the needs of the industry. This chapter sets out to answer the following research question:

"How does the industry currently measure safety performance, how does it compare to best practice and how could it be improved?"

The contribution of this Chapter is:

- assessment of existing safety performance methods used in the OWI with comparison to best practice.
- detailed analysis of OWI accident statistic data by work activity.
- proposals for improvements to existing safety performance methods.

The outcomes of this Chapter will help business and regulators identify weaknesses in their performance measurement systems and allow for better decisions to be made to manage safety performance in offshore wind.

4.2 Methodology

The first stage of the research process was a two phase literature review to identify sources of offshore wind industry performance data and best practices from the research on safety performance measurement. Searches were carried out with Compendex and Google Scholar, using relevant keywords for safety performance data and the OWI. Keywords are included in table 4.1 . Searches returned 37 peer reviewed journal papers of which 7 were found to be relevant and were exported for further analysis. Additional google searches were also completed to find safety performance reports published by industrial organisations.

Key words				
incident	wind farm	KPI	wind farm	H&S
injury(ies)	wind energy	Key Performance Indicator	wind energy	Health & Safety
accident(s)	wind industry	indicator	wind industry	Safety
fatality	offshore wind		offshore wind	
TRIR	wind turbine		wind turbine	
LTIR				

Table 4.1: Keywords used for literature search

4.2.1 Performance measurement assessment

The second stage set out to identify the latest research on safety performance measurement best practices. The Compendex search engine was used to find papers on performance measurement. Keywords used were, leading indicators, lagging indicators, synonyms such as trailing indicator, passive indicator and risk indicator were also included. When the search was restricted to offshore wind, only 2 relevant papers were found. The search was then expanded to include offshore oil & gas and construction. over 270 results were then returned. An initial review of abstracts highlighted the 9 most relevant recent papers for initial study, and the literature search was then expanded by the snowball method to identify key papers in the field [169].

Assessment of existing performance measurement methods

The third stage of research is an analysis of the performance measurement methods identified within the offshore wind industry. The intent is to identify strengths and weaknesses in the current methods in order to propose improvements. Based on findings from the literature review, two methods for the assessment of safety performance measurement systems were selected. One qualitative method and one quantitative method.

For the qualitative methodology a five point assessment framework from Sgourou et al. was applied [170].

The five point methodology was developed and tested by Sgourou et al. with the goal of helping organisations identify the best performance management systems for themselves. This evaluates performance measurement systems using conceptual, methodological and practical characteristics. The assessment criteria represent a holistic approach to performance measurement and consider that technical, organisational and human factors should all be considered for an effective system. The methodologies are qualitatively assessed against five criteria, these are set out in Table 4.2. These criteria have been applied in this research to the performance measurement systems currently used in offshore wind. An advantage of this system is that it can be applied to any industry or methodology. There will always be some subjectivity in determining the best safety performance methods but using a multi criteria 'holistic' approach helps to make a rounded assessment and judgement can be applied as to which criteria are the most important factors.

In order to try to strengthen the assessment process it was decided to also apply a quantitative methodology to complement these results.

For the quantitative assessment a methodology developed by Erkal et al for commonly used safety performance metrics was selected [168].

This quantitative framework was developed by using a Delphi-style expert elicitation methodology. In the study by Erkal et al. a panel of subject-matter experts was

Ref	Category	Assessment question
1	Theoretical framework	Is there an underlying scientific theory or model presented in the research?
2	Holistic features	Consideration of technical, organisational and human factors in the methodology?
3	Validation	Have reliability and validity tests been successfully completed?
4	Required expertise	Level of required expertise to implement the methodology?
5	Motivation for improvement	Does the methodology motivate for improvements?

Table 4.2: Assessment criteria adapted from Sgourou et al. [170]

asked to score commonly used safety performance measurement techniques against a set of criteria identified as important for effective performance measurement, namely predictive-ness, validity, objectivity, clarity, functionality and importance. The eight most widely used performance metrics were evaluated on each criterion, and the resulting average scores are summarised in Figure 4.2.

In this work the scoring developed by Erkal et al. and shown in figure 4.2 is applied to make an assessment of the OWI performance methods.

These scores provide a structured, quantitative comparison of different performance metrics based on expert judgement rather than statistical estimation. The framework has the advantage of being transparent and reproducible; however, it also inherits the limitations of expert elicitation: the scores depend on the composition of the expert panel, implicitly assume equal weighting of criteria, and were originally developed in the construction context rather than offshore wind.

For this reason, the results in Figure 4.2 are interpreted as a comparative indication of the relative strengths and weaknesses of different metrics, rather than as a precise quantitative ranking.

This research has then applied these radar plots to assess how OWI reports present their data. The radar plots can be combined to give composite scores for performance methods depending on which of the eight methods are employed [168]. For example the first radar plot in Figure 4.2 shows the scoring for the G+ assessment. The G+ report includes near miss, TRIR and fatality reporting, so the result is a composite of these three radar plots from Figure 4.1.

By combining both the qualitative and quantitive methods the goal is to make as objective an assessment as possible of existing performance measurement methods and make an unbiased judgement as to how these can be improved.

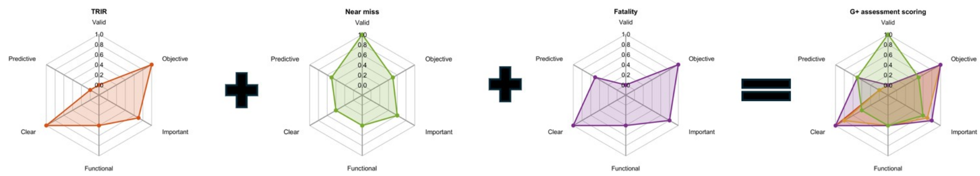


Figure 4.1: Method for constructing

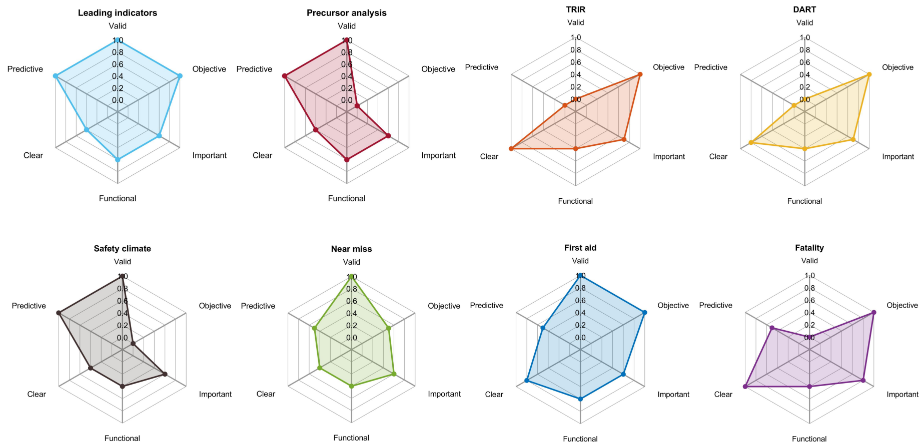


Figure 4.2: Scoring of assessment criteria as per Erkal et al [168]

4.2.2 Data analysis methods

The accident data from offshore wind was analysed using methodologies identified during the literature review. This is done to identify potential changes in risk levels and assess the validity of reported data.

The accident data used in this chapter consist of yearly counts of incidents X_t and corresponding exposure hours E_t. Following Hallowell et al, [46], each worker-hour can be viewed as a Bernoulli trial in which an injury either occurs or does not occur. For rare events with small probabilities of occurrence, the binomial model is well approximated by a Poisson process, and the yearly counts may therefore be modelled as

$$X_t \sim \text{Poisson}(\lambda_t E_t), \tag{4.1}$$

where λ_t is the underlying incident rate per hour. This is a standard approach for low-frequency safety events in high-hazard industries.

4.2.3 Statistical validity

The Construction Safety Research Alliance have developed proposals for assessing the statistical validity of TRIR and for improving how it is presented and reported [46]. Their work shows that TRIR has low statistical validity when used as a point estimate without uncertainty bounds and recommend that it should always be reported together with confidence intervals. For rare injury events, a simple and robust way to compute these intervals is to use the Wilson score confidence interval (WCI) [46], [171].

Let X denote the number of recordable incidents observed in a given period with total exposure n worker-hours. The estimated probability of an incident per worker-hour is then

$$\hat{p} = \frac{X}{n}. \tag{4.2}$$

The Wilson $(1-\alpha) \times 100\%$ confidence interval for $\hat{p}$ is given by

$$\tilde{p} = \frac{\hat{p} + \frac{z^2}{2n}}{1 + \frac{z^2}{n}}, \tag{4.3}$$

$$h = \frac{z}{1 + \frac{z^2}{n}} \sqrt{\frac{\hat{p}\,(1-\hat{p})}{n} + \frac{z^2}{4n^2}}, \tag{4.4}$$

$$\hat{p}_{\text{lower}} = \tilde{p} - h, \qquad \hat{p}_{\text{upper}} = \tilde{p} + h, \tag{4.5}$$

where z is the critical value from the standard normal distribution corresponding to the chosen confidence level (for example, $z = 1.645$ for a 90% confidence interval and $z = 1.96$ for a 95% confidence interval). Confidence intervals for TRIR on the conventional 200,000-hour basis are obtained by multiplying both bounds by 200,000.

Wilson intervals are used because they provide better coverage than simple normal-approximation intervals for rare events and small counts. For the range of counts considered in this study, Wilson intervals are numerically very similar to exact Poisson intervals, but are straightforward to compute and interpret [171]. The width of the resulting confidence interval indicates the precision of the TRIR estimate: a very wide interval implies that the available data are insufficient to estimate the rate precisely and that TRIR has limited value for comparison or trend analysis in that case. In this chapter, the WCI is applied to the available OWI incident data to assess whether observed year to year changes in TRIR are likely to reflect real changes in underlying risk or merely random variation.

Annual incident rates are reported as events per 200,000 hours worked, consistent with industry practice for TRIR and LTIIR. For each year t, the point estimate of the rate is

$$\hat{\lambda}_t = \frac{X_t}{E_t} \times 200{,}000. \tag{4.6}$$

For Figure 4.5, the data used for each point are therefore the annual incident count X_t and the corresponding exposure hours E_t, the assumed distribution is Poisson/binomial as described above.

4.2.4 Accident trends analysis

The literature review identified the Norwegian Trends in Risk Level Project (RNNP) as a best practice in terms of the use of incident data [64] [65].

One of the key aspects of the RNNP was the application of statistical methods to better understand incident data. The theory behind this is set out by Kvaløy and Aven [66]. The process applies a predictive Bayesian approach, which uses observed data to generate a probability distribution.

Kvaløy and Aven [66] argue that classical statistical tests often detect a trend only after the change in risk has become substantial, so the “alarm” comes too late to support proactive safety management. Instead of testing a null hypothesis of “no trend”, their predictive Bayesian approach asks whether the most recent observations are surprising given past data.

In this case a Poisson distribution is generated based upon existing data which can then give a 90% confidence interval of the number of events expected in a subsequent period. If the actual value of events falls outside the 90% confidence interval this acts as a potential notification of a change in the risk level.

In this context the charts are intended as screening tools rather than formal hypothesis tests. The aim is to highlight years where the observed counts are potentially unusual and merit further investigation, rather than to prove or disprove a specific hypothesis at a strict significance level. A 90% band provides a practical balance between avoiding excessive false alarms and maintaining sufficient sensitivity to possible changes in underlying risk for low-count data.

The Poisson distribution is generated as shown in equation 4.7.

$$P(x) = \frac{\lambda^x e^- \lambda}{x!} \tag{4.7}$$

where $\lambda =$ the expected value of x. Confidence intervals for a poisson distribution can be calculated in a straightforward manner using software such as Matlab. Developing this confidence interval allows for alternate methods of presenting incident data, these are used in the RNNP and have been adopted here and applied to OWI incident data in section 4.3 [66] [64] [62].

A second step to the proposed method is to then complete a screening process using the same methodology. Where there are, for example, five years of data, a poisson distribution would be applied with mean from those five years to generate a confidence interval for the sixth period. Next a poisson distribution is generated from the first four years of data and the confidence interval is applied to the actual number of incidents from years five and six together. This process can be looped over each set of time periods and can give an indication of an improving or worsening trend over the entire time period [66]. This method has also been applied to OWI data in section 4.3.

In this thesis, the resulting prediction intervals are used as *screening tools* rather than as formal hypothesis tests: they identify years where the observed number of incidents appears surprising under an assumption of constant risk and therefore merit closer investigation.

4.3 Results

4.3.1 Performance reporting assessment

The literature review returned the following sources of safety performance reports for the industry:

- G+ - Industry level data reporting [172]
- IMCA - Marine Contractors reporting [173]
- Health and Safety Executive (HSex) - Government safety regulator [174]
- Operator and developer annual reports - Corporate reporting [175] [176] [177]

G+ publish annual accident data reports from their members [172]. The international Marine Contractors Association (IMCA) publish incident data submitted by members on an annual basis [173]. The data includes offshore wind work as well as other marine construction activities, so will not be specific to the OWI.

Governmental organisations such as the Health and Safety Executive (HSEx) publish industrial safety statistics, but statistics for offshore wind are included in broad categories in their reporting system, so no specific data for offshore wind is published.

Incident data can also be found in the annual reports of major wind farm developers and operators. These typically present the TRIR or LTIF rates reported for each year to one decimal place along with the associated numbers of incidents and hours worked [176] [177] [175].

To create a benchmark for the analysis, two performance reports from a comparable industry were selected. The international association of oil & gas producers (IOGP) annual safety performance report was selected as it is a major publisher of annual oil and gas safety statistics [72]. In addition, the trends in risk level report (RNNP) from the Norwegian Oil industry was also selected.

4.3.2 Quantitative analysis

Table 4.3 summarises the reporting features that are included or not in each of these reports. Based on the inclusion of these features, each reporting system was then scored by applying the assessment scoring technique from Erkal as described in section 4.2 using the scores as set out in Figure 4.2.

Ref	Data Source	First aid rates	TRIR	LTI / DART	Fatal injury rate	Leading Indicators	Near miss reports	Precursor analysis	Safety climate
1	Industry data reporting	No	Yes	Yes	Yes	No	Yes	No	No
2	Marine contractor reporting	No	Yes	Yes	Yes	No	No	No	No
3	Government regulator reporting	No	No	Yes	Yes	No	No	No	No
4	Corporate reporting	No	Yes	Yes	Yes	No	No	No	No
5	Oil & Gas industry reporting	No	Yes	Yes	Yes	No	Yes	No	Yes
6	Norwegian oil industry reporting	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No

Table 4.3: Incident data sources reporting features

The resulting composite scores for each report are shown in Figure 4.4. A radar plot is generated for each reporting method being assessed, these include scoring from Erkal et al. based on which methods are included in their reporting.

For example the radar plot for G+ is a combination of the near miss plot (light green), fatality plot (purple) and TRIR plot (orange) from figure 4.2. The combination of these three plots gives the overall scoring for the G+ reporting system.

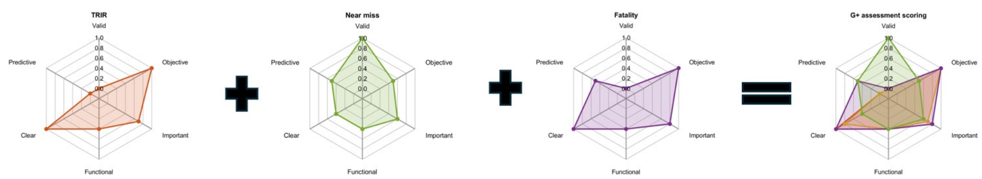


Figure 4.3: Visualisation of the construction of the scoring shown in figure 4.4

The more comprehensive and holistic the methodology the greater coverage of the radar plot it will have. The RNNP report that was included as a best practice scores the highest on the qualitative assessment as it has the greatest coverage of the radar plot. G+ and IOGP reporting have similar scores, with both methodologies lacking in predictive ability and functionality. Corporate, IMCA and government regulator (HSEx) reporting have the least coverage of the radar plots, with low score for validity, productiveness and functionality.

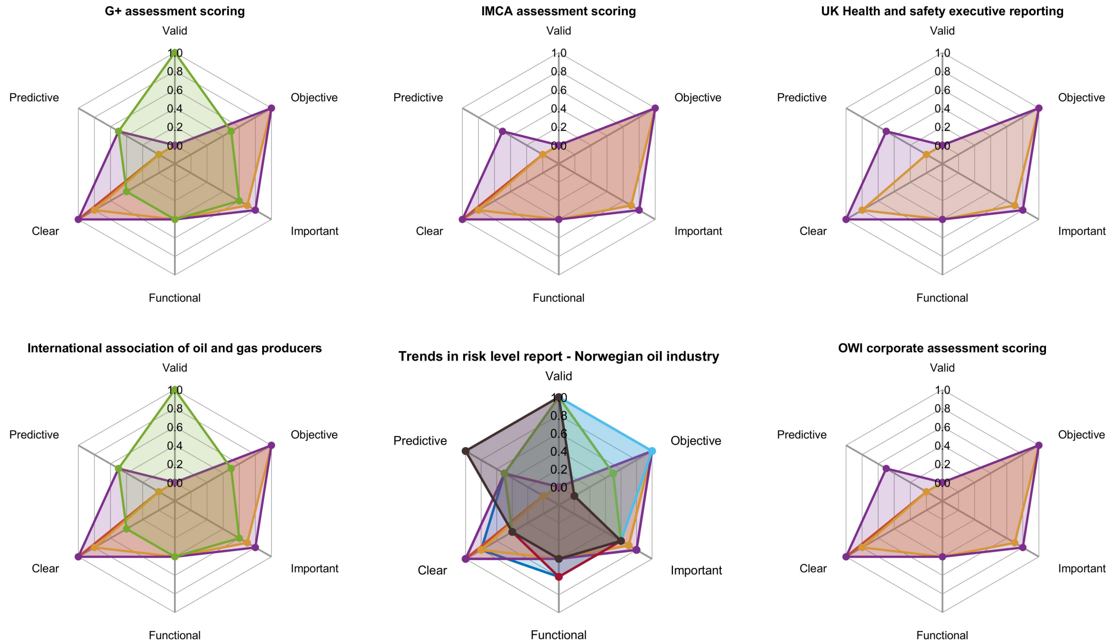


Figure 4.4: Scoring of OWI performance measurement systems

4.4 Qualitative analysis

Each report as set out in Table 4.3 was assessed by applying the criteria from Sgourou et al. as described in section 4.2. The key elements of each report and any related research is set out below, summary of the qualitative analysis is set out in Table 4.4

Ref	Category	G+	IMCA	UK HSEx	OWI Corporate	IOGP	RNNP
1	Theoretical framework	No	No	No	No	No	Yes (Vinnem 2010)
2	Holistic features	No	No	No	No	No	Yes
3	Validation	No	No	No	No	No	Yes (Vinnem 2010)
4	Required expertise	No	No	No	No	No	Yes
5	Motivation for improvement	Potential motivation for improvement	Potential motivation for improvement	No	Potential motivation for improvement	Potential motivation for improvement	Good potential for motivation

Table 4.4: Qualitative assessment of reporting

4.4.1 OWI Industry reporting

Offshore wind industry safety organisations publish reports to provide an overview of health and safety incidents occurring globally across the sites of the members [172]. For the report selected for analysis, members are located in Europe, East Asia and North America. The report provides safety statistics showing annual performance since the inception of the organisation in 2016. The report provides summary statistics, annual highlights and analysis of high potential incidents. Analysis of incidents broken out by work location i.e nacelle, tower, barge etc and also by work process. Geographic spread of incidents and site type (operational, development or construction) is also presented. Reporting is limited to traditional lagging indicators such as TRIR, and presentation of incident numbers by category in tables and charts. Research has shown that these indicators do not have an underlying theoretical framework and are not statistically valid. The report does not include any holistic features and relies on lagging indicators. The required expertise to understand the report is low, data is presented in simple charts and figures. The report does provide motivation for the industry to improve as it highlights which areas have had the highest numbers of incidents and that may need attention.

4.4.2 Marine contractor reporting

Reports are available from the marine contracting industry containing safety performance data which is reported voluntarily by their members. The data includes all types of marine construction activities and is not exclusive to offshore wind. The report includes traditional lagging indicators such as TRIR and LTIR and has data available since 1996. Accidents are reported with summary statistics and are also reported by cause. A safety observation rate is included and rates are also reported by categories of company size. Again, the reporting features of this report are not backed by a theoretical framework and the lagging indicators have low statistical validity. The low number of hours worked mean that the statistics should be reported with a confidence range. The report does not contain any holistic features but is easy to understand and does not require special expertise for interpretation. The report has some potential for motivation for improvement, it highlights safety observation rates, highlights area with the highest frequency of incidents and provides a comparison to similar industries.

4.4.3 UK Regulatory reporting

The UK Health and safety regulator reports accidents that are submitted to them in accordance with the RIDDOR legislation [174]. This requires that all reportable accidents are submitted. These are reported by broad industry categories. The UK regulator reporting includes offshore wind reporting in a a broad industrial category. UK regulator accident reporting uses lagging indicators similar to other reports which do not have a theoretical background. Reporting is simple and easy to understand but does not provide motivation for improvement as their is no specific reporting for the industry.

4.4.4 OWI Corporate reports

The annual reports of three major developers and operators were reviewed for their safety reporting content [176] [177] [177]. The review of corporate reports is limited to those that are made publicly available. Most corporations will be reluctant to publish their data, however all reports reviewed contained some safety reporting. Corporate reports were all found to include TRIR and/or LTIF rates, reported to one decimal point. The reporting features do not have an underlying theoretical framework and have low statistical validity. The reports did not contain any holistic features but do not require expertise to be understood. The reporting of accident statistics in a public high profile report will provide motivation for improvement, however reporting statistics without a confidence interval could lead to a misinterpretation of annual variations in accident rates.

4.4.5 Oil & gas industry reporting

IOGP safety reports contain safety statistics from members globally and are reported annually. Data is presented from 51 member companies across over 92 countries. Reports include lagging indicators such as TRIR and LTIR. Results are reported by region and by function (construction, drilling, production). The lagging indicators included do not have an underlying theoretical framework and the report did not contain any holistic features. The high number of hours worked mean that the injury rates can be reported to a decimal point accuracy so are statistically valid. The required expertise to understand the report is low and the report will provide some potential motivation for improvement as it provides data from the global industry including breakdown of geographical regions and industry sectors.

4.4.6 Norwegian oil industry reporting

The trends in risk level report is published every four years by the authorities responsible for regulating safety in the Norwegian oil industry [62]. Oil company operators and helicopter transport companies provide data for the production of the report. Development of the reporting system has a theoretical framework and has been published in peer reviewed research literature [65]. The report contains a range of safety indicators. Reporting includes, helicopter incidents, precursors with major accident potential, safety barrier performance, maintenance performance and traditional lagging indicators such as personal injury rates. Safety barrier performance rates are used as leading indicators, as it is considered that the performance of safety barriers gives a leading indication of the potential for serious incidents. Statistics are reported including confidence intervals and are statistically valid. The report also includes holistic features including the results of a questionnaire based survey for divers involved in the industry, this covers topics including safety climate, perceived accident risk and working environment. The report provides a detailed and comprehensive summary of safety performance across the industry, it has a holistic approach and can provide a strong motivation for the industry to improve.

4.5 Data analysis

This section introduces the results of further analysis on accident data reported by the offshore wind industry. Industry data was taken from publicly available reports and has been re-presented with further analysis as discussed in section 4.2 to explore the possibility of improving standard incident reporting practices in the offshore wind industry.

4.5.1 Offshore wind industry rates

Table 4.5 shows the OWI incident rates as they are currently presented in industry reports [172]. Figures are presented on an annual basis since reporting began, standard lagging indicators such as lost work days along with the standardised injury rates, TRIR and LTIF, are shown.

Year	Hours worked	Fatalities	Lost work day injuries	Restricted work day injuries	Medical treatment injuries	Total	TRIR	LTIF
2014	23,710,000	-	44	14	85	143	6.03	1.86
2015	21,220,000	-	41	32	53	126	5.94	1.93
2016	21,726,000	-	43	35	42	120	5.52	1.98
2017	26,815,000	-	49	30	78	157	5.85	1.83
2018	25,359,000	-	39	34	45	118	4.65	1.54
2019	22,374,000	-	62	23	38	123	5.50	2.77
2020	25,318,000	-	43	30	22	95	3.75	1.70
2021	32,342,000	-	50	22	34	106	3.28	1.55
2022	44,640,000	-	46	36	44	126	2.82	1.03
2023	61,900,000	1	65	33	70	169	2.73	1.07
2024	78,800,000	1	99	57	74	231	2.93	1.27

Table 4.5: OWI incident statistics as presented in existing reports

Data is also available for incident rates by work activity and work location. A selection of data by work activity is show in Table 4.6. Numbers of incidents are reported by the work activity type, data are also available for incident by work location, such as vessel or nacelle.

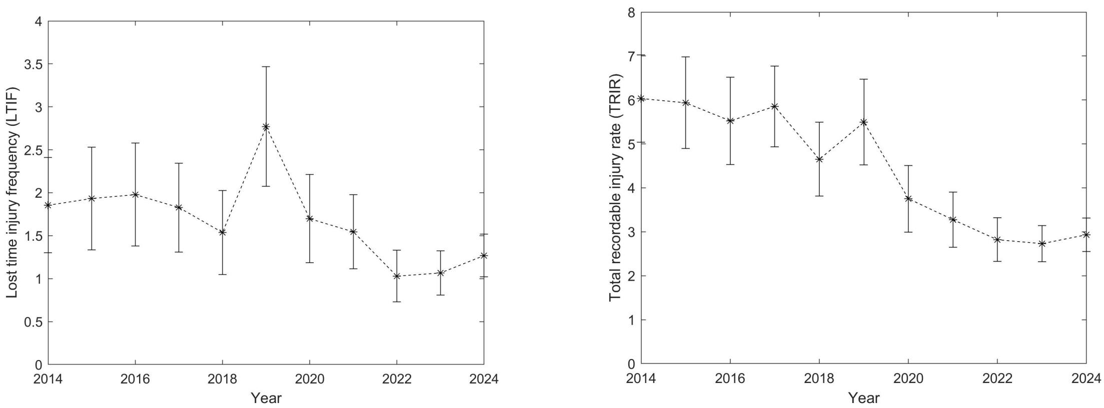
4.5.2 Industry injury rates validity

Offshore wind industry injury rates are typically presented with simple line charts or tables without further statistical analysis. Following the approach proposed by Hallowel et al [46] and described in section 4.2, the TRIR and LTIF for the OWI have been plotted with bars indicating the range of the 95% confidence intervals (Figure 4.5). For each year where the TRIR data is reported the 95% confidence intervals have been calculated using the process described in section 4.2. The bars create a band of around

Year	Hours worked	Working at heights	Vessel operation (including jack ups and barges)	Transfer from / to vessel	Manual handling	Lifting operations
2014	23,710,000	72	59	69	61	127
2015	21,220,000	71	39	23	42	83
2016	21,726,000	114	10	5	72	94
2017	26,815,000	40	26	36	71	156
2018	25,359,000	43	24	39	47	72
2019	22,374,000	41	42	33	77	93
2020	25,318,000	43	41	31	60	94
2021	32,342,000	31	48	32	73	95
2022	44,640,000	34	52	38	67	119
2023	32,342,000	33	58	39	108	207

Table 4.6: OWI incident numbers by workstream

1 above and below the TRIR plot line and 0.5 above and below the LTIF line. It can be expected that the value of TRIR will fall within this area with a 95% probability. The size of the error bars are determined by the number of hours worked associated with the data. The greater the number of hours the smaller the error bars will be.



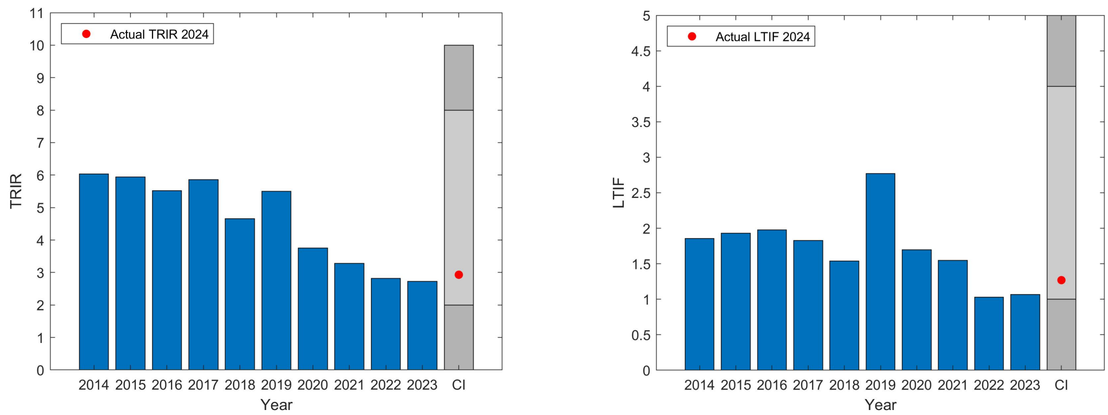
(a) LTIF with error bars (b) TRIR with error bars

Figure 4.5: OWI industry injury rates presented with 95% confidence interval

Figure 4.5 shows that while industry injury rates are reported to two decimal places, the uncertainty around the actual incident rate is much higher. This indicates that small annual fluctuations may often be random variation than any significant trend in industry performance.

4.5.3 Statistical analysis of accident data

This section shows industry accident data presented using methodologies described in section 4.2 [64] [65] [66]. The data used is shown in Tables 4.5 and 4.6. Analysis is presented for the top eight workstreams by incident number and for emergency response incidents.



(a) TRIR with 90% confidence intervals (b) LTIF with 90% confidence intervals

Figure 4.6: LTIF and TRIR bar charts with confidence interval

Figure 4.6 shows bar charts of the TRIR and LTIF data reported by G+ [147]. Data from the period 2014 to 2023 is used to create a poisson distribution that provides a 90% confidence interval for the predicted value for the period 2024.

The shaded area shows the 90% prediction interval for the incident count (the region between the 5th and 95th percentiles of the Poisson distribution under a constant-risk assumption). The lower and upper lines correspond to the 5% and 95% prediction limits, respectively.

This is illustrated by the shaded bar, if the value for 2024 falls within the light grey section it can be expected that any change could be due to normal random variation. A value falling in the dark grey section indicates that there may have been a change in the underlying risk level. The actual values for 2024 are indicated by a red dot, and in both cases these fall within the 90% confidence interval so while the value has changed for the year it may not represent a significant change in performance.

Figures 4.7 to 4.12 show the incident rates for key work activities reported for the offshore wind industry [147]. Industry reports typically present these without statistical analysis, here they are presented using methodologies developed for the Norwegian risk level project. In each case, the chart (a) shows the number of incidents normalised by hours worked for the period 2014 to 2022, this data is then used to produce a confidence interval for the 2023 period. The actual incident rate for 2023 is indicated by a red dot overlayed on the confidence interval bars.

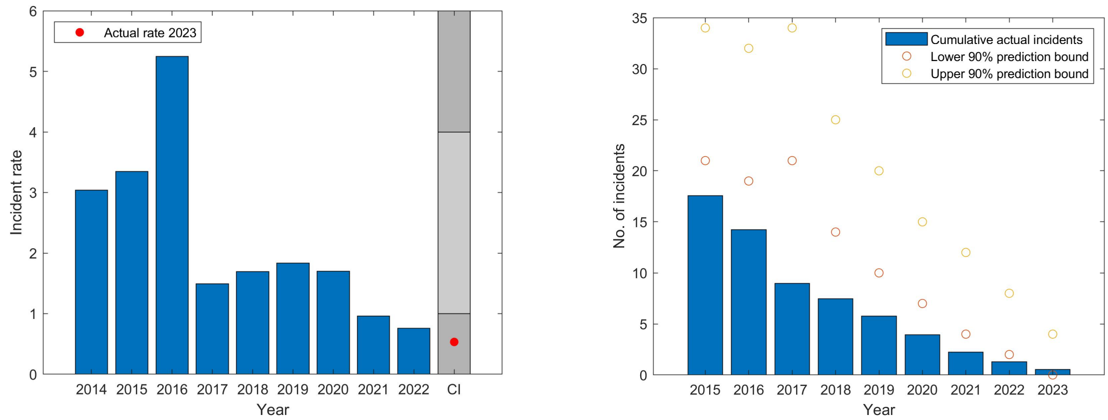
Some workstreams do not have data reported for the full period. Figure (b) show a representation of the screening process described in section 4.2 [66]. Each year includes points showing the 90% confidence interval derived from the preceding years data predicting the 90% range of cumulative number of incidents that would be expected in the subsequent periods. The bar for each year then represents the actual cumulative number of events experienced in the subsequent periods. If the bar falls above or below the confidence interval bounds, this indicates there is a significant trend occurring at that time, either upwards or downwards. This visualisation can help show where upwards or downwards trends in risk level began, which may help identify what factors could have caused the change.

Several of the workstreams and years considered in Figures 4.7 to 4.15 have very few incidents. As such, confidence intervals are wide and statistical power to detect changes is limited. As highlighted in recent work on the statistical invalidity of TRIR, small apparent differences in annual rates often reflect random variation rather than genuine changes in underlying risk [46].

The Poisson based charts in this chapter are therefore used as *screening tools*: they highlight years where the observed counts are surprising under an assumption of constant risk, but any potential trend must be interpreted cautiously.

Figure 4.7a shows that the actual incident rate for 2023 falls just outside the 90% confidence interval indicating that this may indicate a change in risk level. The screening process in Figure 4.7b shows that for each year since 2015 the number of incidents has fallen outside the 90% confidence interval band, this also indicates there may have been a change in the underlying risk levels.

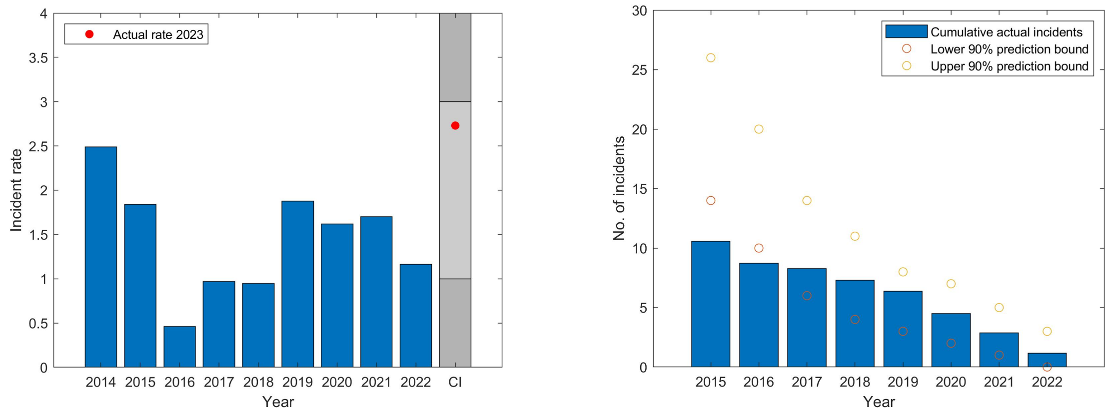
Figure 4.8a shows that there was an increase in vessel operations incident rates in



(a) Work at height rates 90% CI

(b) Work at height screening chart

Figure 4.7: Work at height incident rates



(a) Vessel operations incident rates 90% CI

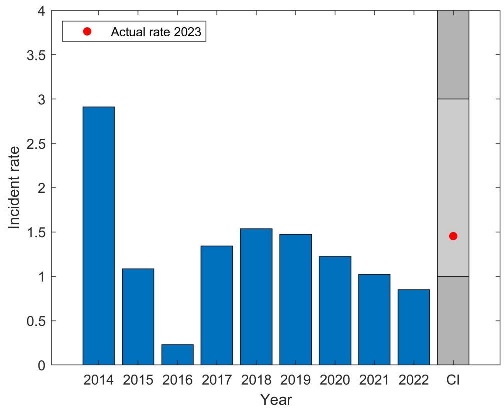
(b) Vessel operations screening chart

Figure 4.8: Vessel operations incident rates

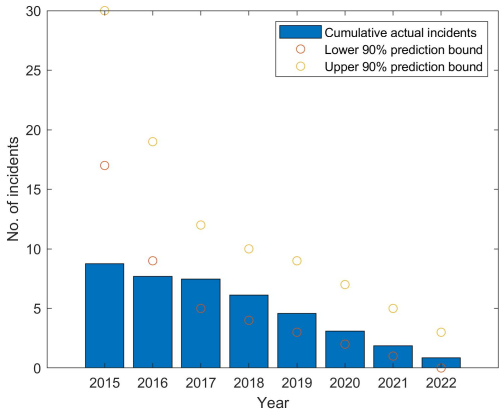
2023, the change may not be significant as it falls within the 90% confidence interval band. Figure 4.8b shows that there may have been a trend of improvement in 2015 and 2016, however each year since then the number of vessel operations incidents has fallen within the expected range.

Figures 4.9a shows the actual value for 2023 vessel transfer incidents has increased but is within the 90% confidence interval, indicating no significant change. Figure 4.9b shows that the current trend indicates the actual incident numbers are falling within the expected ranges but on the lower end of the 90% confidence interval.

Figure 4.10a shows that there may have been a statistically significant improvement

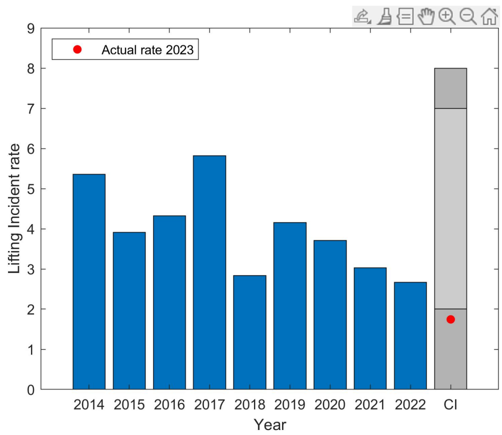


(a) Vessel transfer incident rates 90% CI

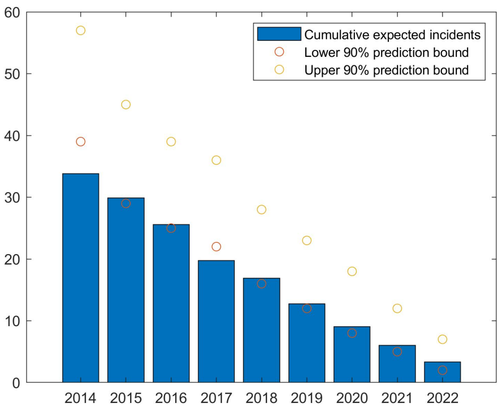


(b) Vessel transfer screening chart

Figure 4.9: Vessel transfer incident rates



(a) Lifting incident rates 90% CI

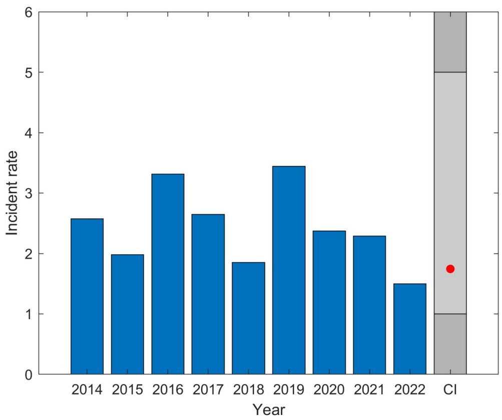


(b) Lifting incidents screening chart

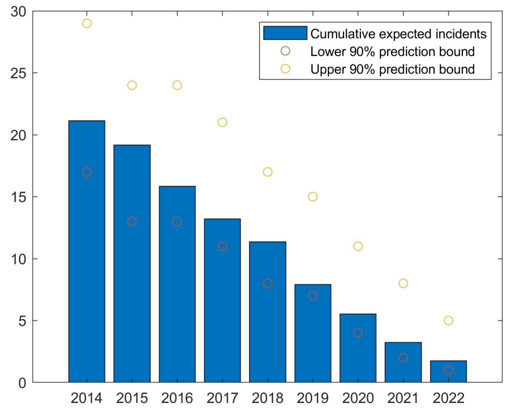
Figure 4.10: Lifting incident rates

in the number of lifting incidents in 2023. The screening chart also shows the cumulative incidents in each period falling at the very lower end of the confidence intervals again indicating there may have been a real trend of performance improvement in this activity in the preceding years.

Figure 4.11a shows that the number of manual handling incidents for 2023 falls within the 90% confidence interval band, while there was a small increase for the year this does not indicate a trend of improvement. The screening chart 4.11b also shows the same trend, for each period the cumulative number of incidents has fallen well within the 90% confidence interval band.

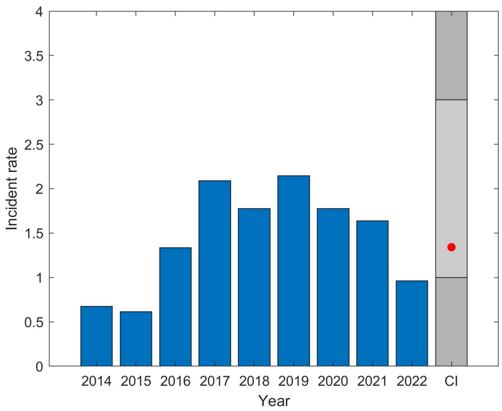


(a) Manual handling incident rates 90% CI

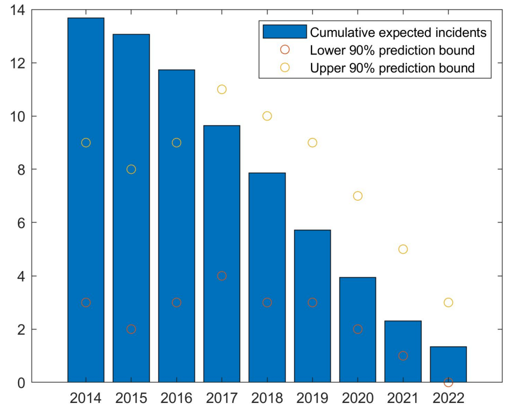


(b) Manual handling incidents screening chart

Figure 4.11: Manual handling incident rates



(a) Hand tools incident rates 90% CI



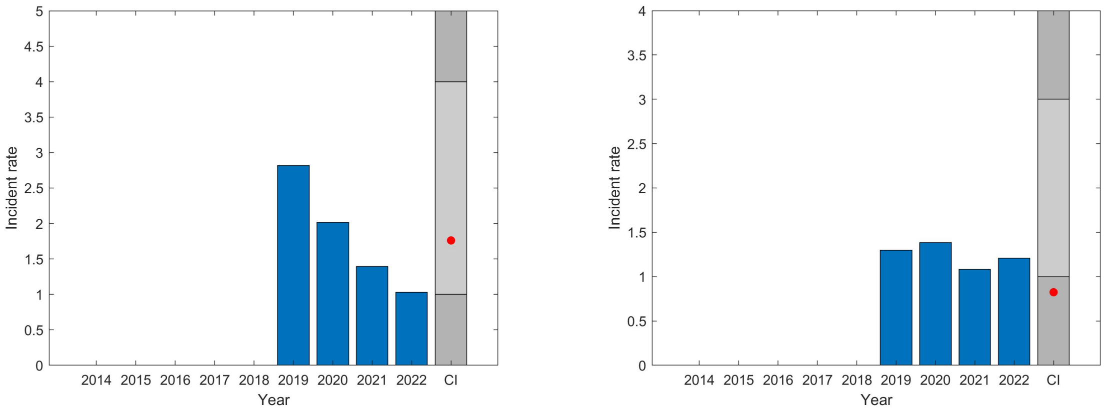
(b) Hand tools screening chart

Figure 4.12: Hand tool incident rates

Figure 4.12a shows that there was a small increase in the number of incidents for 2023 and this fell within the 90% confidence interval. The screening chart shows that from 2014 to 2016 the there was a negative trend in performance in this activity however since 2017 there appears to be an improvement as the number of incidents has gradually moved closer to the lower bounds of the 90% confidence interval.

Figure 4.15a shows the incident rates for routine maintenance and electrical systems work incidents. Both of these datasets only include figures from 2019 so there is not sufficient data to produce a screening analysis.

Figure 4.14 shows the rates for incidents during turbine access. Again, there was



(a) Routine maintenance incident rates 90% CI

(b) Electrical systems work incident rates 90% CI

Figure 4.13: Routine maintenance and electrical systems rates

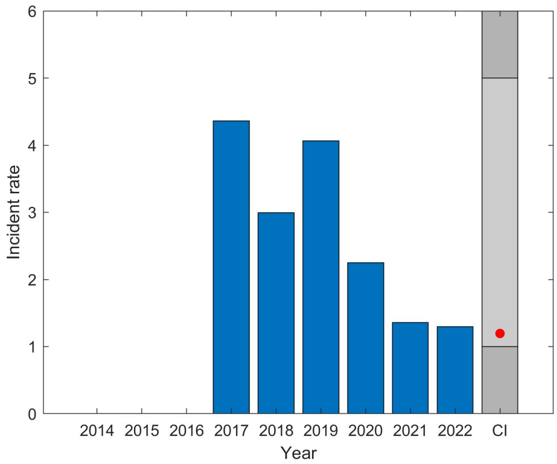
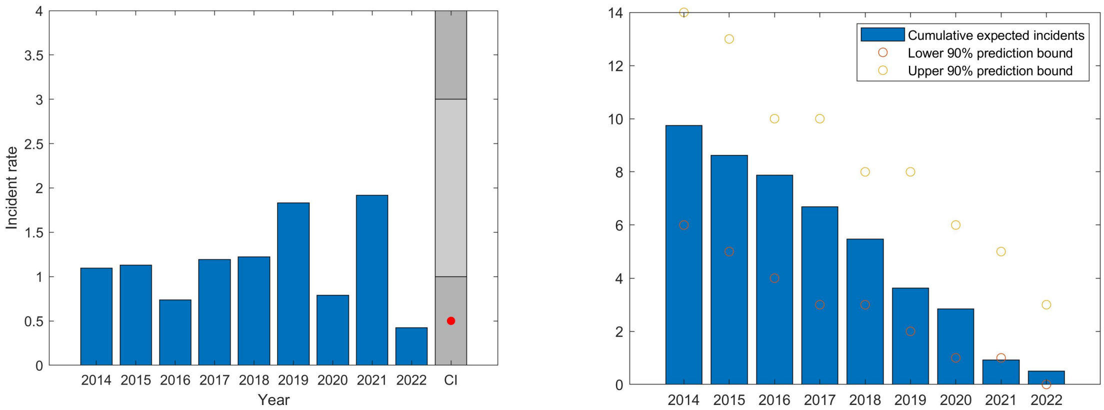


Figure 4.14: Access incident rates 90% CI

not sufficient data available for a screening chart. The figure for 2023 falls within the 90% CI indicating there has not been a statistically significant change in 2023.

Figure 3.6 is the final set of charts and shows data for emergency response incidents across the industry. The annual rate chart shows that 2022 has seen a statistically significant drop, however the screening chart shows that the incident rates have been consistent between 2014 and 2021.



(a) Emergency response rates 90% CI (b) Emergency response screening chart

Figure 4.15: Emergency response rates

4.6 Conclusions

The first objective of this Chapter was to assess performance measurement methods used in the offshore wind industry and compare them to best practices. This is the first study that has made a detailed assessment of safety performance reporting methods and accident statistics in the offshore wind industry. The results reinforced initial findings from Chapter 3 and showed that reporting methods lack statistical validity, rely on lagging indicators and lack holistic features. Reports were easy to understand but lack any predictive value or underlying theoretical framework.

The comparison with reporting best practices from the literature showed that the wind industry has not yet adopted learning from the latest research. An analysis of industry data using methods adopted from the oil & gas industry has shown that reporting can be improved and that this can highlight unseen trends and identify where annual variations are statistically significant or not.

Of particular concern is that corporate reports misunderstand the statistical validity of the data. Figure 4.5 showed that reported accident statistics from the offshore wind industry have significant uncertainty due to the low number of associated worked hours. While statistics are reported in industry documentation or corporate reports to one or two decimal points, the uncertainty around the actual figures could be +/- 1. Reporting without this statistical analysis could lead to overconfidence in the results and the interpretation of trends where there are actually no statistically significant changes. Financial reports show that corporate bonuses are linked to small variations in TRIR which are likely to be no more than random variation.

The analysis confirmed that the RNNP reporting method can be considered as a best practice and that the offshore wind industry could benefit from the adoption of additional methods such as leading indicators of risk specific to the industry.

Overall, this chapter has shown that the offshore wind industry currently measures safety performance predominantly through lagging indicators such as TRIR and LTIF, reported on an annual basis and typically without treatment of statistical uncertainty. Compared with best-practice examples in other high-risk sectors, such as the Norwegian RNNP programme these approaches are less mature in their use of holistic indicator sets, exposure normalisation, confidence intervals, and screening for emerging trends.

The analysis presented here suggests that offshore wind safety performance measurement could be improved by adopting more balanced sets of indicators that combine injury rates with leading metrics, by routinely reporting exposure-normalised rates together with confidence or prediction intervals, and by applying screening charts to key activities. These changes would align industry practice more closely with established best practice and provide a stronger basis for proactive, risk-informed safety management.

Chapter 5

Development of leading performance indicators

5.1 Chapter contribution

Chapter 4 has shown that the offshore wind industry could benefit from improved safety performance measurement tools and the development of leading indicators of risk. These points then bring the focus of this research to look at what are the next steps that can be done to improve how we manage H&S in the OWI. The first part of this question is how could leading indicators of risk be developed to help the industry monitor risk levels in the future and prevent the occurrence of serious accidents? This research question is the focus of this chapter.

Where Chapters 2–4 focus on understanding the current safety performance and its limitations, this chapter addresses the 'measure and predict' element of the research question by developing a framework for leading indicators specific to offshore wind.

Chapter 2 set out a summary of the latest literature around leading indicators in offshore wind and in related industries. This Chapter will draw on that research to build a suitable framework for leading indicators development specific to the offshore wind industry and to propose a set of leading indicators which could help industry monitor risk levels. As was discussed in Chapter 4 safety performance and risk levels have traditionally been measured by the use of lagging indicators and with a focus on past events. This paradigm has continued in the offshore wind industry. Data collected is focused on specific events that have occurred, therefore the majority of data available is only telling us about higher probability and probably lower risk events. In a relatively young industry such as offshore wind, how do we find the risk levels of rare but high impact events? This should be one of the goals of developing leading indicators. To do this, traditional risk assessment methodologies focusing on event chains are probably not adequate and we need to consider the entire system of an offshore wind farm maintenance organisation to consider all potential hazards. Some of which may not have been encountered yet.

The contributions of this Chapter are:

- Develop a framework for leading indicators development specific to the OWI
- Review of currently available leading indicators
- Proposal of a set of leading indicators specific to the sector

Amongst the literature many different terminologies have been used related to safety performance indicators. Zhen et al. has pointed out that there has been significant confusion and that this has become a distraction from actual useful research in the area [67]. From the point of view of this research it is important that definitions are clarified and used consistently. This thesis uses the term safety performance indicators as a catch all for all types of indicators, and will clarify whether these are lagging or leading indicators where necessary. In this work a leading indicator is something that aims to highlight a change in risk levels before an incident occurs.

5.2 Useful safety indicators for the offshore wind industry

Chapter 4 also proposed that the development of leading indicators of safety performance would be beneficial to help the industry implement a holistic performance management system and also create a tool to help indicate if risk levels have increased before serious accidents occur. It is of course important to ask whether it is possible to create performance indicators that are useful and can be predictive of changing risk levels?

A comprehensive literature review of leading indicators by Xu found that the available research shows that a link between leading indicators and safety performance is hard to establish [59]. Lingard looked at the temporal effects of leading indicators on construction projects and concluded that establishing a correlation between leading indicators and incident rates was extremely complex [178]. There are studies from construction research that have shown a negative correlation between injury rates and certain indicators such as pre-task safety meeting and safety inspections [59] [58] [56]. Salas and Hallowell found factors for leading indicators that correlated with a reduction in TRIR [179]. However, given we know that TRIR is an unreliable measure of safety performance this research may not be reliable. Proving any correlation of leading indicators with safety performance is of course extremely difficult. In a construction project or operational plant, conditions are changing from week to week and month to month, so it is close to impossible to have a controlled experiment. Despite, these doubts there is still a strong consensus in the research and industry that developing leading indicators has value [55] [180] [59]. A cross industry survey from ERM found that 92% of respondents believed the use of data was key to improving safety performance in their organisation [181]. A key milestone in the indicator debate was the Baker report following the Texas city refinery explosion, this recommended the implementation of leading and lagging indicators to monitor process safety and highlighted the importance of measuring process and personnel safety [70]. The American Petroleum Institute and the UK Health and Safety Executive both recommend their use and publish guidance on their implementation for process industries[160] [182]. Recent research from the construction industry has called for further implementation and highlighted eight benefits identified from a literature review, including accident prevention, early warning of risks and improved legal compliance [183].

It may never be possible to prove correlations between leading indicators and accident rates, however on balance it seems that developing leading indicators is likely to be a positive step for improving safety performance.

5.3 Leading indicator frameworks

To develop proposed risk indicators for the offshore wind industry as a whole, we will look at all available methodologies in the existing research.

The first step in designing a set of leading indicators for offshore wind, is to understand existing frameworks that have been developed. Several methodologies have been used to develop leading indicators for both systems hazards and occupational hazards. Research from process industries such as oil & gas has focused on systems indicators, which are designed to guard against major accident risks [65]. Research from construction has focused on occupational hazards that are more relevant to construction activities [59]. Both aspects can be applicable to offshore wind so will be considered in this framework.

Zhen et al. has identified that there are three main methodologies for the development of what they call "major accident indicators" [67]. These are, event chain methods, resilience engineering methods and also systems based methods. There are also ad hoc approaches that seem to be more common in the construction industry for the development of occupational accident indicators.

Thus, the four main methodologies that have been proposed for leading indicator development are:

- Ad hoc methodologies
- Event chain indicator method
- Resilience engineering method
- Systems engineering method

This chapter will consider all of these methodologies and then propose the approach for developing offshore wind safety leading indicators.

5.3.1 Ad hoc methodologies

Ad hoc methods are common in the construction field where leading indicators may simply be chosen because the data is readily available and easy to collect. This can include items such as number of management site tours or pre-work safety briefings carried out [52]. Ad hoc methods will tend to look at the available data and use the judgement of professionals involved in the organisation to select measures they feel will be useful based on the risks of the operations they are involved in [58]. Ad-hoc methods lack a theoretical framework but can be easily implemented based on the available information. It is not clear that there will be a predictive effect of such indicators but if expert opinions with experience of the work are used they could help to focus efforts on important areas within the industry or project. The ad hoc approach can also be combined with other methodologies to help developed a holistic safety performance measurement system overall.

Event chain methodology

The RNNP project which was reviewed in Chapter 4 has successfully developed a comprehensive system for leading indicators based on an event chain or precursor analysis methodology [64] [65] [184].

The work done by Vinnem et al. has a focus on the establishment of major risks associated with the oil & gas industry related to handling hydrocarbons. While the same level of major hazard risk does not apply to offshore wind, there is still the potential for major accidents related to fires, structural failures, heavy lifting works, marine or flight operations. Vinnem set out criteria for useful major risk indicators, these include [65]:

1. Easily observable
2. Intuitive
3. Not requiring complex calculations
4. Quantifiable
5. Sensitive to change
6. Transparent and easily understood

7. Robust against manipulation

8. Valid

In this approach leading indicators are linked to accident precursors, in order to develop an indicator that will give an advance warning of a change in risk level and the potential for a incident to occur. The list below shows the key steps involved in identifying the leading indicators, which align with the process used in the RNNP [63] [65] [184].

- Identify hazards
- Classify hazards - major or occupational
- Identify precursor events
- Identify precursor indicators
- Identify barrier indicators
- Collect data on barrier indicators

Event chain methodologies have a theoretical framework behind them and have been used with success in the oil & gas industry. Their strength lies in the use of real data from the relevant industry, and the use of precursor events and barrier indicators allow for the detection of changes in risk levels prior to the occurrence of serious accidents.

Resilience Engineering methodology

Resilience Engineering is a concept developed by Holnagel, which has been inventively applied to the problem of managing safety [28]. Resilience Engineering (RE) defines safety as the presence of desirable outcomes rather than the absence of incidents. Penazola et al. has published a literature review of how Resilience Engineering methods are used and proposes the use of RE methods to assess safety performance measurement systems [185]. Penaloza et al. proposes more use should be made of RE methods for performance measurement but are not clear on how to measure the effectiveness. The

FRAM methodology is part of the RE toolkit and has been applied to develop safety and security goals for an offshore wind farm [40]. This study produced goals rather than leading indicators, so the potential for the application of this methodology to leading indicators is unclear.

Systems safety methodology

The use of systems engineering methods to manage safety has been proposed in a framework by Leveson set out in a key book on this topic [80]. The development of leading indicators using the STAMP methodology involves mapping out the control structure of the industry or organisation and then following the STPA hazard analysis process.

The systems safety methodology has a strong underlying theoretical framework, and the STAMP methodology has been used successfully in many industries and has been shown to be able to uncover hazards that are not necessarily shown up buy other risk assessment methods. It is likely that the development of the control structures model for an organisation may also improve the overall understanding of the system and potentially identify other improvements. However, the time and resources to develop the model is significant.

The systems safety methodology has high potential to help improve the understanding of how the industry manages safety as a whole as well as potentially identifying additional risk indicators or changes that could be made to the industry development structures, operational systems, legal frameworks or policies. The systems safety process is a complex challenge in itself so the implementation of this will be further explored in Chapter 6.

5.3.2 Methodology selection

This section has set out the four main methodologies for leading indicator development. The ad-hoc methodology can be a quick method to implement some simple indicators based on expert opinion and using available data. Resilience Engineering methods have some existing research but lack any examples of real world implementation. The precursor methodology has been used with success in the oil & gas industry. The systems engineering method is novel and has the potential to identify issues not found by other methodologies.

Based on this review the precursor methodology will be used for further development of indicators in this section. In addition use of the ad hoc approach will be considered by reviewing any existing leading indicators available in the research. The resilience engineering method will not be applied due to its current lack of successful applications. Finally, the systems engineering methodology will be explored in the following Chapters.

5.4 Assessment of existing leading indicators

As a starting point the ad hoc methodology will be applied by completing a rapid review of existing leading indicators that have been proposed in applicable research. 68 leading indicators have been identified and are included in appendix B. Indicators were included from the research from construction, oil & gas and from one existing paper for offshore wind.

Assessment criteria for each potential leading indicator were developed from those proposed by Vinnem et al.[63]. A simplified version of an evaluation methodology for safety performance metrics developed by Erkal has then been applied to make an initial filtering of these leading indicators and determine which ones are considered worth for further analysis [168].

The eight assessment criteria are set out in table 5.1, each indicator was scored against these using the judgement of the author. Where there is clear evidence that the indicator meets the criteria a score of 1.0 is assigned. Where the evidence or ambiguous a score of 0.5 is assigned and where there is no evidence a score of 0 is assigned. The scoring was done with specific consideration of the applicability of the indicators to use in offshore wind. The goal of this assessment is not to make a final decision on the usefulness off these indicators but to act as a quick filter for any indicators which are clearly not suitable and can be disregarded for further consideration at this stage. The full list of indicators and scoring can be found in Appendix B.

Evaluation rules for assessment criteria	Assign 1.0	Assign 0.5	Assign 0
Easily observable	Data could be readily collected in daily operations of an offshore wind farm without significant additional effort.	Data could feasibly be collected in daily operations of an offshore wind farm but would require additional resources to be applied.	Data would not be easily observable and would require significant additional resources.
Intuitive	There is a clearly intuitive and understandable link between the metric and risk levels.	There is potential for a link between the metric and risk levels but not easily identifiable.	Link between the metric and risk levels is not easy to identify or understand.
Not requiring complex calculations	Metric can be calculated by a simple arithmetic calculation.	Metric can be calculated with some calculations but no complex arithmetic required.	Metric will require complex calculations, requiring development of spreadsheets or code.
Quantifiable	Metric can be quantified using existing data.	Metric can be calculated with development of simple quantification rules.	Method is not easily quantifiable.
Sensitive to change	Metric will be able to generate sufficient amounts of data that will change over relatively small intervals i.e. daily, weekly.	Metric will be able to generate sufficient amounts of data that will change over mid-range intervals i.e. monthly, quarterly.	Metric will be unlikely to generate sufficient amounts of data to show variations over a year.
Transparent	Metric can be calculated using open data that will not be confidential.	Metric can be calculated using existing data but underlying raw data may be hidden to preserve confidentiality or commercial sensitivity.	Metric would be confidential or commercially sensitive.
Robust against manipulation	Metric will be hard to manipulate by manipulation of data.	Metric could potentially be manipulated.	Metric likely to be susceptible to manipulation.
Valid	Metric will generate sufficient amounts of data, and has empirical studies indicating its validity.	No clear evidence showing validity, there may be conflicting evidence.	Metric likely to have a lack of data, or studies have shown it is not statistically valid.

Table 5.1: Rules for assessment criteria

5.4.1 Review of existing leading indicators

The following subsections set out the results of the assessment exercise.

Construction indicators

Proposed leading indicators no 1-29 (Appendix B) are those compiled by Xu et al. from research across the construction sector [59]. These are all related to occupational accident risk, as this is more relevant to typical construction work. Many of these activities may also be relevant to offshore wind construction or operations and maintenance. The initial scoring filter exercise found 11 of the 29 indicators scoring 6 or greater out of 8, this will be taken as a benchmark for those worth considering further. All of the indicators scoring six or greater concerned training, competence and auditing. All of these scored highly for observability, intuitiveness and complexity, however scoring for transparency, robustness and validity was varied.

Offshore wind indicators

Indicators 30 to 64 are those proposed by Seyr & Muskulus [41] in the only existing leading indicator study specific to offshore wind. Many of the indicators are related to recording incidents such as work at heights, vessel incidents or dropped objects. These are proposed to be collected as a percentage of the work actions completed, as such these are score poorly for observation, quantification and complexity. The work associated with calculating these incidents per work action would be significant, furthermore, these indicators are all related to past incidents and cannot be considered leading indicators. These measures are all currently reported in G+ data without normalisation. Chapter 4 showed proposals for presentation of the same data with normalisation and confidence intervals. 14 of the indicators proposed by Seyr were taken from oil &gas research on KPIs for maintenance readiness. These have been considered before as leading indicators of risk for oil & gas as it is thought that a backlog in maintenance could indicate worsening operating conditions, possible degradation in safety systems and more pressure to complete tasks when they are finally started. These all seem plausible as a useful risk indicator although having 14 may be counter productive. Other indicators relate to the cost and time performance of a project, these were proposed as it has been put forward that cost and schedule pressures have been factors in major oil & gas accidents that have occurred in the past [42]. An advantage of a maintenance based indicator is that it is likely that operators will be able to collect information through their CMMS system without significant effort. A disadvantage would be that operators would likely consider this information as commercially sensitive and would not want to share it at an industry level. Seyr & Muskulus also proposed the use of system failure rates as a risk indicator. The use of system failure rates in oil & gas is more obvious as the failure of a system could results in a hydrocarbon leak with serious consequences, however this type of risk is less serious in an offshore wind turbine. Only two of the indicators from Seyr & Muskulus scored higher than six, these were for incidents related to helicopter transportation and vessel transportation, however, while these are valid safety KPIs they record past events and can not be considered as leading indicators.

Offshore oil & gas leading indicators

Leading indicators for the oil &gas industry as they have been implemented by the RNNP project have been included for consideration. Four of the measures scored higher than six and related to fire protection, fire detection, watertight door tests and ballast system tests. All of these will be included for further consideration.

5.4.2 Ad hoc analysis results

Following this analysis of the potential leading indicators in the existing research, 15 indicators are considered for inclusion in the final proposal for offshore wind indicators, these are included in Table 5.2. Many of the common issues with leading indicators were identified with the indicators found in existing research. particularly difficulties with observing and quantifying the indicators without creating significant amounts of new work. Many of the indicators also could not be defined as leading indicators and are in fact lagging indicators.

Ref	Indicator subject	Organisational level	Reference	Source Industry	Description	Measure
1	Fire detection	Firm or project level	PSAN 2020	Offshore oil & gas	Performance of fire detection system tests	Percentage of fire detection systems passing function tests
2	Fire protection systems	Firm or project level	PSAN 2020	Offshore oil & gas	Performance of fire protection system tests	Percentage of fire protection systems passing function tests
3	Watertight doors	Firm or project level	PSAN 2020	Offshore oil & gas	Performance of watertight door tests	Percentage of watertight doors passing function test (for floating structures)
4	Ballast sytem function	Firm or project level	PSAN 2020	Offshore oil & gas	Performance of ballast system tests	Percentage of ballast systems passing function test (for floating structures)
5	Training and orientation	Firm level	Xu 2021	Construction	Improving skills, knowledge, attitudes and experiences of managers, supervisors and workers to effectively manage safety	Percentage of workers trained
6	Client engagement	Project level	Xu 2021	Construction	Client is engaged in construction safety throughout a project.	Frequency of safety audits for contractors in a specific time frame
7	Site communication	Project level	Xu 2021	Construction	Familiarizing operatives with a job, informing risks and improving task-specific competence to prevent accidents	Percentage of operatives who receive induction prior to commencement of work
8	Site communication	Project level	Xu 2021	Construction	Familiarizing operatives with a job, informing risks and improving task-specific competence to prevent accidents	Frequency of toolbox meeting
9	Worker involvement	Group and individual level	Xu 2021	Construction	Workers' level of involvement in establishing, operating, evaluating, and improving safety practices.	Percentage of attendance of workers at safety events, e.g., training and induction/toolbox meeting
10	Competence	Group and individual level	Xu 2021	Construction	Ensuring that employees have the skills, knowledge, attitudes and experience to safely carry out assigned tasks.	Number of certification cards
11	Organizational commitment	Firm level	Xu 2021	Construction	Client, designer, principal contractor and subcontractor commitment to safety	Frequency of safety walk by senior management
12	Safety auditing	Firm level	Xu 2021	Construction	The process of collecting independent information on the efficiency, effectiveness and reliability of the safety management system and drawing up plans for preventive actions.	Frequency of internal/external audits completed to schedule in a specific time frame.
13	Training and orientation	Firm level	Xu 2021	Construction	Improving skills, knowledge, attitudes and experiences of managers, supervisors and workers to effectively manage safety	Hours of training received by workers in a specific time frame including contracted workers
14	Designer engagement	Project level	Xu 2021	Construction	Principal designer and other designers (including designers of temporary works) is engaged in construction safety throughout a project.	Frequency of qualified walkthroughs in a specific time frame,
15	Principal contractor engagement	Project level	Xu 2021	Construction	Principal contractor is engaged in construction safety throughout a project.	Percentage of subcontractors audited monthly vs. total number

Table 5.2: Selected leading indicators from existing research

5.5 Precursor methodology for OWI

5.5.1 Precursor method

This section will apply the precursor methodology to develop leading indicators for offshore wind as has been set out by Vinnem et al [64] [65]. This will use data published by G+ as has been set out in Chapter 4 and existing risk analysis documents from offshore wind industry research. The flowchart for this methodology is set out in figure 5.1.

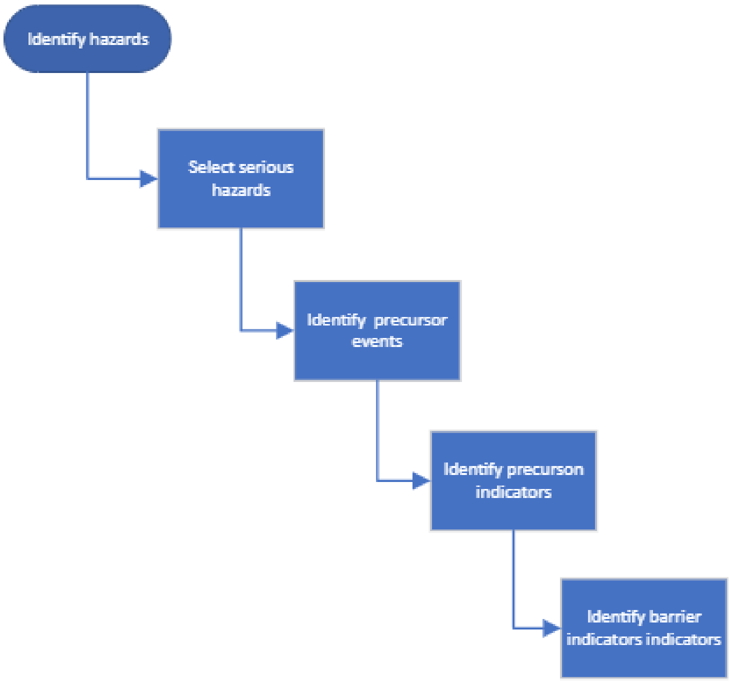


Figure 5.1: Precursor analysis flowchart

The first step is the identification of hazards in the industry. The primary concern for managing risk in any industry should be managing the risk of major incidents, in the oil & gas industry this is determined as an event with the potential for five or greater fatalities. However this research will consider the potential for serious risks which we define as anything with the potential to cause more than one fatality. The second step is the identification of precursor events which have the potential to lead to serious incidents related to the identified hazards. Thirdly, barrier elements will be identified. Barrier elements are the items installed to protect against the major hazards that have been identified by the pre-cursor analysis

Vinnem set out that major hazard risks for workers on offshore oil & gas can be split into the following [65]:

- Major hazards during stay on the installation.
- Major hazards associated with helicopter transportation.

For offshore wind these can be adjusted to:

- Serious hazards while on wind farm structure.
- Serious hazards associated with transportation to and accessing the wind farm.

Peter Lloyd has pointed out that no guidelines for an offshore wind energy hazard list currently exist, as they do for the the oil and gas industry [186]. The following list of hazards with the potential for a serious incident resulting in one or more fatalities has been developed by review of available industry risk assessment reports, safe by design guides and research papers. From these major hazards a list of potential precursor events can then be developed. The G+ Integrated offshore emergency response plan also includes a risk assessment considering potential for accidents involving one or more fatalities. The report highlights a number of serious incidents that have been reported within offshore wind farms that reinforce the need both emergency response and risk indicators to help the industry be aware of their risk levels [187]. A recent letter from the HSEx to the G+ members highlighted that they believed key risks for major accidents in the industry included HV electrical incidents, aviation impact, vessel impact, diving operations and structural integrity [188].

Offshore wind serious hazards are identified as:

- Offshore fire or explosion
- Offshore medical emergencies

- Exposure to hazardous mechanical or electrical energy
- Aviation or vessel impact to structure
- Major structural failure (fixed or mobile structure)
- Helicopter crash or ditching
- Diving operations
- Lifting operations
- Work at height

Based on the identification of hazards, serious hazard precursor events are set out in table 5.3. Discussion of each SHPE and the rationale for selection are also included below.

It is recognised that several of the proposed indicators rely on data that are not yet routinely collected or shared at an industry level. As such, the indicator set should be viewed as a target state for offshore wind safety measurement. Implementing even a subset of these indicators, where data are available, would represent a significant step towards more proactive monitoring of major hazard risk.

Where data is available plots for the precursor indicators are included. It should be noted that the results presented in Figures 5.2 to 5.5 are based on relatively small sample sizes. In several categories only a limited number of events were observed, which means that the apparent differences between categories or years may be strongly influenced by random variation. As a consequence, these figures should not be interpreted as providing statistically robust estimates of underlying risk, but rather as exploratory, indicative results that help to highlight patterns and inform the development of the proposed leading indicator framework.

1 Fire or smoke in wind turbine, vessel or other infrastructure

The G+ Integrated offshore emergency response plan highlights an offshore fire or explosion as a serious hazard for offshore wind safety [187]. This could involve fire in a

Ref	Serious Hazard Precursor Event	Proposed measure
1	Fire or smoke in wind turbine, vessel or other infrastructure	Incidents per hours worked
2	Structural damage to turbine, foundation or anchor (floating turbines)	Incidents per hours worked
3	Vessel collisions	Incidents per hours worked
4	Major mechanical component damage	Incidents per MWh
5	Potential for hazardous energy exposures	Incidents per hours worked
6	Medical emergencies	Incidents per hours worked
7	Vessel transfer incidents	Incidents per crew transfer
8	Heavy lift failures / high energy dropped objects	Incidents per hours worked
9	Jackup vessel mishaps	Incidents per hours worked
10	Work at height incidents	Incidents per hours worked
11	Flight operations incidents	Incidents per hours worked

Table 5.3: Serious Hazard Precursor Events

vessel, part of a wind turbine or other offshore infrastructure such as a substation. At least one serious fire involving multiple workers has occurred in an offshore substation in Chinese waters, the fire broke out due to a lightning strike forcing 19 workers to jump into the water [189] [187]. There have also been recorded deaths in onshore wind turbines when a nacelle caught fire during maintenance activities. Wind turbine fires while workers are present are likely to be low probability but high consequence events, so the capturing of precursor data can be valuable in monitoring if risk levels related to wind turbine fires change throughout the industry. In 2015 G+ have also published a report on a safe by design workshop dedicated to escape from a wind turbine nacelle in the event of a fire [190]. The report concluded that fire detection systems should be considered during the design phase of the wind turbine and that the industry would benefit from improved regulatory guidance on what the minimum requirements should be [190]. Fire detection systems are not currently installed as standard in offshore wind turbines. The report also recommended the consideration of refuge points, and fire suppression systems for turbines and offshore substations.

The collection of data on fire or smoke incidents across the wind industry can be a useful serious hazard precursor event, but there is no data currently available.

2 Structural damage to turbine, foundation or anchor

Structural damage could be a precursor to the collapse of a wind turbine. This would be a low probability but very high impact event, but is one potential event that could lead to multiple casualties in the offshore environment if it occurred on an occupied structure [187]. If the turbine is unoccupied then there would still be the loss of an extremely valuable asset. The risk of damage to anchor cables with the loss of stability of a floating wind turbine will also become an event which needs serious consideration as floating wind farms move into commercial scale operations. Research on the probability of a structural failure of offshore wind turbines has shown that it is a very low probability event based on the risk from extreme wind and waves [191]. Reliability from the offshore oil & gas industry have shown that the risk of structural collapse of offshore structures is very low, but the actual recorded number of incidents is higher than expected. The differential was found to be human factors which contribute to between 75 to 90% of the accidents. While data is not currently available for structural damage incidents, G+ do report high potential asset damage incidents, this data is presented in figure 5.2.

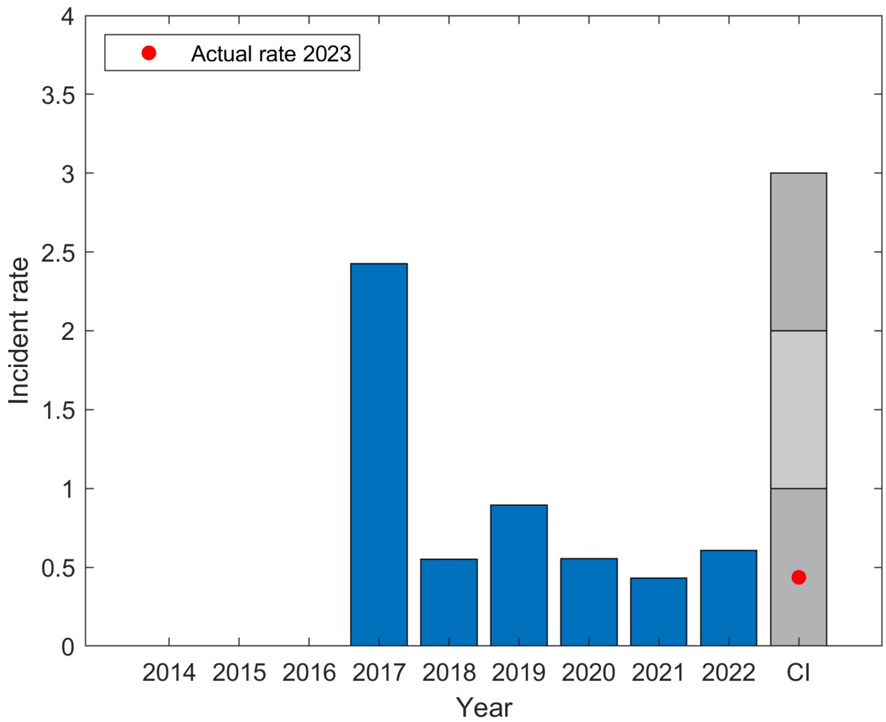


Figure 5.2: High potential asset damage incidents

3 Vessel collisions

Research has shown that offshore wind turbines are at risk of structural collapse if struck by larger vessels [192]. Collisions between offshore wind farm service vessels and wind turbines have already been documented, but there is also a known risk of other vessels accidentally entering the wind farm safe limits and damaging a turbine. The marine coastguard agency (MCA) publish guidance for the layout design of wind farms and require that shipping route surveys are completed prior to wind farm design and construction to ensure that safe exclusion zones between wind farms and shipping corridors are maintained [193]. Data published by G+ does not categorise vessel collisions or near misses however a recent study published data received from the MCA by a freedom of information request [194]. The study compared collision rates to those that would be predicted by published navigational risk assessments in the UK and concluded that the risk of collision is currently overestimated. The majority of collisions to date have been between service vessels and wind turbines and there are no documented collisions between commercial vessels. However, the G+ Emergency response guidelines reported that at least one major marine incident concerning a commercial barge breaking tow and drifting towards a wind farm [187]. As offshore wind farms continue to grow and develop into new waters there is potential for these risks to increase and a risk indicator of this measure could be beneficial for the industry.

MCA guidance indicates that shipping lanes less than 926m from a wind farm boundary would be outside of tolerable risk levels. This limit could therefore be used as a guide for reporting potential collision risk. The measure could include actual recorded collisions, near misses and vessels observed to be breaching an exclusion limit of 900m.

4 Major mechanical component damage

Major component damage resulting in debris could pose a potential hazard to vessels and workers operating within the offshore wind farm area. As turbines continue to grow in size this risk could potentially increase. Orsted reported the failure of a main shaft in an offshore wind turbine in 2022 [195]. The failure resulted in the separation of the rotor from the nacelle, there were no service vessels at the turbine at the time, but this could have resulted in a major incident if it occurred during maintenance operations [196]. There was no indication from the vibration monitoring or maintenance records that warned of a problem with the shaft prior to the incident. Following the accident a frequency analysis showed that an indication could be seen in the 1P and 2P harmonic of the rotor speed. Orsted presented their findings at the WindEurope Technology conference in 2022 and recommended that main shaft crack monitoring be implemented by other operators [195]. Major damage to turbine blades could be another item that could me monitored as a risk indicator to monitor the risk to workers of vessels in the wind farm, however as turbine blades will be stopped at the time of any service vessels docking the risk of blade failure and debris to operatives is probably extremely low.

5 Exposure to hazardous energy

G+ identified serious electrical or mechanical injury as a major risk to persons on a wind farm, tracking of the risk of exposure to hazardous energy could be a powerful SHPE [187]. The wind turbine safety rules were written in collaboration with G+, the Energy Institute and industry members and set out guidelines to be followed to implement isolation on low voltage equipment and mechanical equipment whenever maintenance works are carried out [197]. The rules require approved written procedures to be put in place for work on mechanical or electrical systems and this is the main mechanism for protecting workers involved in this type of work. A key challenge in the offshore wind industry is that technicians will be working in remote conditions in small groups, so the responsibility for maintaining the isolation system as well as completing the works will all fall on the same people. The importance of isolation procedures was highlighted by the case of Darren Hoadley an offshore wind farm technician who lost their arm while working on a turbine that they mistakenly thought was isolated and shutdown [198]. Measuring exposures to energy as a precursor is not an easy task, Erkal and Hallowel have proposed the implementation of high energy control assessments [199]. This is proposed as neither a leading or lagging indicator but a monitoring tool whereby ongoing work is audited and assessed for exposures to high energy. High energy is classed as an energy source with potential for releasing greater than 1,500 joules, which has been shown by research to have the potential to cause serious or fatal incidents. Personnel require training to carry out these assessments, but in the absence of another source of data this could be a useful pre-cursor measure for the industry to implement. Maintenance related indicators as proposed by Seyr and Utne could also be considered as a proxy for this risk. The reasoning that a greater backlog of maintenance works, or poorly planned work could lead to increased pressure or workers greater risk of procedures not being followed [41] [42]. Within the G+ annual incident reports the numbers of high potential incidents by work process are recorded and this includes data for electrical systems since 2019. Reporting these as a dedicated measure normalised by a suitable factor would also be a useful precursor indicators.

So potential measures proposed are:

- High energy control assessment scores
- % of old Work Orders
- % of work orders with one or more operations containing man-hour estimations over 1 hour
- High potential electrical incidents

6 Medical emergencies

Due to the remote nature of offshore wind sites medical emergencies pose a unique challenge to the industry. In the G+ emergency response guidelines they note that where there have been medical emergencies the split between illness and injury was roughly equal [187]. G+ currently report data for emergency response activities that result in a medical evacuation, however according to the emergency response guidelines not all medical emergencies are captured in current data. A risk indicator of emergency response evacuations grouped by evacuation due to injury or illness would be a useful precursor indicator.

7 Vessel transfer incidents

G+ have reported incidents related to transfer from and to vessels since 2014, with an average of 24 incidents per year. This measure normalised by transfer numbers or hours worked as shown in Chapter 4 can be used 'as is' as a useful precursor indicator of more serious incidents. As the industry transitions from predominately CTV based push on transfers to W2W systems from larger SOVs and also transfers to floating turbines, monitoring of risk levels will become more important. Research from Puisa has highlighted the potential for unforeseen hazards arising due to the interaction of multiple systems such as W2W gangways and other systems [22]. There have also been recent incidents reported due to the malfunction of walk to work gangways [200]

8 Heavy lift failures / high energy dropped objects

Heavy lift failures and high energy dropped objects, clearly have the potential to result in serious incidents that could result in multiple fatalities. In 2021 a major incident occurred at the Ormonde offshore wind farm where a hub, 3 turbine blades and other equipment fell to the sea during a major component exchange [166]. The lifting incident reports are not currently segregated by severity. Applying a grading based on energy potential would help identify the risk levels associated with these incidents [199]. Using the high energy control assessment methodology with an energy level of 1,500 joules could be used to categorise serious risks. The same method can be applied to dropped objects which can also pose a major risk to workers. Lifting operations incidents are presented in Chapter 4, data for high potential dropped objects is presented in figure 5.3 below.

9 Jackup vessel mishaps

Jackup vessels are an important part of offshore wind installation works and also major maintenance operations [201]. G+ don't currently track or provide any data specifically related to the use of jack up vessels, nor have they reported any serious incidents due to the use of jack up vessels. However, these are likely to be low probability but high impact events and due to the young age of the industry any incident is less likely to

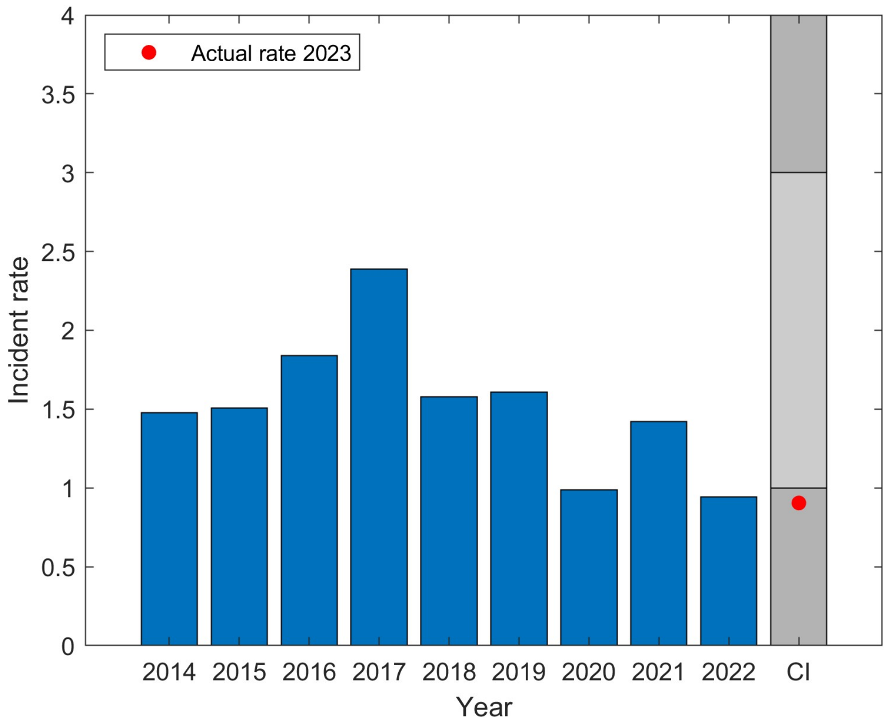


Figure 5.3: High potential dropped object incidents

have occurred. There has been at least one media report of a jackup vessel incident in China which resulted in multiple fatalities [151]. The industry guideline on emergency response also list a jack up vessel incident as being one with the potential for causing a major accident [187]. As such, the collection of suitable data on jack up vessels could be a cautious measure for the industry to implement. Research from jack up incidents in the oil & gas industry have shown that jack up vessels are much more likely to have a failure than fixed offshore structures, the main causes of incidents where related to towing and punch through failures [202] [203].

10 Work at height incidents

Work at height is a serious risk activity and is one of the precursor areas where data is already collected by the industry. The reporting methodology set out in Chapter 4 can be used for this. Figure 4.7 showed that this is an area with an improving trend and is a current success story for the industry.

11 Flight operations

Helicopter operations are an important activity in offshore wind O&M, but have the potential for serious incidents resulting in multiple fatalities in the worst case. The use of helicopters for crew transfer is expected to increase as wind farms move further offshore and as such, good practice guidelines for the industry have recently been published [19] [204]. The Norwegian oil industry collect data from helicopter operators for any incidents or near misses, these are reported by incident type, risk class, severity, type of flight, phase of flight and departure and arrival information [62]. The industry also publish data on the number of flight hours and passenger flight hours. Similar data sets could be collected and reported for the offshore wind industry. The G+ data set currently includes some limited data for "flight operations", this is presented in figure 5.4.

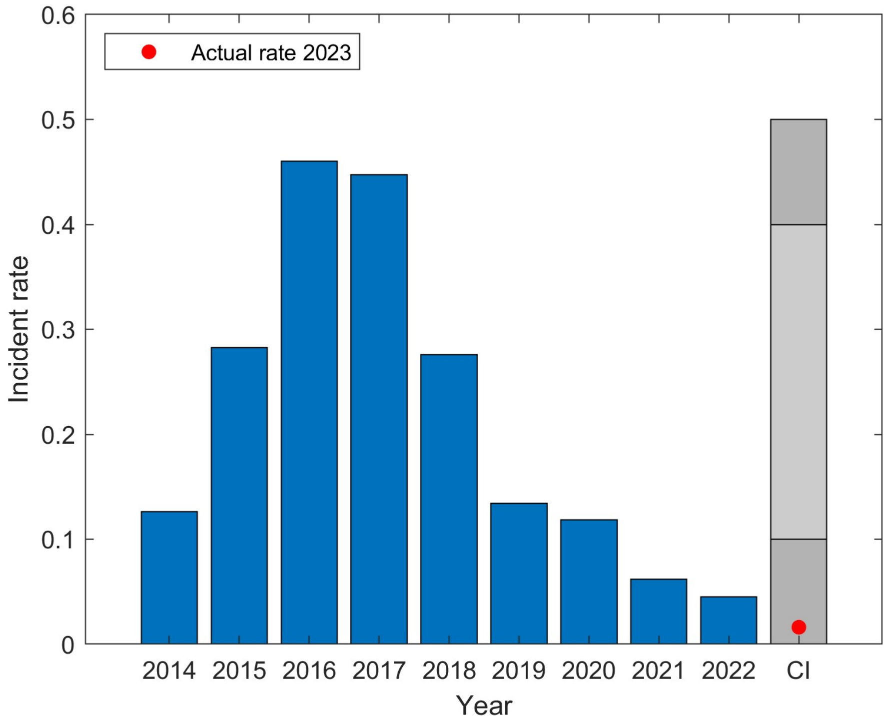


Figure 5.4: Flight operations incidents

12 Diving operations

Diving is a high risk activity for the individuals involved in it. The G+ emergency response guidelines reference that there has been at least three fatal diving incidents in the industry [187]. G+ note that the industry is working to remove the need for diving operations, but as it is not a well established part of the industry procedures are not well developed and where incidents have occurred there was a lack of detail in risk assessments. Diving operations are not included in annual G+ incident reports but data for some diving incidents can be extracted from the database on the G+ website [172] [147]. The UK Health and Safety Executive have recently written to the offshore wind industry through the G+ organisation to declare their intentions to begin auditing the management of diving operations in the industry. The Norwegian trends in risk level project uses a safety climate questionnaire with divers involved in the industry as the main method of gauging any trends in risk level [62]. It is recommended that a similar practice be adopted within the offshore wind industry, this would then provide actionable data which would complement any relevant incident data, and provide awareness of issues before serious incidents occur. The available incident data from diving operations is presented in figure 5.5

5.5.2 Barrier element analysis

The second part of this analysis will aim to identify, where possible, complimentary barrier elements. Barrier elements are items that can be objectively measured which aid the prevention of more serious accidents. The example from the Norwegian oil industry is the testing of fire and gas detection systems, as these are a key defence against hydrocarbon explosions. Barrier elements are beneficial as they can act as true leading indicators, as they will show changes in risk level before an adverse event has occurred. Potential barrier elements that could be measured and are relevant to offshore wind are set out here and summarised in table 5.4.

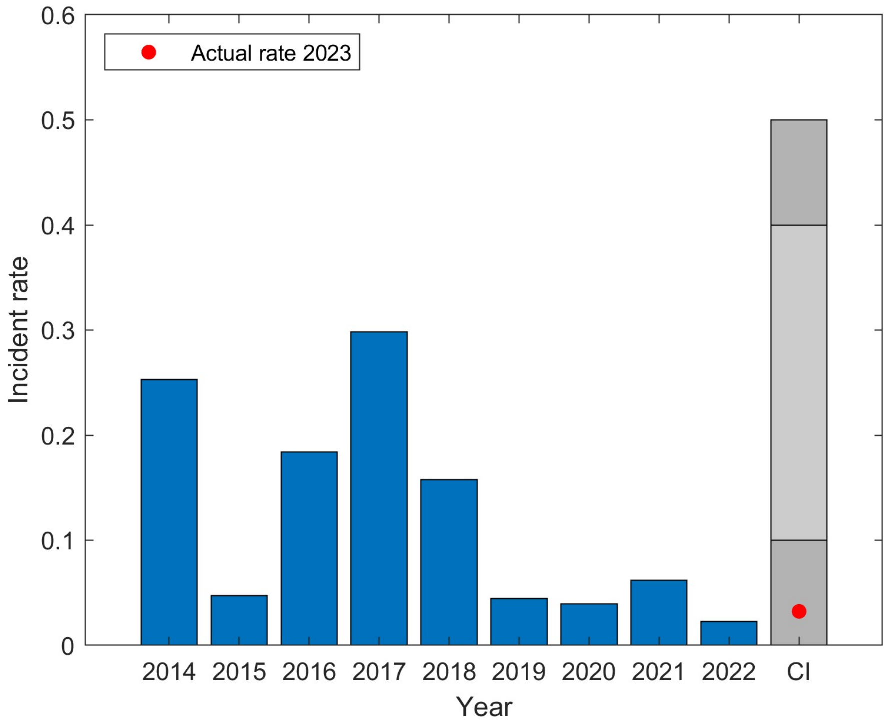


Figure 5.5: Diving operations incidents

Fire and gas detection

In 2015, G+ ran an industry workshop to analyse design safety in respect of escape from the Nacelle in the event of fire in on a wind turbine. The key design controls identified were fire detection systems and fire suppression systems [190]. The installation of fire detection and suppression systems will be determined at the design stage of the wind farm by a fire risk assessment and according to relevant legislation and codes. Whatever the systems that are selected they will be operating in an extremely tough offshore environment so monitoring of their effectiveness will be critical. Proposed

Ref	Proposed Barrier element measures	Normalisation	Organisational Level	Attributor group
1	Fire detection system functionality performance	% of failures	Firm / project	Conditional
2	Fire protection system functionality tests	% of failures	Firm / project	Conditional
3	Basic first aid training complete	no. per technician transfers	Firm / project	Organisational
4	Enhanced first aid training completed	no. per technician transfers	Firm / project	Organisational
5	Emergency response capacity	SAR assets per technician transfers	Firm / project	Operational
4	Emergency response drills	completed drills per year	Firm / project	Operational
5	Emergency response times	average response times	Firm / project	Operational
6	Radar beacon function tests	% of failures	Firm / project	Conditional
7	AIS function tests	% of failures	Firm / project	Conditional

Table 5.4: Barrier elements

barrier indicators for fire risk are therefore:

- Fire detection system functional test performance (% of failures)
- Fire protection system functional test performance (% of failures)

Medical intervention capability

Medical emergencies offshore are an important risk due to the challenges of emergency response and time required to reach a medical facility. As larger SOVs and floatels become more common for offshore wind farms medical facilities offshore will become more common, however currently first aid will likely be provided by fellow technicians if a worker is injured or taken ill. The GWO recommend that all offshore personnel have basic first aid training and that part of the workforce have enhanced first aid training [187]. A suitable barrier indicator to determine the medical intervention capabilities offshore would therefore be:

- Basic first aid training completed.
- Enhanced first aid training completed.

GWO publish annual data for these training modules to be completed and these can be normalised by technician transfers as a measure of offshore work activity[205].

Emergency response capacity

Emergency response capacity and response times could be considered as useful barrier elements to serious incidents. While they do not prevent incidents themselves timely response can prevent a serious injury from turning into a fatal injury. As the offshore wind industry grows there is the potential for increased pressure to be placed on a limited search and rescue (SAR) resource. A measure of search and rescue capacity as well as response times can be a useful industry level measure to give a warning if resources are not keeping up with industry growth. Total emergency response capacity can be measured by the availability of SAR helicopters by installed capacity of turbines, or by technician transfer numbers. The numbers of emergency response drills and emergency response times can also be calculated and reported.

- SAR Helicopters v technician transfer numbers
- Emergency response drills
- Emergency response times

Vessel and aviation collisions risk

According to the Marine and Coastguard Agency in the UK, marine navigational markings need to be considered to reduce risk to vessels [193]. Items such as radar beacons (racons) and automatic identification systems may be required to reduce risks. As such tracking of the function of these items could be a useful barrier indicator for collision risk. As not all wind farms will have these items, this may be more be useful as a specific wind farm indicator only, rather than an industry level indicators.

- Radar beacon function tests (%)
- AIS function tests (%)

5.6 Precursor indicator and barrier elements discussion

The proposed SHPEs and barrier element data can be presented using the same methodologies discussed in Chapter 4. It is recommended that that the offshore wind industry consider capturing and ideally sharing at an industry level these indicators. As per the criteria for useful risk indicators all of these proposed indicators are easily observable, intuitive, easy to calculate and quantifiable. They can all be calculated using data that operators should have available, and all have a clear link to hazards that have been identified by industry as presenting a serious risk to offshore wind workers. The indicators will also be sensitive to change and can be easily understood by anyone involved in the industry. Furthermore, research undertaken in for the Norwegian oil industry has shown their validity. Possibly the most challenging criteria for any indicator is the robustness against manipulation. Whenever data is collected and performance is measured there is the risk that parties will feel pressured to manipulate data to suit there outcomes. From this point of view it is critical that the industry takes a positive viewpoint of data collection. Where indicators show a negative trend the focus should be upon what can be done to help improve outcomes, rather than fault finding. It is also important that financial incentives are not linked to the performance of the indicators.

The introduction of barrier elements can be a positive step for the industry as these are not linked to incidents or negative outcomes, these can be framed in a more positive sense.

5.7 Conclusions

This section has made a review of proposed leading indicators for the measurement of risk levels in the offshore wind industry. It has collected potential leading indicators proposed in research from the oil & gas industry, construction and offshore wind. It has then evaluated these indicators against criteria for effective risk indicators and found the majority had low suitability or effectiveness. It has then applied a methodology for the development of risk indicators using a precursor and barrier element system. This has made an analysis of serious hazard risks and incident data to propose nine precursor indicators and seven barrier element indicators specific to the offshore wind industry. The implementation of precursor indicators can highlight to the industry the risk of incidents that have the potential to cause fatal incidents. Barrier element indicators can act as leading indicators of risk for serious incidents. Individual organisations could implement these indicators at their own project or firm level and can follow the same process for the implementation of additional indicators following the same methodology. The indicators can then also be implemented in an industry level and monitored on an annual or bi-annual basis. As the industry develops and with the introduction of increased floating wind systems, autonomous systems and other technologies the indicators should be reviewed and updated where new hazards or new data becomes available.

Chapter 6

Systems based risk analysis of the OWI

6.1 Chapter contribution

Chapter 5 identified that systems safety theory could have potential for the development of leading indicators of risk. This section sets out to explore the potential for the application of systems safety to the offshore wind industry. To do this it will utilise the STAMP model which was developed by Leveson at al [27]. This Chapter aims to answer the following research question:

"How can systems safety theory help the industry understand and manage its safety challenges and also identify further leading indicators of risk?"

Where Chapters 2 to 5 focus on understanding the current safety performance of the offshore wind industry and on how it is measured and predicted, this chapter addresses the final part of the research question by applying systems safety methods to identify how safety challenges can be addressed at a system level.

STAMP (Systems Theoretic Accident Model and Processes) is a relatively new accident causation model introduced by Leveson in 2004, building on work by Rasmussen et al which developed a hierarchical model of safety control [206] [27]. STAMP was developed to analyze complex systems and takes into consideration technical, social and organizational factors in its analysis. Whereas traditional accident causation models focus on component failures, STAMP also considers component interactions and external disturbances [81].

Originally developed for the design and assessment of complex systems such as missile control systems, it has also been identified as a method for organisational or whole industry analysis and improvement projects [85].

Within STAMP theory, STPA has been developed as a hazard analysis technique. While STAMP and STPA were originally developed for technical engineering systems, they have also been applied to management and organizational analysis [84] [80]

Recent literature reviews provide an extensive history of the development and applications of STAMP, these have shown while STAMP has grown in popularity and has recently been applied to the aviation, process, medical and maritime sectors, it has seen little application in the renewable energy sector [90] [91].

The only existing study applying these theories to offshore wind looked at the application to SOV operations for fixed bottom turbines [22]. Systems safety approaches have been used for organisational level analysis of the NASA space development engineering organisation [84] and even at an industry level to look at the safety of the drug development industry in the USA [87].

The offshore wind industry can be considered as a complex system, it includes many stakeholders which interact in different ways, these stakeholders cooperate to design, build, operate and maintain the offshore wind infrastructure. In order to improve the operation of this system to make it safer for those who work in it, all parts of the system and their interactions need to be considered. For this reason, a systems approach analyzing the operations of the industry and developing risk indicators may be beneficial.

The contribution of this Chapter is:

- Scoping of a systems safety based analysis of the offshore wind industry;
- Mapping of the offshore wind industry safety control structures;
- Risk analysis of the offshore wind industry safety control structures;

- Assessment of STAMP theory as a useful tool for leading indicator development.

6.2 Systems safety theory

Rasmussen's research was originally focused on improving the safety of control systems for process plants, however, when looking at accident causes they found that they had to look much further than just the control system technical function and also look at aspects such as control room design, display screen layout, managerial, legal and regulatory issues [206].

Building on these insights, systems safety theory proposes that safety is an emergent property of a complex system, and it takes a whole system approach to analyse and design safe methods [80]. Systems safety recognises that accidents are usually not the result of a single point of failure but rather as a multitude of factors that lead to rising risk levels over time, ultimately leading to an accident [206].

Systems safety uses a different accident causality model to more traditional approaches. While any model will struggle to fully describe any system, creating a model helps us understand a system. The traditional accident model is the chain of events model. This assumes that accidents are caused by a chain of events and that there is a single root cause, these models can cause a focus on one single event while ignoring systemic factors such as managerial or organisational problems or more complex factors such as component interactions [206] [80].

Rasmussen's analysis of the Herald of Free Enterprise ferry disaster found that there were many systemic issues that led to the system migrating to a high risk state where the accident could occur [206]. The proximate root cause of the ferry disaster had been found to be that a boatswain had overslept and failed to close the loading doors before departure. However, a system wide analysis found issues relating to vessel design, harbour design, vessel operation and others which all led to a state where the accident could happen. The ferry doors being left open on their own would not have caused the accident and, in fact, this had occurred before without leading to the ferry flooding and capsizing.

Consideration of recent incidents in the fixed bottom offshore wind industry from a systems based approach can help demonstrate how these ideas apply to offshore wind in general. A recent high profile incident in offshore wind involved a technician suffering an arm amputation [207]. This accident occurred offshore during preparation works for turbine installation and the proximate cause was declared by the judge to be failure of workers to replace a safety barrier and failure of the injured person (IP) to follow the isolation procedure [198]. However, further analysis of the findings from the case report indicate there may have been many systemic factors that led to the work migrating to a high risk state that ultimately allowed the accident to occur. These are highlighted in figure 6.1. Issues such as work scheduling, communication, workplace culture all played a part in leading to the accident [198].

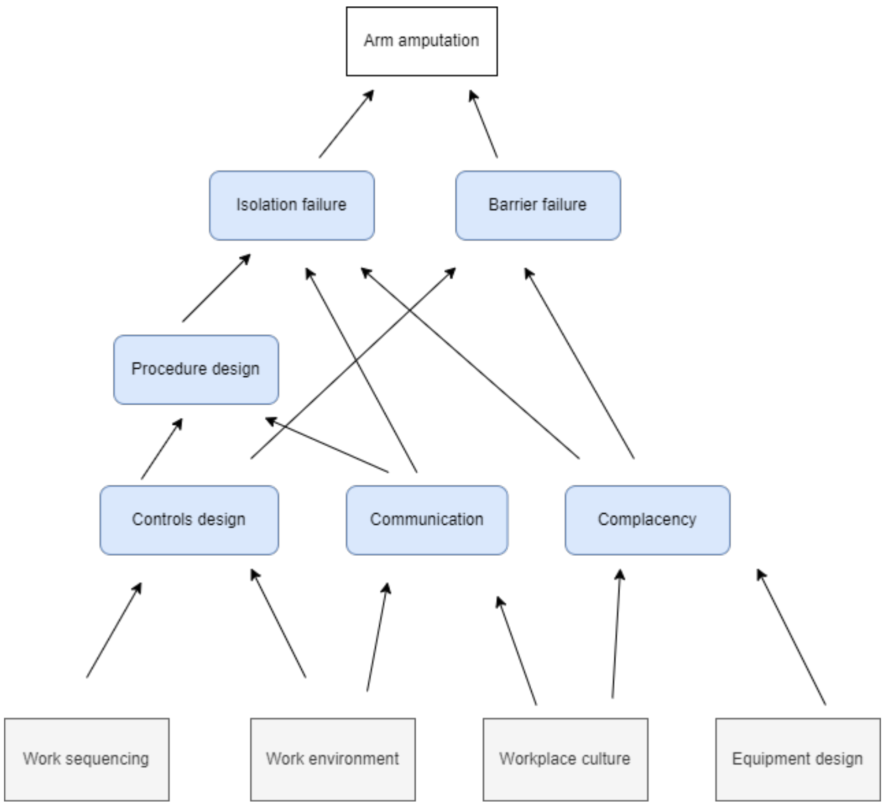


Figure 6.1: Hoadley v Siemens accident systemic factors [80]

STAMP uses a dynamic control system model to manage safety. As safety is considered as an emergent property of a complex process, this emergent property is controlled by enforcing safety constraints. These constraints can be applied through system design, process management, or social controls such as regulations or cultural changes [80]. Figure 6.2 shows a typical engineering control diagram. A controller containing a process model and control algorithm, controls a process. This is done via control actions and feedback sensors [80].

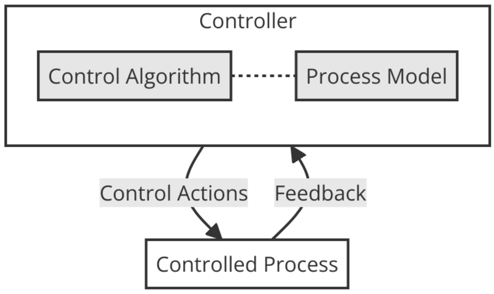


Figure 6.2: Generic control loop

A second recent offshore wind incident involves the interaction of human controllers with automated systems. A CTV transiting to a wind farm to complete a push on test collided with a wind turbine foundation [208]. The accident report highlighted that operator error on the part of the vessel master was the cause. The autopilot was operating at the time and the vessel master expected it was going to change course. The autopilot was found to be working properly, a systems based view of the accident causation would highlight the human and automation interaction. Other listed causal factors included, that the vessel master had additional duties and was completing paperwork and that the autopilot was not clearly visible due to the cockpit layout. The growing use of automation in offshore wind systems and increasing complexity could increase the risk of these types of accidents.

These examples reinforce that the application of systems safety methods could be beneficial to the offshore wind sector.

6.3 Methodology

6.3.1 STAMP analysis

Figure 6.3 is adapted from Dulac et al. and shows the overall procedure for completing a STAMP analysis [83]. Step 1 consists of a preliminary hazard analysis to define system level hazards. Step 2 involves mapping the control structure of the system to be analysed, in 3 the requirements of the system to manage safety are identified. Step 4 then carries out an initial gap analysis and step 5 a detailed hazard analysis using the STPA methodology. Risks are then categorised in step 6 and findings are assessed. The control structure and findings can also then be used to develop a system dynamic model. This chapter includes steps 1 to 6, development of a system dynamic model will be discussed briefly but is out of scope of this thesis and could be explored as a part of future research.

STPA (Sytems Theoretic Process Analysis) is a hazard analysis tool which is part of the STAMP model [88]. STPA is used to complete the detailed hazard analysis as part of step 5 of the STAMP methodology.

6.3.2 Industry interviews

The analysis will be done with industrial consultation to assist with the following aspects:

- Development and validation of the control structure;
- Development of a set of industry level safety goals and requirements;
- Formal STPA analysis on the control structure;

Sampling for industry members was completed using a non probabilistic, purposeful and convenience sampling method [209]. Industry members were identified with the aim of interviewing people with experience of as many aspects of the offshore wind industry as possible. Recruitment criteria were at least one year of experience in the relevant control structure element and at least three years overall experience in the offshore wind sector.

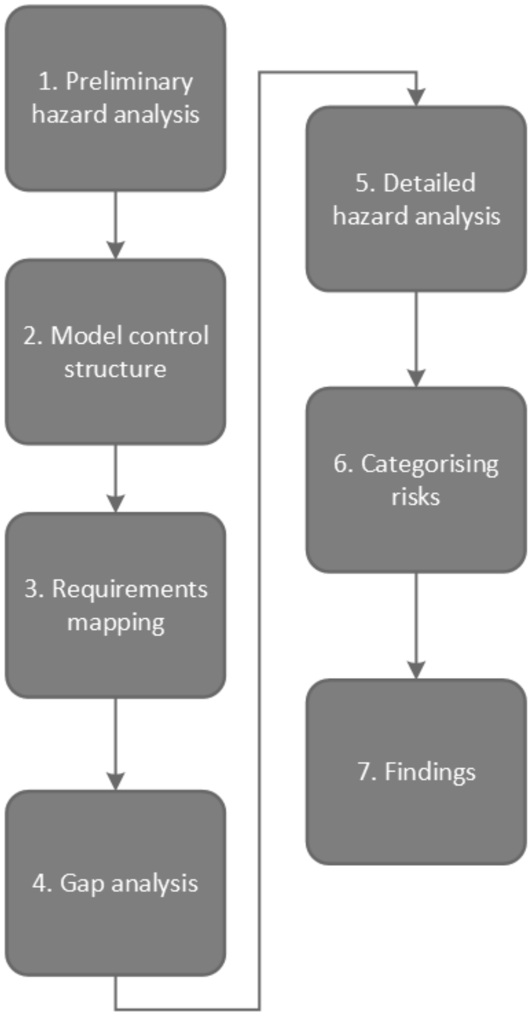


Figure 6.3: STAMP process adapted from Dulac et al.

Ref	Role in offshore wind	Years experience in industry
1	Security expert	5
2	Member of Parliament	5
3	Operations H&S and Emergency Response	13
4	Developer H&S	10
5	Operations & maintenance	3
6	Operations & maintenance	16
7	Construction	9
8	Engineering	9
9	Risk and legislation	7
10	Emergency response	9
11	Operator H&S	9
12	Risk management	15
13	QHSE Management	16
14	Developer H&S	6
15	Emergency response	6

Table 6.1: Details of interviewees

Semi-structured interviews were carried out using the draft control structure and an interview guide, these documents are included in Appendix C. Prior to the interviews candidates were provided with reading materials to give them a background on the STAMP process, this was then followed up with a short presentation at the start of the interview to make sure candidates were familiar with the process and the theory behind the analysis. Interviews were recorded (audio only), immediately following the interview a one page interview memo was completed to record initial impressions about the interview. Transcripts were then taken of the interview and the audio recordings were destroyed. Transcripts were then coded in NVIVO using STAMP guide words as a coding system to aid in the interpretation of the results [210]. In total 15 candidates were interviewed over the course of a four month period, interviewees had an average of nine years of experience in the offshore wind industry and had experience in a range of roles including security, emergency response, design, operations & maintenance and construction. For confidentiality only generic job titles were recorded, and any references to specific organisations of projects were removed from interview findings. The full list of interviewees is included in table 6.1.

Construction	Control Actions	Control Structure	Developers	Emergency response
Feedback	Government	G+	HSEx	Legislation
Maintenance	MCA	OEMs	Operators	Regulation
Regulators	Standards	Suppliers	System Hazards	Trade Unions

Table 6.2: Coding keywords

The interviews were coded using relevant words associated with the control structure and the STPA process, these are included in table 6.2

Coding allows for the organisation of the interview transcripts into relevant grouping based on the relevant parts of the analysis.

The coded interview data were then used to refine the preliminary control structure, to identify additional system hazards and functional requirements, and to populate the gap analysis..

6.4 Preliminary hazard analysis

6.4.1 Scoping

In order to begin identifying system level hazards the boundary of the system must be defined. The overall goal of this research was improving the safety of the offshore wind industry. To simplify the scope, this study will be limited to the UK offshore wind industry. Obviously different jurisdictions have different systems that govern safety. Although they will be similar, important aspects such as the legislative system will vary. So this will be focused on the UK system. The system boundary will also be focused on all offshore operations, it will not include works that take place onshore such as onshore substation works, or structural fabrication. Again, this will help simplify the analysis and also takes into account that there are different regimes managing onshore and offshore works. Offshore works also have their unique set of challenges which make the offshore part of the industry higher risk. Whereas onshore operations will have more in common with typical construction and fabrication works found in many other industries. While the study will use the UK as an example, lessons learned will be applicable to the offshore wind industry around the World. The UK has one of the largest and most developed offshore wind sectors and, is therefore, an excellent model to be used to learn lessons for the wider industry.

6.4.2 System goals and loss events

The system goals (SG) of the offshore wind industry for the purposes of this safety risk-based analysis can be defined as:

- SG-1: Offshore wind infrastructure is designed to provide a safe workplace for persons involved in installing, operating, and maintaining it.
- SG-2: The offshore wind industry develops an open and transparent safety culture where all persons feel able to raise concerns and report incidents.

The goal of this analysis is to improve safety outcomes for personnel working in the industry, so losses are restricted to those involving harm to people. A loss event is defined as:

- A person is injured or killed during the installation, operation, or maintenance of offshore wind infrastructure.

6.4.3 System level hazards

System level hazards are framed differently to hazards in traditional risk assessment methods and are defined as "a system state or set of conditions that, together with a particular set of worst-case environmental conditions, will lead to a loss" [88]. System level hazards can be considered from the point of view of the organisational control structures of the offshore wind industry and the technical systems of the offshore wind industry infrastructure.

Criteria for defining system level hazards are [88]:

- hazards are system states or conditions;
- hazards will lead to a loss in some worst case environment;
- hazards must describe states or conditions to be prevented;

Using this definition system level hazards and associated sub-hazards were identified for both systems, these are listed in Table 6.3 and Table 6.4

Hazard ID	Hazard
[OH-1]	Inadequate engineering decision making leads to loss or injury of persons involved in offshore wind operations and maintenance.
[OH-2]	Inadequate management decision making leads to loss or injury of persons involved in offshore wind operations and maintenance.
[OH-3]	Lack of industry regulation or oversight leads to loss or injury of persons involved in offshore wind operations and maintenance.

Table 6.3: Organisational system hazards

Hazard ID	Hazard	Sub-hazard
[SH-1]	Person in uncontrolled contact with wind turbine equipment	-
[SH-1.1]	-	Person exposed to falling material or dropped objects.
[SH-1.2]	-	Person exposed to live, unprotected electrical equipment.
[SH-1.3]	-	Person exposed to unprotected rotating machinery.
[SH-1.4]	-	Person exposed to crushing hazard.
[SH-2]	Person medical emergency on wind farm.	
[SH-3]	Person overboard.	
[SH-3.1]	-	Person falls from vessel during travel to and from wind farm.
[SH-3.2]	-	Person falls from vessel during transfer to turbine or other structure.
[SH-3.3]	-	Person falls overboard from a vessel or turbine during activities offshore.
[SH-4]	Person fall from height.	
[SH-5]	Fire in turbine, vessel or other infrastructure offshore.	
[SH-5.1]	-	Fire in the turbine nacelle.
[SH-5.2]	-	Fire in turbine structure.
[SH-5.3]	-	Fire onboard a wind farm support or construction vessel.
[SH-6]	Person stranded on turbine or other infrastructure offshore.	
[SH-7]	Ship or aircraft in uncontrolled contact with turbine.	Ship in uncontrolled contact with turbine.

Table 6.4: Operational system hazards

For each of these hazards' safety constraints must be applied to control the hazard. The development of the safety constraints can then be used to develop safety requirements for the offshore wind farm. Safety constraints are essentially the inverse of the system hazard [88]. So, for example, a safety constraint for SH-1 Person in uncontrolled contact with wind turbine equipment could be - Turbine design must prevent human contact with rotating equipment in the nacelle. Development of these constraints at a system design stage can help ensure the system is designed with the provision of a safe system as a first principle.

6.4.4 Industry level functional requirements

Industry level functional requirements were developed in consideration of the defined system level hazards and through analysis of existing industry level safety requirements

Requirement ID	Functional Requirement
FR-1	Implement safety into the design of the system.
FR-2	Implement best practices.
FR-3	Audit and measure performance.
FR-4	Investigate all incidents.
FR-5	Define clear roles and responsibilities.
FR-6	Develop robust emergency plans.
FR-7	Foster cross industry safety collaboration and communication.
FR-8	Promote a positive safety culture.
FR-9	Provide safe and healthy working conditions.
FR-10	Eliminate or reduce safety risks to ALARP.
FR-11	Communicate and consult with workers.
FR-12	Comply with legal requirements.
FR-13	Foster a culture of continuous improvement.

Table 6.5: Industry functional requirements

and the published safety goals of offshore wind industry developers and operators [211] [212] [213] [214]. Functional requirements are usually set out at the beginning of the design of the system. The requirements are set out in Table 6.5. These requirements in addition to constraints generated from the system hazards can be used to develop a full set of industry safety requirements.

6.4.5 Safety control structures development

Figure 6.4 shows the mapping of the offshore wind industry control structures. This structure was initially developed from the authors personal experience and available industry reports and documentation [147] [197] [102]. It was then revised and validated based on expert feedback during the interview process.

The safety control structure diagram shows the layers of hierarchy which combine and interact to control safety in the offshore wind industry. Each layer of hierarchy places constraints on those below it. STPA proposes that accidents occur when the control system is not functioning due to improper control, improper feedback or unexpected interactions between components of the system [88]. Entities are grouped together by categories such as government, regulation, trade unions and regulatory. Arrows indicate information flows between entities, and these are labeled with specific

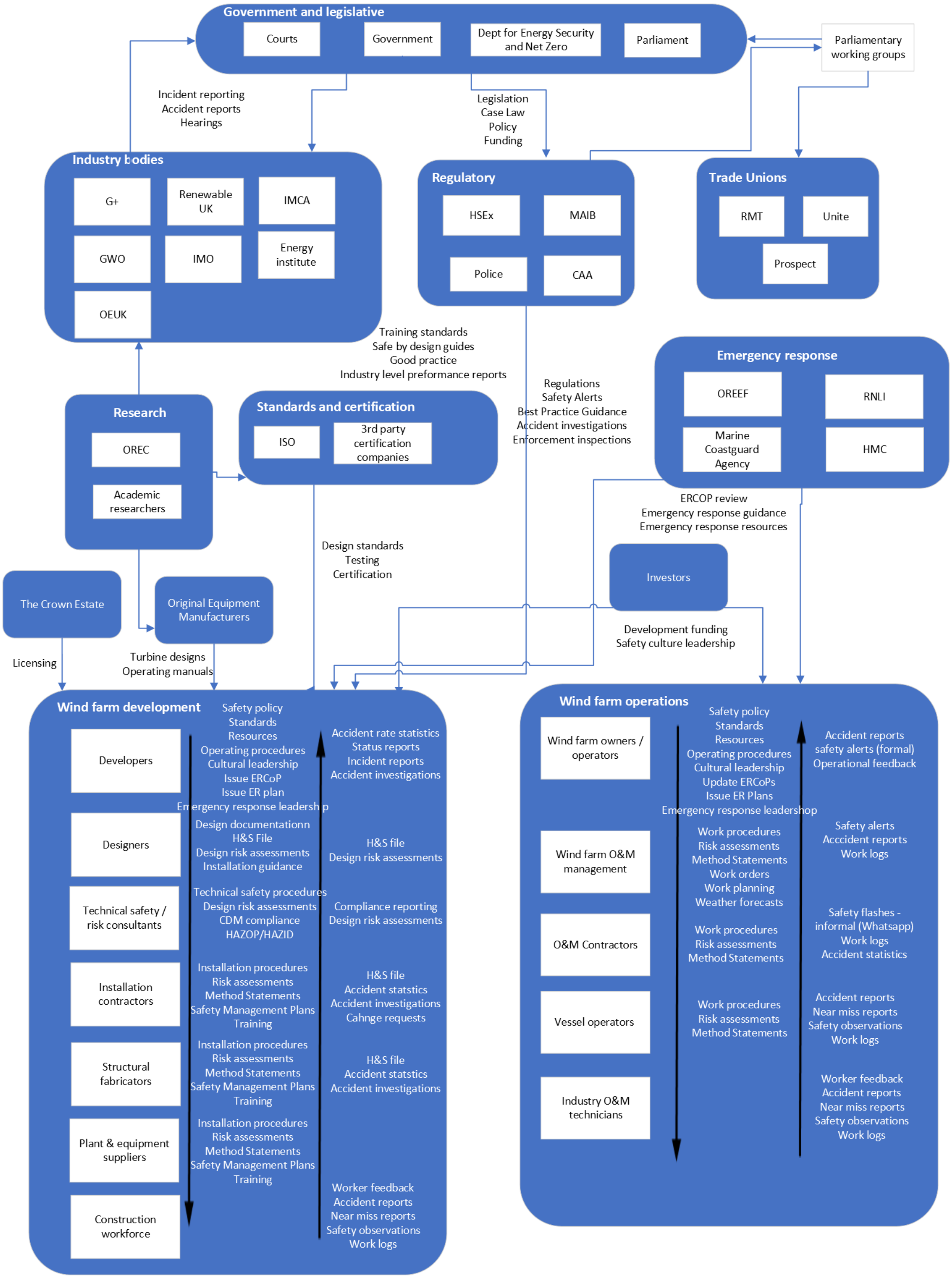


Figure 6.4: OWI Safety control structures

types of control signal and feedback type.

Controller responsibilities, control actions and feedback mechanisms are fully described in the STPA documentation included in Appendix E. The control actions, feedback mechanisms and responsibilities were populated using guidance from the industrial interviews as well as relevant industry publications and the websites of the individual organisations [102].

The governmental and legislative groups of the UK industry are comprised of the Courts, Parliament, Government and the Department for Energy Security and Net Zero. Policy for development targets of the industry are set by the Government through the Depart for Energy Security and Net Zero, who are responsible for ensuring the UK have a secure energy supply and meets its net zero policy commitments. Parliament is responsible for drafting and issuing new legislation, and would therefore have a key control action of issuing or updating any new safety legislation impacting the OWI. Key bodies that were identified as having the potential to influence Parliament were the UK Health and Safety Executive, Trade Unions and Offshore Energy UK (OEUK). OEUK are an industry body set up to represent the interests of all offshore energy industries and are actively involved in offshore wind and oil & gas. In 2023, a Parliamentary working group for offshore wind safety was established following a debate in Parliament over concerns about the application of safety legislation in the offshore wind sector. The working group was designed to bring together Unions, industry and regulatory bodies to discuss the application of safety legislation in the sector and how it may be improved.

The Crown Estate is an independent organisation which is responsible for managing land for the benefit of the UK, including UK coastal waters. The Crown estate manages the licensing processes for sea bed and therefore has a key role in wind farm development. This includes control of the procurement qualification processes which have safety requirements included for developers to adhere to. There are also many industry bodies which have a role in the management of the industry, these include G+, the Global Wind Organisation and IMCA.

Regulatory bodies play a critical role in the enforcement of safety legislation, accident investigation, best practice guidance and support to industry. In the UK the

Health and Safety Executive (HSEx) is the primary regulator for the sector and they are highly engaged with the offshore wind industry. The Maritime and Coastguard Agency (MCA) and His Majesties Coastguard (HMC) are responsible for enforcement of Merchant Shipping regulations and coordination of maritime search and rescue operations respectively. The HMC are extensively involved with the industry, supporting through the issue of guidance documents, training and involvement in review of emergency response plan development as part of the wind farm site licensing process. Helicopter operations are an important part of offshore wind operations and maintenance, the Civil Aviation Authority (CAA) are responsible for regulation of aviation safety and the Air accidents investigation branch (AAIB) are responsible for investigating any accidents involving aircraft.

The wind farm industry sector can be split into development and operations. Development takes on the role of the planning, design, procurement, construction and commissioning of a wind farm development. The actual structure of the wind farm development will depend on the contracting structure used. Depending on the project structure roles of developer, designer and contractor could all be held by one of multiple organisations. Following completion of a wind farm construction and commissioning, the original equipment manufacturer (OEM) will typically take over maintenance for the first years of operation. Following this the operator may take O&M activities in house, extend the OEM contract or engage speicalist maintenance contractors.

6.4.6 Requirements and gap analysis

Once the control structure and system requirements have been developed, the next stage of the STPA process involves a gap analysis of requirements against the existing industry control structure. Industry functional requirements and constraints based on the system hazards can be mapped to each entity in the control structure, gaps where requirements or constraints are not adequately addressed by the control structure can therefore be identified.

Key questions to consider as part of the gap analysis are [210]:

- which entities are responsible to implement the system requirements, and are any not being implemented?

- are there gaps in the control structure that are not compatible with the requirements for the system?
- is there the potential for uncertainty in the system due to missing communication or coordination?

The gap analysis was completed using the system functional requirements as identified in table 6.5. Each requirement was compared to the control structure map and using the coded outputs from industrial interviews gaps where requirements may not be implemented were identified. This assessment identified 33 gaps across the 13 functional requirements. Only for two requirements were no gaps identified at this stage. These requirement gaps can provide areas for industry to focus on improvement initiatives to improve future safety performance. The full table of gaps are included in Appendix D.

6.4.7 Gap analysis results

The gap analysis is the preliminary step in the STPA process for an organisation, key issues raised by the gap analysis are summarised here.

Functional requirement 1 (FR-1) identified that safety must be implemented into the design of the system; the gap analysis identified there are problems with the implementation and understanding of the CDM regulations within the industry. As set out in Chapter 2 the CDM regulations are intended to improve coordination between the design phase, construction phase and operational phases of a project. Furthermore, the industry interviews highlighted that technical safety or 'safe by design processes' are not yet well implemented within the industry. The level of sophistication in implementation of safe by design is not consistent and design issues causing safety issues in the O&M phase have been a common issue.

FR-2 requires the implementation of best practices; gaps identified were that the offshore wind industry has been reluctant to learn from other industries such as offshore oil & gas and has tended to develop its own procedures from first principles. One success highlighted was the development and implementation of the Wind Turbine Safety Rules (WTSR), these set out detailed procedures for safe systems of work for offshore maintenance tasks working with mechanical and electrical systems. While this has been a success, it was also noted that it has had the potential to lead to complacency where processes are taken from the WTSR without consideration of the unique aspects of the specific job to be done.

FR-3 requires audit and measurement of performance, gaps identified here were related to performance measurement methods and lack of leading indicators of risk. This reinforces the findings of Chapters 3 and 4. Furthermore, a lack of regulatory inspectors with the HSEx was also identified, with currently only four inspectors allocated to the offshore wind sector. This gap also related to FR-4 which requires all accidents to be investigated. A potential shortage of resources in this area was highlighted as a shortcoming.

Nine gaps were identified relating to FR-5 which requires the definition of clear roles and responsibilities. These gaps related to uncertainties around the applicability of legislation to the sector and the issues with works taking place outside of territorial waters. Again, confusion over the application of CDM regulations was highlighted as well as the transitory nature of the offshore sector workforce.

FR-6 requires the development of robust emergency response plans weaknesses here related to the review process of emergency response plans and also the lack of industry performance standards for emergency response times.

FR-7, 8 and 9 did not immediately highlight any gaps from this section of the process. FR-7 requires cross industry collaboration and communication, G+ are the key stakeholder in cross industry communication and are highly active in this area. FR-8 requires the promotion of a positive safety culture, safety culture is not an easy phenomenon to define or quantify, however it is widely regarded as a critical part of any organisation that wishes to have an exemplary safety performance.

FR-10 requires the elimination or reduction of risks to "as low as reasonably practicable", the initial gap identified was related to the lack of coordination of the design across the supply chain, creating difficulty to manage the design process.

FR-11 relates to the communication with the workforce, this is not a formal requirement within the industry and happens on a sporadic basis and was also identified as a gap. FR-12, compliance with legal requirements, a lack of industry specific guidance and legislation was highlighted as a gap which makes it harder to endure compliance.

FR-13 requires a culture of continuous improvement and the key gap identified here was the lack of an effective feedback loop to demonstrate industry safety performance. Specifically the reliance on lagging indicators as identified and discussed in Chapter 4.

The gap analysis was shown to be an effective process to identify weaknesses in the system, some of these reinforcing findings of previous Chapters. These findings will be considered together with the results of the STPA analysis which is explored in the next section.

6.4.8 STPA Analysis

Figure 6.5 shows the detailed STPA process. Steps 1 and 2 have already been completed in the previous sections as part of the full STAMP modelling project. The next steps for the STPA are the identification of unsafe control actions and the identification of loss scenarios. This is done by a systematic review of the operation of the control structure. STPA uses four control action scenarios that can produce an unsafe condition, these are [88]:

1. Not providing the control action leads to a hazard;
2. Providing the control action leads to a hazard;
3. Providing a potentially safe control action but too early, tool late or in the wrong order;
4. The control action lasts too long or is stopped to early;

The full STPA output is included in Appendix E, this section discusses how unsafe control actions (UCAs) and loss scenarios (LS) were identified and includes a discussion of the key findings.

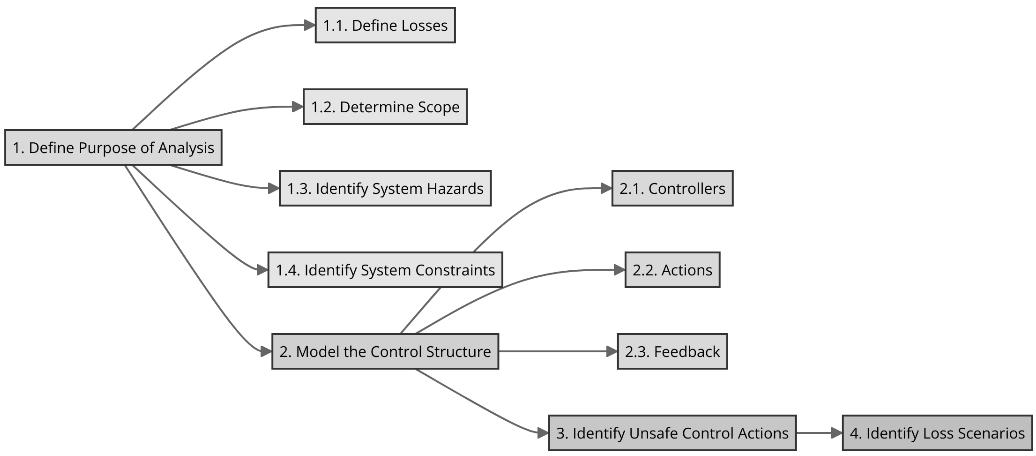


Figure 6.5: STPA process

The STPA analysis was carried out using coded responses from the industry expert interviews. Each coding reference was reviewed and identified how it related to a component in the control structure, a control action or a feedback loop. The STPA hazard analysis was then applied to that element of the structure to identify unsafe control actions.

The STPA analysis was completed for key control activities which were highlighted during the industrial interviews stage. The STPA considers the potential effects of the control actions being applied in the four conditions listed above. Potential loss scenarios are then identified based on the control actions.

For example, the first control structure group analysed was the Government and legislative, which includes Parliament as a key controller. By analysis of the interview keywords it was found that many concerns were raised over the development and issue of adequate legislation. So this control action ”issue or amend safety legislation was applied using the STPA process. So the question is asked what will happen if:

1. Not providing the control action leads to a hazard;
2. Providing the control action leads to a hazard;
3. Providing a potentially safe control action but too early, tool late or in the wrong order;

4. The control action lasts too long or is stopped to early;

This leads to the identification of loss scenario 1 as explained further below.

While full lists of UCAs and loss scenarios are included in Appendix E. Unsafe control actions and loss scenarios are discussed further here.

Identification of unsafe control actions and loss scenarios

38 potential unsafe control actions were identified through the STPA analysis, resulting in 41 identified loss scenarios. All UCAs and Loss Scenarios are included in the full STPA worksheets in Appendix E. The unsafe control actions were identified by issues raised during the industry interviews which were then coded using the relevant codes form table 6.2. For example, the issues around safety legislation governing the industry was a topic commonly raised in interviews. The issue or amendment of safety legislation can be considered as a control action by the Controller body Parliament. The STPA analysis can then explore the relevant control action possibilities. These can be:

- Parliament does not provide legislation sufficient to enforce minimum standards in the OWI [OH-3];
- Parliament provides too much legislation for the industry to be able to implement or manage [OH-3];
- Parliament provides legislation too late to enforce minimum standards in the OWI [OH-3];
- Parliament stops legislation too soon or is applied too long [OH-3];

Each unsafe control action can then be considered for its potential to develop into a loss scenario, when the UCAs are listed they are followed by the relevant system hazard, in this case Organisational Hazard-3 (OH-3). **UCA-1, 2 and 3** are very similar and can be used to generate loss scenario 1 (LS-1). A lack of specific safety legislation and a lack of guidance can lead to confusion, inconsistency of standards and poor implementation across the industry. Some of the key concerns, with reference to relevant quotations from interviews are:

"It didn't seem to be quite as clear in the renewable energy sector (compared to oil & gas) of how that legislation worked or who was responsible for what"

"My concern is that the law is so complicated, it should be known, if not to everyone, it should be known at least to, you know, a lot of professionals involved and at least be understandable to the man in the street as it is the man on the street. Just has no idea."

"Anyway, I would have thought you know the trigger is either some disaster that forces it because it comes to Parliaments attention, or some sensible agreement that there is a gap in the law and something should be done"

"Well, the the legislation is very weak. It isn't there. We're ahead of legislation (interviewee's organisation), to put it bluntly, and even even the HSE has said that they will not put any more legislation out there unless there is legislation taken away. So for example, you have an ACOG requiring you to do certain things in emergency response for the oil and gas industry. We haven't got one for renewables."

The industry viewpoints highlighted the concerns over a lack of clarity and specific guidance for the industry. In order for a control action to be effective it requires constraints and a feedback loop that allows for the control to be adjusted. The feedback loop in this case would relate to industry performance feedback to Parliament, one interviewee with experience of Parliament indicated that this can either be a serious accident that raises the profile or could come from cooperative dialogue between industry and government. The relevant feedback loops in the control structure are industry reporting and the Parliamentary working group. As previous Chapters have established, performance reporting must be improved to include more accurate statistical methods and leading indicators of risk. The Parliamentary working group can also be utilised as a key part of the control system, this currently has little industry representation, and of the interviewees, only one was aware of it. Improved engagement from industry to the working group to identify how legislation could be effectively amended and improved performance reporting could both mitigate this risk.

Proposed changes to the system based on this loss scenario would be:

- Changes to feedback structure - industry risk reporting;
- Changes to the control structure - greater powers for the working group to review and propose legislative changes;
- Controller constraints - implement a formal review of legislation for the industry;

The full analysis output is included in Appendix E and unsafe control actions are summarised and discusssed below, where applicable quotes from interviews are included for emphasis:

UCA-4 considers the setting of government policy for industry development. With an unsafe control action relating to the government setting overly ambitious development targets for industry, this could lead to a loss scenario where development speed and supply chain pressures put too much strain on the industry leading to a lack of resources and an increase in accidents. Again, this lacks an effective feedback loop to determine if risk levels are falling before a serious incident occurs. Key points from industry interviews included:

"I mean, in an ideal world, you get your processes and procedures and everything else lined up with you, and then you would start building. But it seems to be there's a bit of. Let's just try and do everything exactly at same time and and we need a significant amount of offshore wind or renewable energy to do that so."

"(there is) an awful lot of heavy lifting stuff out there, people under pressure to get things built as quick as the as they can. I think I'll probably see that as the biggest one (risk) - time scales and pressure on people get things up and."

It is clear that industry will always support ambitious government support of offshore wind, in this case constraints for this part of the control system would need to be applied by the regulators, so again this would rely on adequate funding and appropriate data from risk indicators that could identify when risk levels have increased.

UCA-5 considers the control action of the Parliamentary working group with Parliament, while this group was established following a Parliamentary debate and had Parliamentary attendance at its inception it does not currently have any attendance from a representative of Parliament. If the group is to function as an adequate link between industry this would be required. The working group was identified in interviews as a potential driver for legislative change and therefore can be a key part of the control structure.

UCA-6/7 and 8 concern the funding of government regulators, considering the scenarios of a lack of funding and resources to supervise the industry. A lack of resources will lead to a lack of oversight and inspections offshore potentially leading to an increase in accidents. While it was noted in interviews that the HSEx is highly engaged where it can be, it was also highlighted that they are clearly limited by a lack or resources. For example, expert comments included:

"I'm not sure how often they (HSEx) were being able to visit sites and make sure that these new processes and procedures were being implemented due to staffing issues or availability. So I think that was another definite challenge."

"I can't remember how many safety inspectors the HSE has for, for for offshore wind. But it was some ridiculous number I think you know about four or something like that...Whereas you're dealing with over 120 inspectors and gas."

Available reports suggest that there are currently four of five inspectors engaged in the offshore wind industry, with limited funding and as the industry continues to grow rapidly, this is a potential weakness in the control structure.

UCA-9/10 and 11 all concern the issue of guidance and regulations for the industry. Health and Safety regulations are developed and issued by the Health and Safety Commission, and guidance is issued by the Health and Safety Executive. Interviewees highlighted the high quality of guidance issued by the HSEx. The issue of regulations follow the issue of legislation and therefore very similar to UCA 1,2 and 3.

UCA-12 is for the control action of HSEx enforcement inspection, this control action creates the same loss scenario as identified by UCA-6,7 and 8.

UCA-13 and 14 related to accident investigation, interviews highlighted an area of concern around the application of UK H&S law outside of territorial waters and with respect to foreign flagged vessels operating in UK offshore wind farms. There currently exists a situation where an accident aboard a foreign vessel supporting offshore wind farm construction of operations could fall under the jurisdiction of another country.

UCA-15, 16 and 17 identified loss scenario 7 in which losses are caused by a lack of implementation of technical safety process of safe by design guides. While some organisations have developed robust procedures for this, implementation across the industry appears to be mixed and was a common theme in interviews. Strengths identified were that some organisations have already implemented a safety case type design process into their wind farm design development, and are therefore going further than legislative requirements:

"One of the areas ... was developing a safety case approach. The safety case light approach. Taking the lessons from the xxx incident where the xx was lost and trying to avoid the traps involved in trying to create paperwork just for the sake of paperwork." - Note: names are removed for anonymity.

Interviews highlighted that many historical safety issues have been caused due to a lack of consideration of operations in the design phase, and that while this had improved there are still problems, for example:

"...they didn't have a technical safety or whatever you want to call it safe by design process..I think it's something where again, the companies are quite immature...it's not high risk in terms of oil and gas, but it's it's very dynamic...but they just don't seem to have really have a grasp on that."

"The design phase, is very much for the turbines. It's very much driven by the OEM's. They have a lot of power and they have a very standardised product. So if you propose to them that I want you to do this, this and this, instead. It's very, very difficult to get them to vary, and then we do end up; we have ended up with, Defect correction happening after the event.”

UCA-18 and 19 consider the risk of training standards or training delivery not being completed or being completed too late. Loss scenario 12 identified that a lack of training standards or deployment, combined with rapid growth in the industry can lead to declining skill levels and an increase in accidents due to lack of understanding and competence. Interviews identified that training and competence are a key concern and also that quality or training is critical, it can not become a box ticking exercise:

“Well, I think it’s hidden, I think the genuine causes are hidden and there’s a big issue with competency level. Because there is a skill shortage in the industry, you know we’ve got people coming into the industry. You have some of the requirements, that are deemed as competent. And competence isn’t just a tick in the box. ”

It was also noted that a lack or training and a drop in skill levels, combines with poorly designed workplaces will increase risk levels as well as make it harder to recruit new candidates, further worsening skills shortages.

“But with the industry growing as it is right now, we there there will be a need for more people and if we don’t design workplaces in a way show that they make sense so. Not to you and me, because we are, we’re. Never going to go out there. The people that are going to come work there. They are 20 years younger. And if they can choose somewhere else, then they will go into something that’s designed so they will not hurt themselves and not offshore wind.”

“I think renewable energy companies were quite keen not to be seen as oil and gas’s little brother or and and they said there was a reluctance to take on the learnings.” -

UCA-21 control action is the provision of adequate designs from OEMs to allow for safe installation. Industrial interviews highlighted that OEMs have a very strong position in the project development process and are often reluctant to change aspects to suit the operational requirements of developers. This is combined with pressure to reduce costs across the industry which can lead to increasing risk levels in the industry. In turn, once turbines are installed it is significantly more expensive to rectify a safety issue on site rather than before installation.

“I could , cite numerous examples of work in lifting, for example. Lifting engineers have cited various design flaws, various design issues that don’t get changed because once machines are built and operated. It’s very, very expensive to change anything

“How do you know when cost cutting becomes dangerous? And to be honest, we’re probably past that.”

UCA 23 to 30 are all associated with emergency response, many of the industrial interviews identified emergency response as being a critical aspect of offshore wind operations.

UCA-23 and 24 consider the control action of the development and review of emergency response plans for offshore energy developments. As discussed in Chapter 3 their requirements for emergency response in offshore wind are less stringent that offshore oil & gas legislation. In the current system the Crown Estate require an emergency response cooperation plan (ERCoP) to be developed as part of the licensing process. The MCA publish guidelines for the development of the ERCoP and the Marine Coastguard are part of the review process required by the Crown Estate. However, the review by the coastguard is not a statutory requirement and there are also no formal requirements for the update of the ERCoP as the project moves from development to operations. The ERCoP is critical in ensuring that contact details and responsibilities are clear so that the coastguard can assist in serious emergencies. Loss scenarios 16 and 17 consider the potential risks of the current informal system in the event of ERCoPs not being properly updated. **UCAs 25 to 30** also consider unsafe control actions around the management of emergency response loss scenarios regarding emergency response were highlighted related to a lack of testing and exercising, updating of emergency response plans and emergency response coordination. The management of interfaces such as the division of responsibilities between wind farm operators and adjacent offshore transmission network was also found to be a potential loss scenario

(LS-30).

UCA-31 explored the control action of developers setting medical performance standards. Loss scenario 31 identified that a lack of proper medical standards could lead to an increase in medical emergency response events offshore. Medical emergencies offshore requiring urgent medical treatment could lead to a loss if personnel cannot be evacuated and receive treatment in time.

UCA-32 Interface with key stakeholders and interfaces is an important control action as the offshore wind industry develops. Industry interviews identified that most wind farms constructed or under development have not considered that other infrastructure or assets could be co-located in the future. As the offshore renewable energy zones become more developed and with potential future developments of hydrogen production or fisheries stakeholder engagement and interface management will become more important. Two loss scenarios were identified from this UCA. LS-32 identified that helicopter transport routes from oil & gas facilities which cross offshore wind farms could lead to new hazards. In the event of an in flight problem with a transport helicopter they could descend into the wind farm. If this scenario was combined with poor visibility or the failure of warning systems this could lead to a loss. LS-33 identified that failure to manage interfaces with new infrastructure in the marine environment and address emergent risks could lead to unforeseen losses.

UCA-33 control action for the issue of safety alerts was identified in several industry interviews. Safety alerts can be issue by G+, the HSEx and IMCA. A key issue raised was the lack of consistency and timeliness in the issue of alerts. Interviews also identified that informal rapid safety alert reporting takes place via social media messaging groups using applications such as Whatsapp. Informal safety reporting was considered to be beneficial as it gave the opportunity to immediately learn from an incident and allow other projects the opportunity to check for the same hazard. LS-34 identified that if safety alert reporting does not occur rapidly and consistently this could result in a loss where there is a recurrent hazard caused for example by an unsafe piece of equipment.

UCA-34 considers the training of the offshore workforce, this is a key control action for developers, operators and contractors to ensure that field operatives are capable of carrying out their duties safely. Industry interviews identified that there is a huge challenge with the required numbers of personnel to be trained and also with the consistency and quality of training. LS-35 identified that as the industry is expanding outside of UK territorial waters there is the potential for overseas workers not subject to UK H&S legislation to play a greater part in the industry. This factor combined with growth pressure and lack of adequate training could lead to a reduction in worker competence offshore and lead to losses.

UCA-35 and **36** examine the application of the CDM regulations processes and a technical safety design process. Industry interviews identified that CDM and technical safety processes and being poorly understood and inconsistently implemented across the industry. These two potential unsafe control actions helped identify four loss scenarios. Challenges associated with these UCAs arising from industry interviews included, the highly dynamic design process and high levels of innovation in the industry.

UCA-37 is the provision of budget for safety by the offshore wind developer. Provision of adequate budget to implement safety requirements into the design is critical to prevent losses. Industry interviews identified that extreme competition and cost pressures is increasing the risk that safe by design measures may not be implemented in order to reduce operational budgets. Failure to improve designs in consideration of past issues or to implement changes to make the turbines safer to operate and maintain can lead to future losses. This is summarised in LS-40.

The industry interview process combined with the STPA analysis process proved to be useful in identifying weaknesses in the current industry systems. Many of the findings reinforced the outcomes of Chapters 4 and 5 and new weaknesses were also identified. The next section summarises control structure and constraint changes that could be made following these findings.

6.4.9 Control structure changes and constraints

The UCAs and LSs identified by the STPA analysis can be summarised across four key themes, these are; legislative & regulation, emergency response, personnel and design development. This section will discuss the findings of the STPA and consider the potential for changes to the OWI control structure and constraints that can mitigate these risks in the future.

The first key theme of the STPA analysis is legislative & regulation. Numerous unsafe control actions were highlighted arising from the lack of industry specific legislation, confusion over the application of applications such as CDM and also concerns over the application of legislation to offshore wind farms and operations outside of UK territorial waters. The potential for lack of investment in the UK regulatory bodies such as the HSEx was also raised as a key concern. The primary control structure element for legislation and regulation is the UK Parliament. Industry interviews identified that traditionally parliament will only make recommendations to amend legislation when there is attention brought following a major accident. This is clearly not a desirable situation and the control structure requires an improved feedback loop that can propose legislative and regulatory changes. The Parliamentary working group was identified as the best control body for this group, however industry interviews indicated that industry involvement and Parliamentary engagement with this body is currently limited. A key change to the control structure would be to increase the authority and attendance at this working group, possibly through further engagement with industry bodies such as G+ and OEUK. This working group could facilitate a review of legislation and regulation together with HSEx to propose to Parliament the development of new regulations, or amendments where necessary. This feedback loop can be further enhanced by the incorporation of an annual industry risk report, which incorporates the reporting methods and leading indicators as set out in Chapters 4 and 5. The second key part is ensuring that regulatory bodies such as the HSEx and also the Coastguard have sufficient resources to support the industry as it moves forward. This could also be managed through feedback from leading indicators of risk and utilising the parliamentary working group as a route to engaging with Parliament to raise the concerns of the industry.

The second key theme of the STPA analysis is design development. While it is important that the legislative and regulatory framework for the industry is effective, the industry must also have the systems in place to design wind turbine infrastructure that can be built, operated and decommissioned safely. The dispersed nature of the supply chain can be seen in the control structure network. Industry interviews identified that OEMs are often rigid in their willingness to change designs to suit the needs of the developer. The nacelle and associated equipment are the corner stone of the design which the Developer is required to bring together to develop a suitable system. A large complex engineering project like an offshore wind farm will always require a large supply chain as no single organisation will have the capabilities to execute the entire scope on their own. As such, improved methods of interface management are needed, this may be helped by the reform of regulation such as CDM, as was already discussed. The development of design standards to suit O&M was one potential solution raised during industry interviews. The Wind Turbine Safety Rules set out specific procedures for carrying out O&M activities, however no such standards exist for design for O&M, for example minimum work spaces around equipment. The development of guidance for incorporating human factors into design and for worker consultation through the process was also highlighted. These constraints could be implemented through reform of the industry regulations.

The third key theme was personnel; as the industry implements its forecast rapid growth huge numbers of personnel will be trained and deployed into the industry. Several loss scenarios identified the risks of low quality training and low competence of workers in the industry. The second key factor was ensuring the medical fitness of workers to safely operate in the offshore wind environment. The key control structure elements for training are the GWO, Developers and Operators. While training standards are in place for the industry the challenge faced is maintaining the quality of delivery and ensuring that sufficient levels of competence are achieved for new workers. Tracking of training levels across the industry was raised as a potential leading indicator of risk in 5 and this finding reinforces that point. The other key constraint to implement would be a mechanism to ensure that training standards are maintained. This would presumably need to be enforced by auditing by a body such as the GWO.

The fourth and final key theme arising from the STPA analysis was emergency response. Earlier Chapters have discussed how emergency response is a unique challenge for offshore wind due to its remote locations and dispersed nature. The industry interviews and STPA analysis reinforced this finding. Any serious incident that does occur offshore will require an emergency response action to resolve it and the success of the emergency response operation will determine how serious the outcomes of the incident are. The control structure mapping exercise highlighted that the emergency response structures are complex with many parties having an input into policy, regulations, guidelines and the operational performance. Again industry interviews highlighted that the legislation in this area is weak, however many developers and operators have responded to this by implementing their own standards to develop systems that go further than the existing legislation. The offshore emergency response forum OREEF has developed to fill the void of regulation in this area, and the HSEx and HMC are both active in coordinating with industry. 15 of the total loss scenarios identified through the STPA analysis were related to emergency response. Many unsafe control actions stemmed from the lack of industry specific legislation, while the industry has implemented emergency response plans, coordination plans and testing and exercising, the lack of formal requirements in these leads to a vulnerability that there can be inconsistent standards across the industry. Bodies such as OREEF and G+ have stepped in to work with industry in developing guidance but without a formal basis there is the danger that key responsibilities can be missed or that required coordination between parties does not take place. Recommended additional constraints to the system would be the development of industry specific regulations for emergency response, these would formalise the requirements for the approval and regular update of emergency response cooperation plans and emergency response plans for individual wind farms. As the regulator HSEx should have additional resources to formalise emergency response guidelines and develop performance standards for the industry, this can be completed in conjunction with industry bodies such as G+ and OREEF.

6.4.10 Summary of key findings and recommendations

The key findings and recommendations from the gap and STPA analysis are summarised below, reference to the UCA are included:

- In the short term develop and issue formal guidance for the implementation of CDM regulations into offshore wind development. **UCA-1, 2, 3, 9, 10, 11**
- In the mid term a legislative review is required for the industry to assess existing regulations and make recommendations for industry specific legislation, this should include the consideration of a "safety case light" approach which could consolidate and simplify existing legislation to make requirements clearer and address serious accident risks in the industry. **UCA-1, 2, 3, 9, 10, 11**
- Offshore wind Parliamentary group should have greater visibility and attendance from the Department for Energy and industry.**UCA-5**
- HSEx should publish an annual risk indicators report specific for the offshore wind industry, this will help inform decisions of the Parliamentary working group. **UCA-6, 7, 8**
- HSEx requires additional resource for maintaining inspection and auditing of the industry, this should be increasing in line with industry growth.**UCA-6, 7, 8, 12**
- Development of standards for the implementation of human factors into the design to allow for maintenance operations.
- Legislation pertaining to offshore vessels and work outside of UK territorial waters should be reviewed to ensure that the legislation is consistent for all parties engaged in work on offshore wind farms. **UCA-13, 14**
- The industry, possibly through G+ should look to develop and publish guidance for safe by design processes, this could look to set out a process for a "safety case light" approach which could become an exemplar for the industry. **UCA-15, 16, 17, 21, 35, 36**

- The industry should incorporate training levels into annual risk reporting, in addition training standards should be reviewed to ensure it is fit to provide the required competence levels. This will need high levels of focus as the industry continues to grow **UCA-18, 19, 34**
- The review, approval and update of ERCoPs and Emergency response plans should be formalised in updated legislation and should be part of the safety case light approach **UCA-23 to 30**.
- Industry should look to formalise a procedure for the rapid dissemination of safety alerts **UCA-33**.

6.4.11 Indicator based assumptions development

Leveson proposed that risk indicators can be developed through an assumptions based method [81]. Leveson argues that to find more effective leading indicators of risk the assumptions around why accidents occur should be analyzed. This is based on the idea that accidents occur when assumptions made in design or development stage no longer hold due to a migration in the way the system operates.

Leveson defines an assumptions based leading indicator as "...a warning sign that can be used in monitoring a process to detect when an assumption is broken or dangerously weak or when the validity of an assumption is changing" [88].

These are split into three categories, listed here with examples [81]:

- Development and implementation - Assumptions about the system hazards are not correct. i.e., hazards were missed in design development.
- Operations - Changes to the system over time mean that controls are no longer adequate.
- Management - The safety management system is not operating the way it was intended.

Leveson proposed that reducing these types of causes will reduce accidents and that leading indicators can be developed to detect these kinds of changes before accidents occur. For the assessment of the risk of adverse events Leveson proposes using the concept of vulnerability rather than likelihood. Using vulnerability only considers whether an event could occur but does not try to calculate a probability of it. Considering that the system is vulnerable to an event does not mean that controls will be implemented, but it means that the event cannot be disregarded from the outset and must be considered [81].

Leveson has proposed that assumptions based leading indicators can be generated from elements of the STPA analysis, including [88]:

- High level system goals and requirements
- Assumptions about the external environment
- STPA generated hazards, control structure, UCAs and Loss Scenarios

Based on the STPA analysis carried out in this section the proposed leading indicators are set out in table 6.6.

6.5 Conclusions

This section has carried out an industry level systems based risk assessment of the UK OWI development and operational structures. The goal of this section was to assess how the industry operate, identify risks, propose changes and the development of additional leading indicators. This work is novel as the application of STAMP methodologies to the offshore wind industry is extremely limited and has previously been identified by literature reviews as an area that could benefit from its application. The study has mapped out the control structures of the industry and completed a gap analysis and STPA hazard analysis of the structures. To complete the study it has drawn on semi-structured interviews with fifteen industry experts.

The exercise has reinforced findings raised in previous Chapters and also shed new insight into the hazards facing the industry as it grows and develops future wind farms.The gap analysis and industry interviews identified 37 potential unsafe control

Ref	Subject	Assumption	Basis	Potential assumption based indicator
1	Attendance at working groups / holding working group meetings will continue	Existing H&S legislation can be copied from onshore and will be fit for purpose. Feedback loop for legislative effectiveness can be through the working groups and via annual risk level reporting.	Loss scenario-3	Frequency of meetings, no of parties attending meeting.
2	HSEx enforcement inspections	The system of regulation assumes that parties will self regulate and comply with existing legislation. This also assumes that enforcement inspections will be sufficient. As the industry grows this assumption may not hold.	Loss scenario-6	HSEx inspections carried out per turbine installed.
3	Workers will be adequately trained	The system assumes that there will be sufficiently trained workers to carry tasks adequately and safely.	Loss scenario-10	Training certifications completed Measurement of training quality
4	Person in uncontrolled contact with wind turbine equipment	Persons shall not be able to come into contact with uncontrolled equipment i.e rotating equipment, high energy dropped objects, electrical equipment	System Hazard 1	HECA assessments, High potential Electrical and Mechanical Near Misses, Electrical and Mechanical safety screening assessment scores
5	Person medical emergency on wind farm	Persons shall be able to be evacuated within time standards	System Hazard 2	Emergency reponse T&E frequencies ;Emergency response times
6	Person overboard	Crew transfers can be carried out without risk of persons overboard	System Hazard 3	Persons overboard per crew transfer (including near misses or events leading to injury) Near misses related to crew transfer
7	Person fall from height	Persons will not be exposed to risks of falls from height without controls	System Hazard 4	Near misses related to work at height Work at height compliance assessments
8	Fire in turbine, vessel or other infrastructure offshore	Fire prevention systems and protection systems will function as designed	System Hazard 5	Functional performance tests of fire detection systems Functional performance tests of fire suppression systems
9	Person stranded on turbine or other infrastructure offshore	Persons stranded on turbine will not be in danger	System Hazard 6	Near misses related to persons stranded on turbine per crew transfer
10	Ship or aircraft in uncontrolled contact with turbine	Aircraft or vessels will maintain safe distance from wind farm. Navigational	System Hazard 7	Radar beacon or AIS function tests Aircraft lighting function tests

Table 6.6: Leading indicators

actions and 40 loss scenarios. These were focused over four key themes, which included legislation, design development, personnel and emergency response. STAMP as a methodology was developed in order to understand and analyse complex systems, its strength is that it considers all aspects of a system and how the interact. The unique approach to the control structure mapping and development of requirements and system hazards can bring new insight that more traditional risk assessment methods may not find. The development of the control structure was an effective tool to facilitate the discussions in the expert interviews, and the interviews both reinforced findings of previous chapters and also raised new insights into how the industry operates. Following the interviews, the gap analysis was a quick and effective method of recording many of the study findings that could be easily identified. The STPA analysis is a more time consuming method, but benefits from the structured process requiring the assessment of each control structure. In this case the STPA analysis focused on specific actions and entities that became the focus of industry interviews. The study could benefit from further interviews which could expand the control structure further, for example each entity could be studied individually, or a group workshop could be used to facilitate more insights for the analysis. A strength of the STAMP methodology is that it can use abstraction to simplify the control structure for early stage analysis and develop further layers of detail. A detailed analysis of the design process and the emergency response process could be valuable further subjects of an STPA analysis.

The STPA output was also used to propose a set of assumption based leading indicators of risk, this process ultimately produced a similar set of indicators as Chapter 5 but also gave new insight and proposed some new indicators. The outputs of both Chapters can be used by policy makers, developers or operators to select their own set of leading indicators to complement their safety management systems.

Chapter 7

Systems safety methods applied to floating offshore wind

7.1 Contribution

This Chapter will consider however the systems safety methodologies explored in chapter 6 may be applicable to some of the novel technologies within the offshore wind sector. Floating wind is an emerging part of the offshore wind energy sector and is poised for significant growth in the coming years. New offshore wind installations in Europe totalled 2,460 MW in 2022 to make a total installed capacity of over 30,000 MW [215]. Floating wind is forecast to become a significant part of future offshore installations with markets such as the UK having identified the potential for 1 GW of floating in deepwater sites in UK waters by 2030 [4]. Floating wind has the potential to pose greater safety risks than existing fixed bottom assets, sites will be further from shore with harsher weather conditions and lower accessibility [117]. The implementation of new technologies and different O&M strategies will also pose challenges [216]. The floating wind industry is in the very earliest stages of development, and as such it has an opportunity to implement safer methods from the beginning. Floating turbine designs and maintenance strategies are under development with no industry consensus reached, thus there is opportunity to build safe methods of work into the technologies before they go into commercial scale developments.

The contribution of this Chapter is to assess the potential for the application of systems safety theory to the floating wind sector, complete a preliminary analysis and identify opportunities for further research in the sector going forward. This work is novel as to the authors knowledge it is the first application of systems theory to assess safety in the O&M of floating offshore wind operations.

7.2 Methodology

STAMP contains various tools that could have applications to the benefit of FOW safety [27]. STAMP can be applied at all stages of system development from concept design to operations. As the floating offshore wind sector is currently in the developmental stage, this analysis focuses on the organisational structures that will govern how the systems are designed and operated. Leveson identified several benefits of completing an organisational level STPA analysis, these were [88]:

- solving engineering and business problems
- developing organisational culture
- developing organisational requirements and constraints
- hazard analysis of the organisation
- development of leading risk indicators

Steps 1 to 3 of the STAMP process flowchart in figure 6.3 (preliminary hazard analysis, control structure modelling and requirements mapping) will be explored for an organisational level analysis and steps 1 to 2 will be set out for an analysis of a tow to shore maintenance operation. The results of the analysis could then be able used to improve the organisational structure, identify risks and help the industry develop safer systems.

7.3 STAMP analysis results

7.3.1 Purpose of analysis

Firstly, the purpose of the analysis should be defined. This requires the scope of analysis, objectives, loss events and system level hazards to be defined. The scope for this analysis is an organisational analysis of the floating wind development structures, this will be further set out in the development of the control structures. Objectives and loss events are defined as:

System objective: Floating wind systems are developed to allow for operation and maintenance without losses.

Loss events: A person is injured or killed during the operation or maintenance of a floating offshore wind turbine. [L-1]

System level hazard: Lack of integration of safety into the design development of FOW systems leads to losses [SH-1].

Using the system level hazard as a starting point, system constraints that could be applied to prevent this hazard can then be identified. System level constraints are identified in table 7.1, these were selected using the authors judgement and based on outputs from an industry workshop on safe design of floating wind systems [217]. System constraints are identified with the goal that the implementation of these constraints on the system will prevent losses due to the identified hazard.

Ref	System constraint
SC-1	Guidelines for standardisation should developed at the earliest stages, without limiting innovation.
SC-2	Safety related technical decision making should be independent from cost and schedule considerations.
SC-3	Industry level interface guides for key design interfaces should be developed.
SC-4	Operations personnel should be included in design development at all stages.
SC-5	Channels for increased supply chain collaboration should be developed.

Table 7.1: System constraints

7.3.2 Control structure modelling

The next step in the analysis is to develop a model of the industry control structures. A model of the floating wind industry development control structures is included in figure 7.1. The control structure is developed based on available industry documentation and input from expert interviews as documented in Chapter 6 [102] [158] [217].

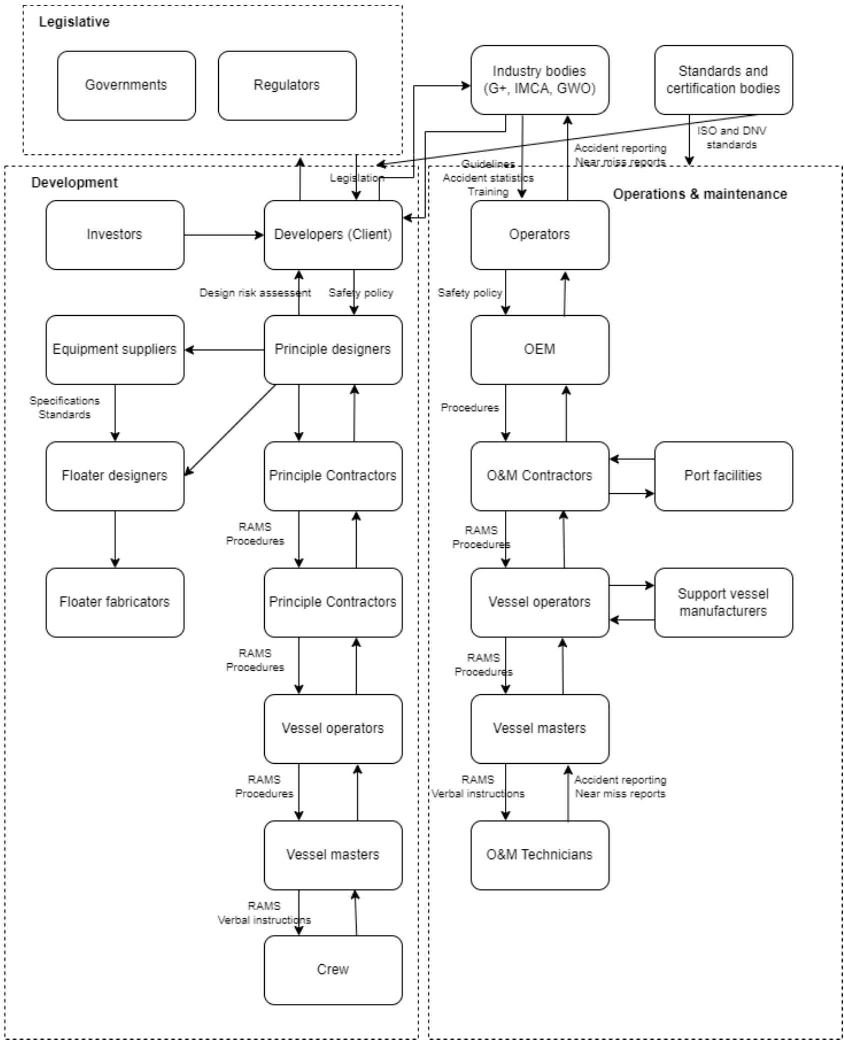


Figure 7.1: Floating wind development control structures

The control structure shows the parties involved in the development of safe floating offshore wind systems. This is a hierarchical structure with government and regulatory bodies at the top and O&M technicians at the bottom. Downward arrows indicate where control actions are placed on one party by the other and upward arrows indi-

Ref	Requirement	Control structure component(s)	Weakness identified
RID-1	Guidelines for standardisation should developed at the earliest stages, without limiting innovation.	Industry bodies, standards and certification bodies	Large number of floater concept designs, multiple boat landing designs etc.
RID-2	Operations personnel should be included in design development at all stages.	Principle designers, O&M Contractors, Vessel operators, O&M technicians	Lack of formal mechanisms, no specific legislative requirements, limited inter-industry collaboration.

Table 7.2: Gap analysis examples

cate feedback. For clarity, not all arrows are included in this diagram, examples of control actions and feedback loops are included. For example, governments and regulations issue legislation and regulations to implement constraints on the development and O&M structures. Contractors and operators typically utilise work procedures, risk assessments and method statements (RAMS) to exert constraints on other parties. Feedback loops include accident reporting, near miss reporting and work reports. In an STPA analysis it is normal to start with the analysis with a high level map of the control structure. Increased complexity can then be added through further iterations or detailed maps of critical areas.

Once the control structure is developed a gap analysis can be completed to identify how the system constraints are implemented by the existing control structure.

7.3.3 Gap analysis

Step 3 in the STPA flowchart involves identification of unsafe control actions. This involves the use of guide-words to identify potential control actions that can lead to hazards and losses in worst case scenarios. In the case of an organisational analysis a simpler gap analysis can be used [88]. The gap analysis considers each of the system constraints and whether there are mechanisms on the the control structure for their implementation. A full gap analysis of all elements is beyond the scope of this Chapter but some example scenarios and potential gaps in the industry are set out here. A gap analysis aims to identify where constraints and requirements are implemented. For example "SC-4 Operations personnel should be included in design development at all stages". The first step is to identify if this constraint is currently implemented and if not, how the control structure could be modified to address this, a control action and feedback loop is required to implement this constraint.

Table 2 sets out two examples of how the gap analysis can be completed. RID-1 is a constraint to implement guidelines for standardisation which could aim to provide guidelines for items such as boat landings which could help to standardise designs across the industry simplifying crew transfers and improving safety. This was a recommendation identified by an industry workshop but the control structure analysis helps identify that there is no existing mechanism to enforce this. R-ID2 is a requirement to engage operational workforce in all stages of the design, it is generally regarded that workforce engagement and feedback to improve design safety is beneficial however there are not always formal mechanisms for this. Discussions with industry as part of this research have identified these are in place in some organisations but not always well implemented. In the UK Oil and Gas industry there is a regulatory requirement through the safety case legislation that workers must be engaged to elicit feedback on safety issues [218]. Development of a formal mechanism for this may be of benefit of floating offshore wind safety. In turn, each constraint can be analysed to assess how it is, or is not implemented, and weaknesses can be identified. This would be done by expert interviews with parties involved in the operations. The full analysis is out of scope of this study, but this preliminary analysis indicates the potential for further application to floating offshore wind.

This type of analysis can also be done for the internal design development structures of developers and operators within the industry and help develop a structure that develops safe systems from the outset. The control structure shown in figure 7.1 can be developed in further detail for key sections within it to aid in this analysis. Leveson has also set out a process that can be applied using these outputs to generate leading indicators of risk for an industry or organisations [81].

7.3.4 Operational analysis

A systems based approach can also be used to identify operational hazards that may arise due to complex interactions. Floating wind tow to shore operations are likely to be complex and unforeseen hazards may arise due to the interaction of multiple systems and automation. This has been shown to be the case for SOV operations and the use of

Ref	Hazards
SH-1	Vessel violates minimum safety distance to floating turbine
SH-2	Person falling from height
SH-3	Person overboard in water
SH-4	Tools, equipment or materials fall or uncontrolled movement
SH-5	Floating turbine movement exceeds design limits
SH-6	People unable to exit or stranded on turbine

Table 7.3: Tow to shore - system level hazards

Ref	Hazards
1	Quayside disconnection and release
2	Connection of towing lines to platform
3	Offshore ballasting operation
4	Transportation of platform to mooring site
5	Cable disconnection
6	Platform temporary station-keeping
7	Mooring lines disconnection
8	Platform transportation
9	Foundation structural repairs

Table 7.4: Hazards identified by industry matrix risk assessment

gangway systems, there are also accident case reports from the fixed bottom industry that indicate failures have occurred due to these unexpected interactions [22].

A proposed set of systems based hazards are set out in table 7.3. The STAMP definition of a system hazard is a system state that in a worst case environmental condition will lead to a loss [88]. It is normal to have 6 or 7 systems level hazards at the outset of an STPA analysis and these can be broken down into sub-hazards as the analysis requires. Table 7.4 highlights the key hazards that have been highlighted by a traditional matrix risk assessment developed by industry collaboration on tow to shore maintenance [219]. The system level hazards constitute system states which could result in an loss in worst case environmental conditions. For example, an uncontrolled movement of materials due to turbine motion resulting in contact with an person working on the turbine could results in a loss. A comparison of 7.3 and 7.4 demonstrate the differing approaches of a traditional matrix risk assessment and a systems approach.

The identification of the system level hazards and completion of the STPA process is designed to identify loss scenarios that may not be picked up by a traditional risk assessment. The next step in the STPA process is the mapping of the control structure of the activity, an example of a control structure for a tow to shore operations is demonstrated in figure 7.2. The complexity of the safety control structure and interactions indicate the potential for complexity causing unexpected hazards. The full STPA analysis of the operations will require extensive expert input and is out of scope of this study but could add value to analyse activities which have been identified as high risk for floating offshore wind operations.

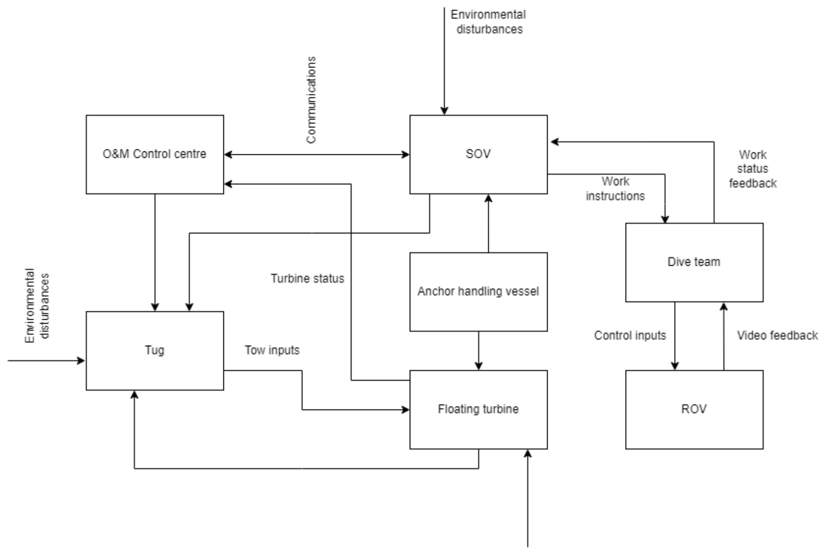


Figure 7.2: Safety control structure - tow to shore

7.4 Conclusions

The objective of this Chapter was to the assess the potential for the application of systems safety principles to the floating offshore wind industry. Offshore wind has been shown to be a high risk industry and the advent of the floating wind sector will bring new complexities that will have the potential to create new hazards. Systems safety methodologies are becoming more widespread across a range of industries but have as yet seen little application to offshore wind. The study has looked at how a systems based risk analysis using STAMP can be used to highlight weaknesses in the structure of the industry as it develops and begins operating floating offshore wind. This has scoped out an initial analysis with examples. A STAMP analysis can be explored further with industry input and could allow for the development structures to be designed in a way improve safety outcomes. These methods can also be adapted for in depth analysis on specific aspects of the industry such as the emergency response organisations, engineering processes and operational processes.

The study has also proposed a set of system level hazards and a preliminary control structure for a tow to shore operation and contrasted these with hazards identified by the industry. Complex operations such as tow to shore are likely to have emergent hazards due to the interaction of multiple systems. This has been seen in fixed bottom SOV operations and this STAMP analysis can be explored further through the engagement of industry to identify the potential for these hazards in floating maintenance operations.

Systems safety approaches have potential for helping the floating wind industry develop and become an example of the implementation of best practices in safety engineering. The development of a safe industry requires the consideration of the entire industry from legislation, through developers, regulators and down to the daily activities of offshore technicians.

Further research would be valuable completing a full detailed STPA of all aspects of floating wind maintenance operations. This would help identify potential emergent risks not identified by traditional analysis methods. This could be applied to tow to shore maintenance, offshore lifting operations and also emergency response operations.

Chapter 8

Conclusions

Chapter 1 set out the background to the safety problems in the offshore wind industry and highlighted it had been coming into criticisms from high profile sources such as the UK Health and Safety Executive, based on this background the research questions was posed, which was:

"How can we understand, measure and predict the safety challenges of the offshore wind industry?"

In order to answer this question several other secondary questions were set out and these were addressed over five chapters of research work. This final section sets out a summary of the main conclusions from each Chapter and addresses the overall research question. More detailed conclusions can be found in each Chapter, finally this section outlines how the work can contribute to industry and discusses the potential for future works in this area.

8.1 Conclusions from Chapter 2

While there is an existing extensive body of research within the safety science literature, there has been very little application of this work to the offshore wind sector. Indeed, existing literature reviews have highlighted that the sector would benefit from the application of this knowledge to the sector. In particular there is a lack of innovation in the analysis or reporting of safety performance data in the industry and this represents a key challenge in understanding or managing performance. Factors such as rapid growth, challenging working conditions and high levels of innovation have created a very dynamic industry which is at risk of worsening safety performance if measure to manage safety are not improved. This thesis set out to address these knowledge gaps.

8.2 Conclusions from Chapter 3

"How does the performance and safety legislation of offshore wind currently compare to a similar industry, and how is the risk profile likely to change in the coming years?"

Existing high level accident statistics indicate that industry performance is 3 to 4 times worse than a comparable industry. Furthermore forecasts of risk exposure to technicians indicate that this performance could worsen without considerable effort. The legislative frameworks in the UK for offshore wind have not been updated to address its unique challenges and are not as robust as other offshore industries.

8.3 Conclusions from Chapter 4

"How does the industry currently measure safety performance, how does it compare to best practice and how could it be improved?"

The industry safety performance reporting methods rely on lagging indicators which are not statistically valid and which are not reported with the necessary context or analysis to ensure they are properly interpreted. Reporting methods have not incorporated lessons from the safety science research or from comparable industries. Industry is relying on unreliable indicators and using these to set executive remuneration. With the adoption of reporting methods from the research, validity of the existing lagging indicator data can be improved and trends can be identified. The sector has not developed leading indicators of risk and these are required to provide a well rounded method of safety performance and risk level reporting.

8.4 Conclusions from Chapter 5

"How could leading indicators of risk be developed to help the industry monitor risk levels in the future and prevent the occurrence of serious accidents?"

The offshore wind industry can learn from oil & gas and implement a leading indicator of risk project to identify if risk levels are increasing and highlight the potential for serious hazards which could cause one or more fatalities. This can be done with the implementation of precursor analysis, some of these can be implemented with the use of existing data, others require new data streams to be collected. In addition a set of barrier indicators can be implemented to act as leading indicators. The implementation of these indicators at an industry and organisational level in conjunction with the measures in Chapter 4 can help the industry focus its efforts in safety management.

8.5 Conclusions from Chapter 6

"How can systems safety theory help the industry understand and manage its safety challenges and also identify further leading indicators of risk?"

Systems safety theory can help identify and manage hazards in complex systems. At an industry level offshore wind has many challenges that cause increased risk levels and could lead to losses. These include the management of a complex supply chain and the challenges associated with implementing safe by design processes. Challenges in the supply chain management during design and a lack of safe by design processes is leading to increased risk of losses in the industry. The management of emergency response is one of the biggest challenges faced, existing legislation is weak in this area and a lack of formal requirements for managing emergency response across the industry could lead to losses.

8.6 Conclusions from Chapter 7

"How can systems safety theory be applied to the emerging floating wind sector?"

Floating wind will pose unique challenges to the industry, and as it is in the earliest stages of development the application of systems based analysis can help the industry manage its design development processes. Systems safety analysis can also be used to help with the analysis of completed O&M processes such as tow to port strategies and could help identify emergent risks that may not be found by more traditional analysis methods.

8.7 Overall discussion

The overarching research question for this thesis asked:

> "How can we understand, measure, predict and address the safety challenges of the offshore wind industry to allow for the reduction of injuries, and the avoidance of major accidents in the future?"

The work presented in the preceding chapters can be viewed as progressing through these three themes. First, Chapters 2 and 3 focus on *understanding* the safety challenges by examining the development of the offshore wind sector, existing accident statistics, and the current regulatory and organisational context. Second, Chapters 4 and 5 *measure and predict* safety performance by critically evaluating existing performance indicators, assessing their statistical validity and applying quantitative methods to offshore wind accident data, and by proposing a framework for leading indicators tailored to the sector. Finally, Chapters 6 and 7 *address* safety challenges by applying systems safety methods to offshore wind and floating wind, identifying system-level hazards, vulnerabilities and opportunities for improvement.

The remainder of this section draws these strands together and discusses their implications for the future development of safety management in the offshore wind industry.

The offshore wind industry is still in relatively early stages of its development when compared to the thermal energy sector or the UK oil & gas industry. The current levels of safety performance lag comparable industries and it is important these are improved. While the industry is incredibly innovative in its development of turbine technology it has been less innovative in the implementation of safety management knowledge. As the industry continues to grow, technician exposure to risk is going to increase, new technologies that are implemented will pose new challenges and more remote wind farm sites will be harder to manage safely. In managing safety a key feedback loop is the understanding of performance and risk levels through the use of data, this is an area where the industry is currently significantly lacking. However, with the application of knowledge from similar industries this can be significantly improved. This work has set out how existing data can be presented and also how more advanced leading indicators of risk can be developed and implemented. Improved understanding of risk levels will help policy makers and industry members better manage their safety outcomes. This work has highlighted that there are existing gaps in how the development and operation of offshore wind is implemented, particularly in the legislative framework and the implementation of safe by design processes. Other industries have often learned these lessons only through disasters that have caused multiple fatalities. The offshore wind industry have the opportunity to learn from other industries and avoid these types of serious accidents from ever happening. The implementation of an industry wide risk indicator report incorporating reporting methods and leading indicators from this work could help the industry identify where to focus efforts in order to make changes before serious accidents occurred. In addition, this work has identified that changes to legislation, regulations and the implementation of safe by design processes must be improved. The work has also shown that the application of a systems based analysis using STAMP can be an effective tool for any industry to implement to identify where it may have weaknesses. This methodology could be implemented further in offshore wind industry to identify more opportunities for improvement.

8.8 Further research

This work could be expanded in several key areas. Figure 8.1 identifies six areas which could benefit from further research building the ideas developed in this thesis and the knowledge gaps set out in the literature review.

Performance statistics would benefit from further detailed analysis of datasets from industry being made available. Developers and operators maintain databases that

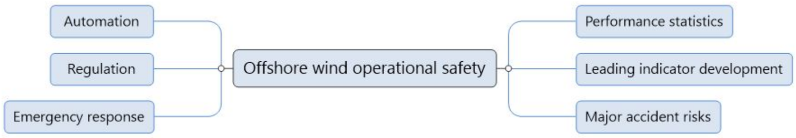


Figure 8.1: Future research areas

capture details of all safety incidents; however, these data are only publicly available at a highly aggregated level. Access to more raw data would allow for detailed analysis, incorporating AI and data science methods to develop insights. The key challenge here will be to overcome the reluctance to publish these data and to address confidentiality concerns. Detailed analysis of these data could identify additional precursor indicators or barrier indicators that could complement those recommended here.

Where there is currently no data available for the leading indicators proposed here, these could be developed if the data became available. The offshore wind industry has yet to experience a major accident and the lack of available data makes it harder to predict where these might occur. Implementing leading indicators of major accident risk is an important tool to prevent major accidents as has been seen in the offshore oil & gas industry.

Further research is also required on the specific risks of major accidents and the appropriate mitigation and emergency response actions. Chapter 5 identified the major accident hazards for the industry such as lifting operations, fire and exposure to hazardous energy. Further specific research into new work methods or designs to limit these risks can be of benefit. Industry interviews identified that the industry can struggle with the implementation of technical safety or "safe by design" processes. Identifying methods to incorporate safe by design thinking into offshore wind can help mitigate these risks at the design stage. There is even greater opportunity for this to take place where novel turbine types are being developed for the floating sector and also multi rotor and vertical axis systems. For example multi-rotor systems have the oportunity to incorporate modular designs and minimize heavy lifting offshore.

The use of automation in the industry is growing, and further research is required on the potential impacts on safety. There can be positive effects by reducing worker exposure however there is the potential for novel risks to also be introduced. The identification of emergent risks due to complex systems can be tackled with further implementation of systems methodologies as was explored in Chapter 7.

Emergency response is a critical part of the industry and as it continues to develop it is important that emergency response capabilities keep up. Emergency response modeling research and the development of performance standards for the industry can be useful tools and would benefit from work in this area.

Finally the work completed in Chapter 6 can be expanded into a dynamic risk modelling project using the methods set out by Dulac [85]. Forrester has discussed that the development of the model can create as many insights as the model itself [220]. The goals of dynamic risk modelling per Dulac [85] are:

- Improve the quality of mental models used to make safety-related decisions.
- Analyze risks identified by system analysts and stakeholders.
- Improve the robustness of systems against time-dependent risk increase.
- Improve risk monitoring to detect and correct potential migration towards higher risk levels.

Appendix A

Research map

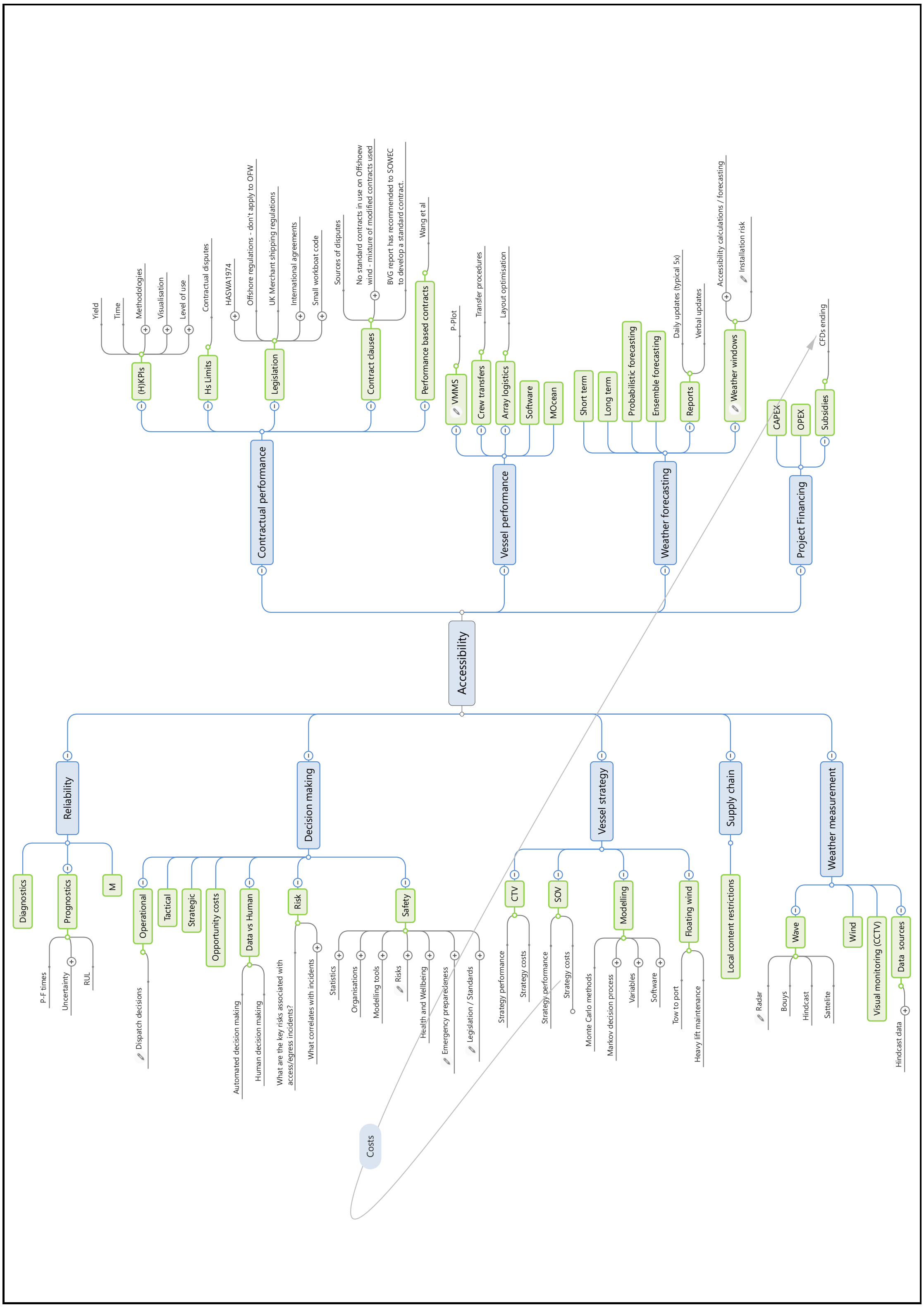


Figure A.1: Research mind map with 3 levels

Appendix B

Leading indicators

Existing risk indicators proposed in research from offshore wind, construction and oil & gas							Scoring								
Ref	Proposed Leading indicator in the research	Organisational level	Source	Source Industry	Description	Measure	Observable	Intuitive	Complexity	Quanitifiable	Sensitivity	Transparent	Robust	Valid	TOTAL
1	Organizational commitment	Firm level	Xu 2021	Construction	Client, designer, principal contractor and subcontractor commitment to safety	Total safety expenditures/total expenditures	1	1	1	1	0.5	0.5	0.5	0.5	6
2	Organizational commitment	Firm level	Xu 2021	Construction	Client, designer, principal contractor and subcontractor commitment to safety	Frequency of safety walk by senior management	1	1	1	1	0.5	0.5	0.5	0.5	6
3	Safety auditing	Firm level	Xu 2021	Construction	The process of collecting independent information on the efficiency, effectiveness and reliability of the safety management system and drawing up plans for preventive actions.	Frequency of internal/external audits completed to schedule in a specific time frame,	1	1	1	1	0.5	0.5	0.5	0.5	6
4	Safety auditing	Firm level	Xu 2021	Construction	The process of collecting independent information on the efficiency, effectiveness and reliability of the safety management system and drawing up plans for preventive actions.	Number of action items suggested based on auditing,	1	0.5	1	1	0	0.5	0	0.5	4.5
5	Safety auditing	Firm level	Xu 2021	Construction	The process of collecting independent information on the efficiency, effectiveness and reliability of the safety management system and drawing up plans for preventive actions.	Percentage of action items that are closed on or before the target date	1	1	1	1	0.5	0.5	0	0.5	5.5
6	Training and orientation	Firm level	Xu 2021	Construction	Improving skills, knowledge, attitudes and experiences of managers, supervisors and workers to effectively manage safety	Hours of training received by workers in a specific time frame including contracted workers	1	1	1	1	0.5	0.5	0.5	0.5	6
7	Training and orientation	Firm level	Xu 2021	Construction	Improving skills, knowledge, attitudes and experiences of managers, supervisors and workers to effectively manage safety	Percentage of workers trained	1	1	1	1	0.5	1	0.5	0.5	6.5
8	Client engagement	Project level	Xu 2021	Construction	Client is engaged in construction safety throughout a project.	Frequency of meetings between client's safety professional and designer teams in a specific time frame	1	0.5	1	0.5	0	1	0	0.5	4.5
9	Client engagement	Project level	Xu 2021	Construction	Client is engaged in construction safety throughout a project.	Frequency of safety audits for contractors in a specific time frame	1	1	1	1	0.5	1	0.5	0.5	6.5
10	Designer engagement	Project level	Xu 2021	Construction	Principal designer and other designers (including designers of temporary works) is engaged in construction safety throughout a project.	Frequency of qualified walkthroughs in a specific time frame,	1	1	1	1	0.5	1	0.5	0.5	6.5
11	Designer engagement	Project level	Xu 2021	Construction	Principal designer and other designers (including designers of temporary works) is engaged in construction safety throughout a project.	Number of meetings with main contractors per role, (including designers of temporary works) in a specific time frame	0.5	0.5	1	0.5	0	1	0.5	0.5	4.5
12	Principal contractor engagement	Project level	Xu 2021	Construction	Principal contractor is engaged in construction safety throughout a project.	Frequency of a safety professional's onsite safety inspection, in a specific time frame,	1	1	1	1	0.5	1	0.5	0.5	6.5
13	Principal contractor engagement	Project level	Xu 2021	Construction	Principal contractor is engaged in construction safety throughout a project.	Percentage of subcontractors audited monthly vs. total number	1	0.5	1	1	0.5	1	0.5	0.5	6
14	Supply chain and workforce engagement	Project level	Xu 2021	Construction	Subcontractors, suppliers and self-employed workers are engaged in construction safety throughout a project.	Number of safety inspection conducted by a subcontractor/ supplier/self-employed worker in a specific time frame,	1	1	1	1	0.5	1	0.5	0.5	6.5
15	Supply chain and workforce engagement	Project level	Xu 2021	Construction	Subcontractors, suppliers and self-employed workers are engaged in construction safety throughout a project.	Frequency of a crew's receiving notices of hazard removal	0.5	0.5	1	0.5	0.5	0.5	0.5	0.5	4.5
16	Safety design	Project level	Xu 2021	Construction	Preventing accidents during construction is regarded as one of the objectives of design.	Number of hazards/risks highlighted and addressed in the design of structure, including temporary works	0.5	1	0.5	0.5	0.5	0.5	0.5	0.5	4.5
17	Safety design	Project level	Xu 2021	Construction	Preventing accidents during construction is regarded as one of the objectives of design.	Number of hazards/risks eliminated by amending design,	0.5	1	0.5	0.5	0.5	0.5	0.5	0.5	4.5
18	Plan for safety	Project level	Xu 2021	Construction	Safety in construction is considered in the planning process, including both preconstruction planning and short-term planning.	Number of hazards and risks highlighted and addressed in site logistics and layout plans	0.5	1	0.5	0.5	0.5	0.5	0.5	0.5	4.5
19	Plan for safety	Project level	Xu 2021	Construction	Safety in construction is considered in the planning process, including both preconstruction planning and short-term planning.	Number of emergency plans, e.g., fires and explosion emergencies, established before construction	0.5	1	0.5	0.5	0.5	0.5	0.5	0.5	4.5
20	Hazard identification and control	Project level	Xu 2021	Construction	The process and outcome of identifying and controlling hazards and risks in workplace.	Percentage of high-risk items identified in a specific time frame	0.5	1	0.5	0.5	0.5	0.5	0.5	0.5	4.5
21		Project level	Xu 2021	Construction	The process and outcome of identifying and controlling hazards and risks in workplace.	Percentage of hazardous items actioned in the agreed time frame	1	1	0.5	1	0.5	0.5	0.5	0.5	5.5
22	Safety learning	Project level	Xu 2021	Construction	Learning from accidents, incidents and relevant experiences.	Number of safety reports with actions implemented in a specific time frame	1	1	0.5	1	0.5	0.5	0.5	0.5	5.5
23	Recognition and reward	Project level	Xu 2021	Construction	Mechanisms to motivate workforce to comply with safety rules and actively participate in safety improvement activities	Percentage of individuals or groups recognized e.g., employee of the month for excellent safety performance in a specific time frame	1	0.5	1	1	0.5	0.5	0.5	0.5	5.5
24	Recognition and reward	Project level	Xu 2021	Construction	Mechanisms to motivate workforce to comply with safety rules and actively participate in safety improvement activities	Percentage of individuals or groups who received safety bonus in a specific time frame	1	0.5	1	1	0.5	0.5	0	0.5	5
25	Site communication	Project level	Xu 2021	Construction	Familiarizing operatives with a job, informing risks and improving task-specific competence to prevent accidents	Percentage of operatives who receive induction prior to commencement of work	1	1	1	1	0.5	1	0.5	0.5	6.5
26	Site communication	Project level	Xu 2021	Construction	Familiarizing operatives with a job, informing risks and improving task-specific competence to prevent accidents	Frequency of toolbox meeting	1	1	1	1	0.5	1	0.5	0.5	6.5
27	Safety climate	Group and individual level	Xu 2021	Construction	Employees' perception of the priority an organisation and workgroup placed on safety-related policies, procedures and practices	Use of quantitative scales (e.g. a five-point scale) for measuring perceived management commitment, supervisor safety responses, co-worker safety response, client safety commitment, principal contractor safety commitment, and error management	0.5	1	0.5	1	0.5	1	0.5	1	6
28	Worker involvement	Group and individual level	Xu 2021	Construction	Workers' level of involvement in establishing, operating, evaluating, and improving safety practices.	Percentage of attendance of workers at safety events, e.g., training and induction/toolbox meeting	1	1	1	1	0.5	1	0.5	0.5	6.5
29	Competence	Group and individual level	Xu 2021	Construction	Ensuring that employees have the skills, knowledge, attitudes and experience to safely carry out assigned tasks.	Number of certification cards	1	1	1	1	0.5	1	0.5	0.5	6.5
30	System failures	Firm or project level	Seyr 2016	Offshore wind	Testing the performance of safety critical systems	Turbine system failure rates	1	0.5	1	1	0.5	0	1	0.5	5.5
31	Lifting	Firm or project level	Seyr 2016	Offshore wind	Performance of lifting operations during installation of maintenance	Number of lifting incidents as a percentage of lifting operations	0.5	1	0.5	0.5	1	0.5	0.5	0.5	5
32	Work at heights	Firm or project level	Seyr 2016	Offshore wind	Incidents related to working at height	Number of incidents during work at heights as a percentage of work actions carried out at heights	0.5	1	0.5	0.5	1	0.5	0.5	0.5	5
33	Falling objects	Firm or project level	Seyr 2016	Offshore wind	Incidents related to dropeed objects	Number of incidents due to falling objects as a percentage of work actions	0.5	1	0.5	0.5	1	0.5	0.5	0.5	5
34	Hub and blade	Firm or project level	Seyr 2016	Offshore wind	Incidents related to work in the hub or blades	Number of incidents occurring in the Hub and Blade area of the rotor of a turbine during work actions. (The number is given as a percentage of the total work actions in the hub and blade area and give the percentage of work at the rotor that results in incidents.)	0	1	0.5	0	1	0.5	0.5	0.5	4
35	Nacelle electrical	Firm or project level	Seyr 2016	Offshore wind	Incidents related to electrical works	Number of incidents caused by electrical work in the nacelle (measured as a percentage of all electrical work actions undertaken).	0	1	0.5	0	1	0.5	0.5	0.5	4
36	Nacelle mechanical	Firm or project level	Seyr 2016	Offshore wind	Incidents related to mechanical works	Number of incidents caused by mechanical work in the nacelle (measured as a percentage of all electrical work actions undertaken).	0	1	0.5	0	1	0.5	0.5	0.5	4

Ref	Proposed Leading indicator in the research	Organisational level	Source	Source Industry	Description	Measure	Observable	Intuitive	Complexity	Quanitifiable	Sensitivity	Transparent	Robust	Valid	TOTAL
37	Contact with substances	Firm or project level	Seyr 2016	Offshore wind	Incidents related to work with hazardous substances	Number of incidents where a worker was exposed to a hazardous substance (measured as a percentage oftotal number ofwork actions performed in a place with possible exposure).	0	1	0.5	0	1	0.5	0.5	0.5	4
38	Substation	Firm or project level	Seyr 2016	Offshore wind	Incidents related to work in substations	Number of incidents occurring in the substation (measured as percentage of the total number of work actions performed in the substation).	0.5	0.5	0.5	0	1	0.5	0.5	0.5	4
39	Helicopter incidents	Firm or project level	Seyr 2016	Offshore wind	Incidents related to helicopter transportation	Number of incidents happening during transportation with a helicopter. (This includes material and worker transportation to and from the wind farm. Given as a percentage of total transportation actions with helicopters.)	1	1	1	1	0.5	1	0.5	1	7
40	Vessel incidents	Firm or project level	Seyr 2016	Offshore wind	Incidents related to vessel transportation	Number of incidents happening during transportation with a vessel. (This includes worker and material transportation both to and from the wind farm and is given as a percentage oftotal (vessel) transportation actions.)	1	1	1	1	0.5	1	0.5	1	7
41	Transition piece incidents	Firm or project level	Seyr 2016	Offshore wind	Incidents related to work in the transition piece	Number of incidents during turbine access in the transition piece area (given as a percentage oftotal turbines accesses in the TP area).	1	1	1	1	0.5	1	0.5	0.5	6.5
42	Collisions internal	Firm or project level	Seyr 2016	Offshore wind	Incidents related to access to the turbine from a vessel	Number of vessel accesses complying with the safety procedure. (Measures the risk of vessels, part of the WF, colliding with the turbine structure or substation by measuring the number of vessel accesses complying with a procedure, like setting the vessel course not directly at the turbine, as percentage ofthe total accesses to the WF.)	0	1	0	0	0.5	0.5	0.5	0.5	3
43	Collisions external	Firm or project level	Seyr 2016	Offshore wind	Incidents related to violation of the wind farm safety zone	Number of safety zone violations. (The number of wind farm accesses per violation of the safety zone measures the risk ofan external vessel colliding with the turbine structure or substation.)	0.5	1	0.5	0.5	0.5	0.5	0.5	0.5	4.5
44	Boat landing structure (presence of a boat landing structure)	Firm or project level	Seyr 2016	Offshore wind	Presence of a boat landing structure	Presence of a boat landing structure	0.5	1	0.5	0.5	0.5	1	0.5	0.5	5
45	Wind	Firm or project level	Seyr 2016	Offshore wind	Incidents related to violation of wind speed rules	Number of vessel/helicopter operation in violation of wind speed thresholds (as a percentage of total number of operations).	0.5	1	0.5	0.5	0.5	0.5	0.5	0.5	4.5
46	Wave	Firm or project level	Seyr 2016	Offshore wind	Incidents related to violation of wave height limits	Number of vessel operations in violation of wave height restrictions (as a percentage of total number of vessel operations).	0.5	1	0.5	0.5	0.5	0.5	0.5	0.5	4.5
47	Seismic risk	Firm or project level	Seyr 2016	Offshore wind	Seismic risk indicator	Peak ground acceleration factor. (This is a factor of standard gravity g providing information about the risk of earthquakes. It can be obtained from seismic hazard maps.)	0.5	0.5	0.5	0.5	0	1	1	0.5	4.5
48	Maintenance work order (WO) with low manours	Firm or project level	Seyr 2016 referencing Utne 2012	Offshore oil & gas	Work orders with low manhour estimates (<1 hr)are thought to be an indication of poorly planned work	% Work orders with one or more operations containing man-hour estimations <1 hour	1	0.5	1	1	0.5	0.5	0.5	0.5	5.5
49	Maintenance WO location codes	Firm or project level	Seyr 2016 referencing Utne 2012	Offshore oil & gas	Work orders with known location code. Location is required to effectively complete the work	% of WO with location code	1	0.5	1	1	0.5	0.5	0.5	0.5	5.5
50	Maintenance WO material availability	Firm or project level	Seyr 2016 referencing Utne 2012	Offshore oil & gas	Work orders will all material available can be an indication of work planning	% of WO with material fully received in plant	1	0.5	1	1	0.5	0.5	0.5	0.5	5.5
51	Maintenance - WO short text	Firm or project level	Seyr 2016 referencing Utne 2012	Offshore oil & gas	Work orders with short text available, short text is important for work planning	Short text on WO operations exists	1	0.5	1	1	0.5	0.5	0.5	0.5	5.5
52	Maintenance	Firm or project level	Seyr 2016 referencing Utne 2012	Offshore oil & gas	Indicates if work requires a shutdown or not	% of WOs with work scope challenge (WSC) performed	1	0.5	1	1	0.5	0.5	0.5	0.5	5.5
53	Maintenance	Firm or project level	Seyr 2016 referencing Utne 2012	Offshore oil & gas	Indicates the number of WOs ready for completion in a shutdown	% of Work orders in WO stage	1	0.5	1	1	0.5	0.5	0.5	0.5	5.5
54	Maintenance	Firm or project level	Seyr 2016 referencing Utne 2012	Offshore oil & gas	Indicates the numer of WOs not released following a quality check	% of Work orders created or released	1	0	1	1	0.5	0.5	0.5	0.5	5
55	Maintenance	Firm or project level	Seyr 2016 referencing Utne 2012	Offshore oil & gas	Indication of the number of work orders being postponed	% of old Work Orders	1	0	1	1	0.5	0.5	0.5	0.5	5
56	Maintenance	Firm or project level	Seyr 2016 referencing Utne 2012	Offshore oil & gas	Indication of the type of work to be done, i.e preventative vs corrective maintenance	Number of Work Orders per order type	1	0	1	1	0.5	0.5	0.5	0.5	5
57	Maintenance	Firm or project level	Seyr 2016 referencing Utne 2012	Offshore oil & gas	Indication of how well shutdowns are being utilised	Number of Work Orders completed during unforeseen shutdown	1	0	1	1	0.5	0.5	0.5	0.5	5
59	Cost	Firm or project level	Seyr referencing Skogdalen 2011	Offshore oil & gas	Coparison of planned vs actual costs for a project	Comparison between planned and actual total costs	1	0.5	1	1	0.5	0.5	0.5	0.5	5.5
60	Cost	Firm or project level	Seyr referencing Skogdalen 2011	Offshore oil & gas	Comparison of planned vs total time used for a project	Comparison between planned and actual total time used	1	0.5	0.5	1	0.5	0	0.5	0.5	4.5
61	Maintenance	Firm or project level	Seyr referencing Skogdalen 2011	Offshore oil & gas	System maintenance response times	Time from first indication of subsystem failure to first response	0.5	0.5	0.5	0.5	0.5	0	0.5	0.5	3.5
62	Maintenance	Firm or project level	Seyr referencing Skogdalen 2011	Offshore oil & gas	System maintenance effectiveness	Evaluation of repair action/failure response action	0.5	0.5	0.5	0.5	0.5	0	0.5	0.5	3.5
63	Maintenance	Firm or project level	Seyr referencing Skogdalen 2011	Offshore oil & gas	System maintenance follow up effectiveness	Evaluation of follow up action	0.5	0.5	0.5	0.5	0.5	0	0.5	0.5	3.5
64	Maintenance	Firm or project level	Seyr referencing Skogdalen 2011	Offshore oil & gas	System maintenance performance times	Time before normal conditions are established	0.5	0.5	0.5	0.5	0.5	0	0.5	0.5	3.5
65	Fire detection	Firm or project level	PSAN 2020	Offshore oil & gas	Performance of fire detection system tests	Percentage of fire detection systems passing function tests	1	1	1	1	0.5	0.5	1	1	7
66	Fire protection systems	Firm or project level	PSAN 2020	Offshore oil & gas	Performance of fire protection system tests	Percentage of fire protection systems passing function tests	1	1	1	1	0.5	0.5	1	1	7
67	Watertight doors	Firm or project level	PSAN 2020	Offshore oil & gas	Performance of watertight door tests	Percentage of watertight doors passing function test (for floating structures)	1	1	1	1	0.5	0.5	1	1	7
68	Ballast sytem function	Firm or project level	PSAN 2020	Offshore oil & gas	Performance of ballast system tests	Percentage of ballast systems passing function test (for floating structures)	1	1	1	1	0.5	0.5	1	1	7

Appendix C

Interview guides

Interview guide:

Mapping of the safety control structure of the UK offshore wind industry

Background:

- 5 to 10 minute presentation on the STAMP methodology to make sure interviewees understand the processes being used.

Introductory questions:

1) How long have you been involved in the offshore wind industry?
2) How did you get started in the industry?

Initial orientation question:

Please review this control structure showing the organisation of the UK offshore wind industry safety control structures.

1) Where does your position fit in this structure?
2) What interactions do you have across participants in the system?
3) How do you describe the role you play in safety during the development or operation of the offshore wind industry?
4) How does the culture in the organisation / industry impact safety based decisions?

Structure / model analysis question:

5) Is the chart accurate?
6) How would you change it?

Further questions:

1) What do you think are the biggest safety risks in the OWI today?
2) Please review the list of responsibilities associated with ensuring the safe development and operation of a safe offshore wind industry. If you were to design the system, how would you distribute the responsibilities?
3) What do you think are the most important factors that affect safety in the development of the offshore wind industry?
    a. Can you characterise or discuss the relationship between these factors and safety?

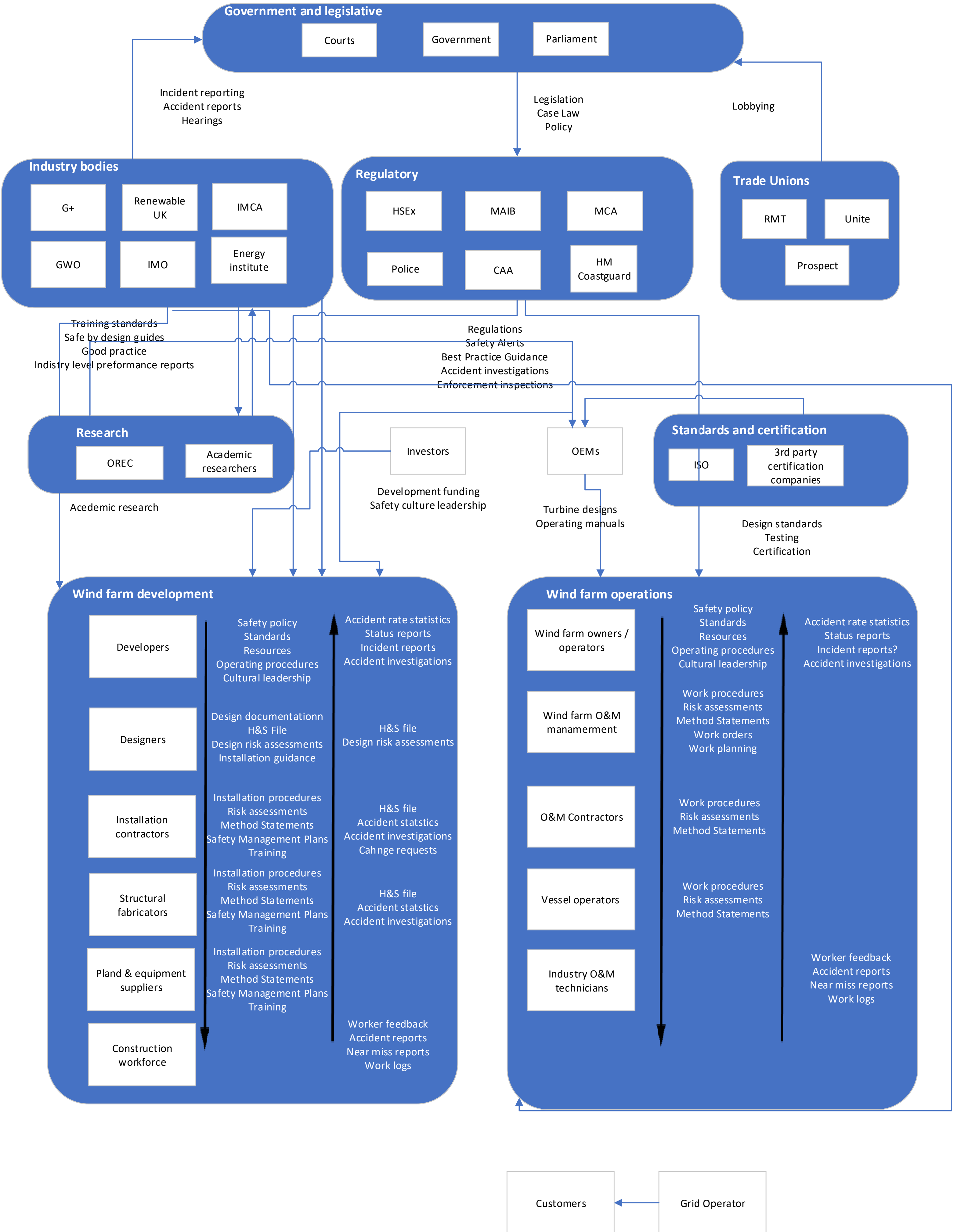
Closing question:

1) Are there any other things you would like to tell us that we did not discuss so far?

Thank you very much for your help.

UK Offshore windfarm industry - operational safety control structure

System Goal: to safely generate electricity and distribute reliably to the UK grid



Appendix D

Gap analysis outputs

GAP-ID	FR-ID	Functional Requirement	Control Structure Component(s)	Weakness identified
GID-1	FR-1	Implement safety into the design of the system	Developers, Designers, OEMs, Standards organisations, Design risk specialists	Implementation of CDM regulations can become a box ticking exercise, not always well understood in the industry.
GID-2	FR-1	Implement safety into the design of the system	Developers, Designers, OEMs, Standards organisations, Design risk specialists	Poorly implemented CDM can lead to lack of design coordination between parties
GID-3	FR-1	Implement safety into the design of the system	Developers, Designers, OEMs, Standards organisations, Design risk specialists	In less mature organisations technical safety, or safe by design processes are not always set up or well implemented. i.e design risk assessments tend to be very general and don't deal with specific risks.
GID-4	FR-1	Implement best practices	Developers, Designers, OEMs, Standards organisations, Design risk specialists, Operators, Contractors	O&M activities are hight standardised and use the WTSR, this can lead to complacency as rather than consider the specific risks, RAMS are taken straight from a folder.
GID-5	FR-2	Implement best practices	Developers, Designers, OEMs, Standards organisations, Design risk specialists, Operators, Contractors	Industry has been reluctant at times to learn from oil & gas and has developed its own procedures.
GID-6	FR-2	Implement best practices	Developers, Designers, OEMs, Standards organisations, Design risk specialists, Operators, Contractors	Very little guidance on how to implement safe by design, not well understood in the industry.
GID-7	FR-3	Audit and measure performance	HSEx, G+, Developers, Owners, Operators, Contractors	Reliance on TRIR and LTIR limit ability to learn from accident data.
GID-8	FR-3	Audit and measure performance	HSEx, G+, Developers, Owners, Operators, Contractors	Lack of industry recognised leading indicators of safety and risk.
GID-9	FR-3	Audit and measure performance	HSEx, G+, Developers, Owners, Operators, Contractors	HSEx data does not recognise the offshore wind industry as a sector for reporting so specific data is not available.
GID-10	FR-3	Audit and measure performance	HSEx, G+, Developers, Owners, Operators, Contractors	Lack of HSE inspection resources limits ability to monitor industry performance.
GID-11	FR-3	Audit and measure performance	HSEx, G+, Developers, Owners, Operators, Contractors	Shortages of qualified safety inspectors in offshore wind create a challenge to monitor and audit performance.
GID-12	FR-4	Investigate all incidents	HSEx	Lack of HSE inspection resources could limit the ability to investigate incidents
GID-13	FR-4	Investigate all incidents	HSEx	Shortages of qualified safety inspectors in offshore wind create a challenge to investigate incidents.
GID-14	FR-5	Define clear roles and responsibilities	Parliament, HSEx, Developers, Operators, G+, GWO, Standards agencies	Unions have raised concern over lack of clarity on the application of legislation to offshore wind.
GID-15	FR-5	Define clear roles and responsibilities	Parliament, HSEx, Developers, Operators, G+, GWO, Standards agencies	There is no specific industry legislation for the UK. ISO standards are applied but are not mandated, this can lead to inconsistency of implementation. For example, oil & gas industry has The Offshore Installations (Prevention of Fire and Explosion, and Emergency Response) Regulations 1995.
GID-16	FR-5	Define clear roles and responsibilities	Parliament, HSEx, Developers, Operators, G+, GWO, Standards agencies	There has been confusion or disagreement over the interface of the OFTO sites and who has primacy over those sites.
GID-17	FR-5	Define clear roles and responsibilities	Parliament, HSEx, Developers, Operators, G+, GWO, Standards agencies	Offshore oil & gas regulations are very clear over who has primacy over a site in an emergency, this will usually be an offshore installation manager. In offshore wind these responsbilities are less clear.
GID-18	FR-5	Define clear roles and responsibilities	Parliament, HSEx, Developers, Operators, G+, GWO, Standards agencies	UK regulation applied within UK territorial waters, within 12 nautical miles. Beyond that limit in the case of an accident then it can be complicated to understand who has jurisdiction for any investigation. For example, a heavy lift crane could be registered in an overseas jurisdiction and their authorities would have responsibility for investigations.
GID-19	FR-5	Define clear roles and responsibilities	Parliament, HSEx, Developers, Operators, G+, GWO, Standards agencies	UK legislation on emergency response is very weak, the industry is often ahead of the legislation. UK oil & gas industry has specific legal requirements which are missing from offshore wind.
GID-20	FR-5	Define clear roles and responsibilities	Parliament, HSEx, Developers, Operators, G+, GWO, Standards agencies	There has been confusion over the application of CDM to the industry for O&M activities.
GID-21	FR-5	Define clear roles and responsibilities	Parliament, HSEx, Developers, Operators, G+, GWO, Standards agencies	Offshore wind lacks an independent review of legal compliance as is found on offshore oil & gas, this means the industry is essentially self regulating. There is no verfiication step which could lead to inconsistency of standards as the industry grows.
GID-22	FR-5	Define clear roles and responsibilities	Parliament, HSEx, Developers, Operators, G+, GWO, Standards agencies	The AOGBO applied all onshore legislation to the offshore renewable energy zone, this was done without consideration for the suitability. This means there is less regulatory efficiency and can cause further confusion.
GID-23	FR-5	Define clear roles and responsibilities	Parliament, HSEx, Developers, Operators, G+, GWO, Standards agencies	The offshore wind workforce is very transient, workers are often on short term contracts. This increases the difficulty with implementation of standards.
GID-24	FR-6	Develop robust emergency plans	Developers, Operators, Contractors, MCA, HSEx, Parliament	The MCA reviews emergency response plans (ERCOP) as part of the marine licensing process, however there is no formal requirement for the MCAs requirements to be implemented. While the informal process currently works it could fail in the future.
GID-25	FR-6	Develop robust emergency plans	Developers, Operators, Contractors, MCA, HSEx, Parliament	The HSE and MCA published an regulators expectations for emergency response document. This is guidance but not a requirements as it would be in the oil & gas industry.
GID-26	FR-6	Develop robust emergency plans	Developers, Operators, Contractors, MCA, HSEx, Parliament	There are no rules for performance standards on emergency response times. These can be found in other jurisdictions such as Germany.
GID-27	FR-7	Foster cross industry safety collaboration and communication	Developers, Operators, Contractors, G+, HSEx	G+ are the leaders in cross industry collaboration and run collaoration initiatives throughout the year.
GID-28	FR-8		Developers, Operators, Contractors	No immediate gaps identified.
GID-29	FR-9	Provide safe and healthy working conditions	Developers, Operators, Contractors	No immediate gaps identified.
GID-30	FR-10	Eliminate or reduce safety risks to ALARP	Installation contractors, O&M contractors, Designers, OEMs	O&M activities are highly standardised and use the WTSR, this can lead to complacency as rather than consider the specific risks, RAMS are sometimes taken straight from a folder.
GID-31	FR-10	Eliminate or reduce safety risks to ALARP	Installation contractors, O&M contractors, Designers, OEMs	Design elements are spread across the supply chain and not necessarily fully coordinated, this can depend on the sophistication of the Client or Developer and the implementation of CDM. O&M may not be involved in the system design.
GID-32	FR-11	Communicate and consult with workers	Workforce	Legislation does not require workforce consultation as is required by Safety case regulations in oil & gas industry, although this does happen depending on the organisation.
GID-33	FR-12	Comply with legal requirements	Developers, Operators, Contractors	Lack of industry specific legislation can make compliance with legal requirements more complicated.
GID-34	FR-13	Foster a culture of continuous improvement	Developers, Operators, Contractors	Continuous improvement requires accurate performance feedback. Industry reliance on lagging data and indicators with low statistical validity can hamper feedback.

Appendix E

STPA analysis outputs

System technical constraints

System Constraint ID	System Constraint	System hazard ID	Description
[SC-1]	Equipment design must minimise risk of uncontrolled equipment or materials contact with people	[SH-1]	- Design that prevents contact with rotating equipment in the nacelle - Preventing contact with live electrical equipment - Design that allows for safe movement of tools and materials and people around, and on and off the wind turbine structure, reducing risk of harm to workers, and minimising manual handling
[SC-2]	Infrastructure design must allow for evacuation of emergency medical cases within time standards	[SH-2]	- Infrastructure must be in place for the industry to ensure emergency response capabilities
[SC-3]	System design must allow for evacuation of emergency medical cases within time standards	[SH-2]	- Evacuation of personnel should be designed in to the turbine and wind farm as a whole
[SC-4]	System design must incorporate standards for prevention of persons overboard	[SH-3]	- System design should allow for safe transfers minimising the risk of persons over board
[SC-5]	System design must eliminate or reduce exposures of people to falls from height	[SH-4]	- System design should minimise exposure to falls and limit reliance on personal fall protection to prevent falls.
[SC-6]	System design to maintain minimum standards for fire protection	[SH-5]	- Fire protection to be considered in all aspects of the design and materials selection
[SC-7]	System design to allow for protection or evacuation of persons in case of fire	[SH-5]	- System design should allow for evacuation in the event of a fire within minimum time standards
[SC-8]	System design to protect persons stranded on turbine in worst case conditions	[SH-6]	- Operations planning should minimise risk of persons stranded on turbine - Turbine design should consider potential for persons stranded on turbine
[SC-9]	System design should prevent uncontrolled contact between ships, aircraft and turbines or other wind farm structures	[SH-7]	- Design should consider potential for vessel or aircraft strikes

Functional requirement ID	Functional requirement
FR-1	Implement safety into the design of the system
FR-2	Implement best practices
FR-3	Audit and measure performance
FR-4	Investigate all incidents
FR-5	Define clear roles and responsibilities
FR-6	Develop robust emergency plans
FR-7	Foster cross industry safety collaboration and communication
FR-8	Promote a positive safety culture
FR-9	Provide safe and healthy working conditions
FR-10	Eliminate or reduce safety risks to ALARP
FR-11	Communicate and consult with workers
FR-12	Comply with legal requirements
FR-13	Foster a culture of continuous improvement

System Control Sructure Details

ID	Controller Group	Sub-element	Controller responsibilities	Controller actions	Feedback mechanisms	Description	Notes / references
C-1.1	Legislative bodies	Parliament / MPs	Voting and debating legislation related to health and safety Debates on industry issues Raising questions to Ministers Receiving feedback via lobbying from industry or unions Raising questions in Parliament over specific concerns	Debating and voting on legislation Questioning responsible ministers	Media reporting Union lobbying Industry lobbying Working groups	Parliament contains two houses then House of Commons and the House of Lords. The House of commons consists of elected Members of Parliament (MPs). MPs represent constituents by voting on bills (draft acts of legislation)	
C-1.2	Legislative bodies	Government	Setting of policy and providing funding in support of the Industry Setting funding for HSEx	Proposing legislation to Parliament Setting policy	Parliamentary questions Media reporting Union lobbying Industry lobbying	The UK has two main governments, the Westminster government and the Scottish government. Government is led by the Prime Minister who appoints Ministers to lead departments.	Scottish government has a Director of Offshore wind responsible for development of policy
C-1.3	Legislative bodies	Courts	Prosecution of cases under legislation in case of breaches Setting of case law to enforce standards	Issuing judgements (case law)	Cases raised by HSEx for prosecution		Case heard in Hansard
C-1.4	Government	Offshore wind investment organisation	Promote international investment in the UK supply chain Develop local supply chain strategies	Engagement with developers			
C-1.5	Government	Department for Energy Security and Net Zero	Ensure UK energy supply security Ensure UK meets net zero commitments Develop policy and propose bills	Issuing policy documents	Parliamentary questions Media reporting Union lobbying Industry lobbying HSE direct communications on regulation		
C-1.6	Offshore wind safety working group	Offshore wind safety working group	Interface between Parliament and Industry Facilitate collaboration of H&S with a focus on legislation	Interface meetings	Direct communication from Unions, HSEx, OEUK, MCA and MAIB	The Parliamentary Offshore Wind Safety Working group was established in 2023 following a debate in Parliament which raised concerns about confusion of the H&S legislation in the sector.	
C-1.7	Procurement	The Crown Estate	Manging the procurement for seabed leases of offshore wind farms	Issuing renewable energy licenses Setting HSE requirements in the procurement process Setting HSE policy for offshore wind procurement	Stakeholder engagement PQQ and ITT submittals during tender process	The crown estate is an independent business which owns and manages land for the benefit of the UK. Source: https://www.thecrownestate.co.uk/	PQQ (Pre qualification questionnaire)requires - HSE Policies, HSE enforcement actions (any offshore breaches) ITT requires - HSE management
C-1.8	Industry bodies	G+	Collating industry accident statistics and reporting Reprint safety alerts Leading and coordinating collaborative safety initiatives Publishing best practice guidance Publishing industry safety performance reports Publishing safe by design guides	Issuing of industry guidance documents. Key documents include: IOER Integrated offshore emergency response document Wind Turbine Safety Rules	Stakeholder meetings Incident reporting from industry Industry working groups	G+ is a an organisation run by industry collaboration to develop improvements in offshore wind health and safety. Its four main workstreams are incident data reporting, good practice guidance, safe by design workshops and learning from incidents.	
C-1.9	Industry bodies	Renewable UK	Historical involvement in development of wind turbine safety rules	n/a	n/a	Safety functions of Renewable UK are now with G+	
C-1.10	Industry bodies	IMCA (International Marine Contractors Association)	Publishing marine contractor accident statistics Publishing safety alerts	Collaboration with other industry organisations Issue of technical and operational guidance documents	Safety alerts Incident reporting from members	IMCA are a trade association that represent marine contractors and other parts of the marine construction supply chain.	https://www.imca-int.com/
C-1.11	Industry bodies	Energy Institute	Provides the secretariat for G+	Issuing of industry guidance documents together with G+	Reporting through G+		
C-1.12	Industry bodies	International Maritime Organisation	International maritime legal treaties	Issue of international conventions		The IMO is an agency of the United Nations. They are responsible for measures to improve safety and security of shipping.	https://www.imo.org/en
C-1.13	Industry bodies	Global Wind Organisation	Developing and issuing training standards	Issue of training standards Publishing training data	Industry incident data Engagement with industry	GWO is a non profit industry organisation founded and owned by manufacturers, owners and operators throughout the industry.	https://www.globalwindsafety.org/
C-1.14	Industry bodies	OEUK	Offshore energy UK	Attendance at forums and working groups	Engagement with industry	OEUK are an offshore energy industry organisation which represents industry members across the UK energy industry.	https://oeuk.org.uk/
C-1.15	OREEF	Offshore renewable energies forum	Stakeholder engagement with private and public sector on emergency response Coordination of initiatives on emergency response Coordinating in development of guidance documents for emergency response.	Committee meetings Developing guidance for industry Integrated Offshore Emergency Reponse guidelines	OREEF Committee meetings Working group meetings	OREEF is made up of representatives from industry and to coordinate on the improvement of emergency response in the offshore wind industry. OREEF is also attended by members or HSEx and HMC.	
C-1.16	Regulatory	HSEx	Enforcement of legislation (issuing notices, guidance on improvements, prohibition notices, prosecution of serious cases) Publication of guidance and expectations documents Incident investigation on offshore energy structures Incident investigation within 12 nautical miles Receiving and reporting accident data under RIDDOR Liaising with industry and unions through roundtables and forums	Improvement orders Enforcement orders Offshore site inspections Attendance at OREEF Emergency response performance standards guidance	Review of ERCOPs Attendance at OREEF Feedback to Department of Energy Attendance at working group meetings Testing and exercise outcomes	The HSEx is Britain's national regulator for workplace Health and Safety.	HASWA 1974 and Merchant Shipping regulations interface (Offshore marine Health and Safety Guidelines) A.1.1.5 https://www.hse.gov.uk/aboutus/our-mission-and-priorities.htm
C-1.17	Regulatory	MAIB (Marine Accident Investigation Branch)	Marine accident investigations within UK territorial waters or UK flagged vessels Issuing safety bulletins	Accident investigation reports		The MAIB investigate marine accidents in UK waters but do not have enforcement powers.	The MAIB is not a regulator and does not have enforcement powers. MAIB / MCA / HSEX have a memorandum of understanding to clarify the interface of their responsibilities.
C-1.18	Regulatory	MCA (Maritime and Coastguard Agency)	Enforcing merchant shipping regulations within UK territorial waters or UK flagged vessels Vessel inspections Review of wind farm developments at consents stage Review of navigational safety risk assessments	Vessel inspections Review of ERCOPs at planning stage	Input to ERCOP process	The MCA is a government agency coming under the jurisdiction of the Department of Transport.	
C-1.19	Regulatory	Police	Police Scotland Energy Industry Liaison Unit (EILU) - assisting in emergency response Incident investigation for fatal or life threatening injuries Investigation of sudden death Testing & exercising Stakeholder engagement - MCA & Operators	Review of ERCOPs prior to Marine License Criminal investigations	Review of ERCOP via MCA	Police Scotland operate an energy industry liaison unit with a responsibility to engage on offshore emergency preparedness.	
C-1.20	Regulatory	CAA Civil Aviation Authority	Regulation of aviation safety			The CAA regulate aviation activities in the UK, this would include helicopter activities associated with wind farm installation and operations.	
C-1.21	Regulatory	HM Coastguard	Coordination of maritime search and rescue operations Search and rescue Participation in testing and exercise regimes Review of emergency response plans (ERCoP) at consents stage	Review of ERCOPs prior to Marine License Emergency response expectations documents Assistance and coordination in emergency response events	Attendance at OREEF Review of ERCOPS Input to G+ Emergency response guidance and OREEF	His Majesty's Coastguard is part of the Maritime and Coastguard Agency. HMC has two parts, Maritime including coordination centres, national rescue team and coastal section. Secondly the policy governance team.	
C-1.22	Regulatory	AAIB (Air accidents investigation Branch)	Accident investigation for aviation accidents	Air accident investigation reports		AAIB are part of the Department of Transport	https://www.gov.uk/government/organisations/air-accidents-investigation-branch

ID	Controller Group	Sub-element	Controller responsibilities	Controller actions	Feedback mechanisms	Description	Notes / references
C-1.23	Trade Unions	RMT, Unite, Prospect etc.	Lobbying for workers interests, improving working conditions and safety issues	Lobbying to industry and government Engagement with G+	Workforce engagement Working groups	Trade Unions such as the RMT represent offshore workers in the industry and are having a growing influence on the safety discussion in the industry.	
C-1.24	Standards	IEC, DNV, ISO,	Issue standards for offshore wind including design and operational standards Certification of designs, testing and inspection	Issue design standards (IEC 61400-3-1:2019 Design requirements for fixed offshore wind turbines)		Bodies such as IEC and DNV issue standards for the offshore wind industry. IEC are the recognised main standards body for the industry.	Ref: Floating Offshore Wind - Application of Standards, Regulations, Project Certification and Classification - Risks and Opportunities, Ramboll, 2021
C-1.25	Certification	DNV, Lloyds, BV etc	Certification of offshore wind design and installation to recognised standards	Issue of project certification	Codes and standards	Project certification is not required as standard in the UK market, but may be required for funding or insurance requirements.	
C-1.26	Research	OREC, Universities, G+	Original research and reports to improve standards and safety in the industry Developing industry best practices and guidance documents	Issue of research papers Issue of guidance documents i.e. WTSR	Engagement with industry	and research centre for the offshore renewable energy sector. Universities also engage in academic research for the offshore wind sector. G+ have issued safe by design guides, emergency response guidance and the Wind Turbine Safety Rules.	https://ore.catapult.org.uk/
C-1.27	Financial	Investors	Provide funding to projects Selection of developers Reviewing safety performance of the industry Cultural leadership	Setting project requirements Cultural leadership	Project incident reporting	Investors such as banks and pension funds can influence technical decision making and procurement strategies which influence safety. Investors will be sensitive to project operational risk.	
C-1.28	Wind Farm Development	Developers	Project development Setting project budget Managing safety performance of suppliers Reporting safety performance Corporate safety policies Cultural leadership Standards Pre construction information Development of emergency reponse capability Coordination of emergency response Oversee technical safety process	Supervision of project design Managing project budget Interface with stakeholders Supervision of contractor Choice of procurement strategy Cultural leadership Setting H&S policies Setting safety standards Issue of Emergency response cooperation plan Development of emergency response plan Issue risk management plans Manage CDM processes	ERCOP to HMC Attendance at OREEF meetings (Optional)	Wind farm developers play a key role in safety leadership. They may act as a client only or may also be the principle designer depending on their expertise and procurement strategy.	
	Wind Farm Development	Original Equipment Manufacturers (OEMs)	Design documentation Installation procedures Operations and maintenance manuals	Design documentation Installation procedures Operations and maintenance manuals		OEMS such as Vestas or GE design and manufacture the main turbine equipment found in the rotor nacelle assembly (RNA)	
C-8.2	Wind Farm Development	Designers	Design documentation H&S File (under CDM) Design risk assessments Collision studies Emergency response assessments Installation guidance Fulfil CDM duties as Principal Designer Implement technical safety processes	Design approvals Issue of design documentation Issue of design risk documentation, H&S file etc Manage CDM processes	Contractor feedback Operations feedback	Wind farm designers will execute the design on behalf of a Client. CDM regulations set specific roles and responsibilities for designers.	
C-8.3	Wind farm development	Design risk specialists	Management of CDM process Principle designer Implement technical safety design processes	Implementation of technical design safety process Development of H&S file Issue of technical documentation i.e. HAZOP, HAZID	Contractor feedback Operations feedback Designer feedback	Design risk specialists are commonly engaged to perform risk assessments such as HAZOP, HAZID or Fire risk assessments and also to help Clients manage their responsibilities under the CDM regulations.	
C-8.4	Wind Farm Development	Principal contractors	Manage the safe installation and commissioning of the wind farm Supervising workforce and subcontractors Coordinating emergency response in the case of an accident Worker recruitment and training Interface management Stakeholder management	Issue construction phase plans Issue of construction documentation i.e. risk assessments, method statements Supervision of subcontractors Supervision of workforce Workforce training Work procedures Safety toolbox talks Workforce inductions Approval of subcontractor RAMS and work authorisations	Incident reporting Audit reports Safety flashes Informal safety messaging i.e. WhatsApp groups Incident reports Safety tour reports	An installation contractor will be engaged by the developer for installation of the wind farm infrastructure. CDM regulations set out specific roles and responsibilities for the Principal Contractor. The installation contractor will also likely have a number of subcontractors working for them and will have to engage with the OEM for wind turbine installation.	
C-8.5	Wind Farm Development	Structural fabricators	H&S Plans Installation procedures Risk assessments Method Statements Workforce training	Issue of construction documentation i.e. risk assessments, method statements Supervision of subcontractors	Incident reporting Audit reports Safety flashes Incident reports Safety tour reports	Structural fabricators design and fabricate structural equipment for the industry such as jackets, towers and foundations.	
C-8.6	Wind Farm Development	Plant & equipment suppliers	H&S Plans Installation procedures Risk assessments Method Statements Workforce training	Issue of installation procedures Issue of operations and maintenance documentation Issue of safety alerts	Incident reporting Audit reports Safety flashes Incident reports Safety tour reports	Plant and equipment suppliers supply developers with plant for the wind farm installation.	
C-8.7	Wind Farm Development	Construction workforce	Worker feedback Accident reporting Near miss reporting Work logs Following and implementing safe systems of work Complying with site procedures	Supervision of peer activities Identification of hazards	Feedback to Unions Feedback to Supervisors Incident reporting Near miss reporting Involvement in design feedback or workshops	The construction workforce is made up of mechanical, structural, electrical and lifting technicians and specialists who will be engaged by the installation contractor directly, or through subcontractors.	
C-9.1	Wind farm operations	Wind farm owners	Setting H&S Policy Cultural leadership	Safety policy Standards Resources Operating procedures Cultural leadership	Corporate Incident statistic reporting	Wind farm owners may be made up of several investors including operators, banks and investment funds.	

ID	Controller Group	Sub-element	Controller responsibilities	Controller actions	Feedback mechanisms	Description	Notes / references
C-9.2	Wind farm operations	Wind farm operators	Setting H&S Policy Cultural leadership Development of emergency reponse capability Coordination of emergency response	Safety policy Standards Resources Operating procedures Cultural leadership Issue risk management plans Issue of Emergency response cooperation plan Issue of emergency response plan	Corporate Incident statistic reporting	Wind farm operations are responsible for the day to day operation of the wind farm.	
C-9.3	Wind farm operations	Wind farm O&M management	Setting H&S Policy Cultural leadership	Work procedures Risk assessments Method Statements Work orders Work planning	Incident reporting Near miss reporting Accident reports Audit reports Safety tour reports	O&M management is typically done by the OEM for the first five years of a wind farm.	
C-9.4	Wind farm operations	O&M contractors	Setting H&S Policy Cultural leadership Subcontractor management Workforce recruitment and training	Work procedures Risk assessments Method Statements Worker selection Worker training	Incident reporting Near miss reporting Accident reports Audit reports Safety tour reports	O&M contractors may be employed for specialist O&M activities.	
C-9.5	Wind farm operations	O&M subcontractors	Managing workforce	Work procedures Risk assessments Method Statements	Incident reporting Near miss reporting Accident reports Audit reports Safety tour reports	O&M contractors may be employed for specialist O&M activities.	
C-9.6	Wind farm operations	Vessel operators	Vessel management Crew and material transfer activities	Mission planning Workforce supervision	Incident reporting Near miss reporting Accident reports Audit reports Safety tour reports	Vessel operators will supply vessels such as SOVs and CTVs to the industry to transport personnel and materials to the offshore wind farm.	
C-9.7	Wind farm operations	Industry O&M technician workforce	Implementing safe work methods Peer supervision Hazard identification	N/A	Worker feedback Accident reporting Near miss reporting Work logs	The O&M workforces is made up of specialist technicians qualified to carry out mechanical, electrical and structural maintenance and repairs.	

Unsafe Control Actions

UCA-ID	Control structure group	Controller	Control action	Does Not Provide	Provides	Too early, late or our of order	Stopped too soon, applied too long	Comment (further explanation on the UCA, if required)	Related Hazard ID	Controller constraints
UCA-1	Government and legislative	Parliament	Issue or amend safety legislation	Parliament does not provide legislation sufficient to enforce minimum standards in the OWI [H1-6]	n/a				OH-3	Parliament must provide sufficient legislation to enforce minimum standards in the OWI.
UCA-2	Government and legislative	Parliament	Issue or amend safety legislation	-	n/a	Parliament provides legislation too late to enforce minimum standards in the OWI [H1-6]	-		OH-3	Parliament must provide legislation in a timely manner to enforce minimum standards in the OWI.
UCA-3	Government and legislative	Parliament	Issue or amend safety legislation	-	Parliament provides too much legislation for the industry to be able to implement or manage.		-		OH-3	Parliament must not provide too much legislation to enforce minimum standards in the OWI.
UCA-4	Government and legislative	Government / Department for Energy Security and Net Zero	Set policy for industry development		Government policy sets targets too aggressive to be safely delivered.				OH-2	Safe development rates and simply chain capacity should be considered in policy setting.
UCA-5	Government and legislative	Parliament	Industry working group engagement	Parliament does not engage with industry		Parliament engages with industry too late		A Parliamentary working group was implemented to engage with industry, unions and regulators to address safety issues.	OH-3	Working group to be expanded to include attendance by Parliamentary representative.
UCA-6	Funding	Government	Funding of regulators	Government does not provide sufficient funding for regulators to supervise industry.	-	-	-	HSEx are the key regulator for the OWI, funding will be dependent on government policy.	OH-3	Government must adequately fund regulators to manage the industry.
UCA-7	Funding	Government	Funding of regulators	-	-	Government provides funding too late for regulators to supervise industry.	-		OH-3	Government must adequately fund regulators to manage the industry.
UCA-8	Funding	Government	Funding of regulators	-	-	-	Government stops funding for regulators to supervise industry.		OH-3	Government must adequately fund regulators to manage the industry.
UCA-9	Regulatory	HSEx / Parliament	Issue safety regulations / guidance	Safety regulations are not provided for the industry sufficiently to enforce required standards, or cover all hazards. [SH1-6]				The HSC (Health and Safety Commission) are responsible for developing new regulations, and the HSE can issue guidance or codes of practice to supplement regulation.	OH-3	Oversight of the quantity and completeness of regulation for the industry is required to ensure it is fit for purpose. Review of funding requirements and resources for HSEx as the indistry grows is also required.
UCA-10	Regulatory	HSEx / Parliament	Issue safety regulations / guidance		Regulators issue too much regulation for the industry to be able to implement or manage . [SH1-6]			The HSC (Health and Safety Commission) are responsible for developing new regulations, and the HSE can issue guidance or codes of practice to supplement regulation.	OH-3	Oversight of the quantity and completeness of regulation for the industry is required to ensure it is fit for purpose. Review of funding requirements and resources for HSEx as the indistry grows is also required.
UCA-11	Regulatory	HSEx / Parliament	Issue safety regulations / guidance			Regulators issue regulation too late to enforce standards or manage hazards. [SH1-6]		The HSC (Health and Safety Commission) are responsible for developing new regulations, and the HSE can issue guidance or codes of practice to supplement regulation.	OH-3	Oversight of the quantity and completeness of regulation for the industry is required to ensure it is fit for purpose. Review of funding requirements and resources for HSEx as the indistry grows is also required.
UCA-12	Regulatory	HSEx	Enforcement inspections	Regulators do not provide sufficient enforcement inspections to enforce required standards.		Regulators provide enforcement inspections too late to enforce required standards.		HSEx are responsible for enforcement inspections of the OWI.	OH-3	Regulator funding should keep pace with industry growth and inspector numbers should be in line with industry size.
UCA-13	Regulatory	HSEx	Accident investigations	Regulators do not investigate accidents associated with the industry [OH-3]				Issues over jurisdiction gaps in the legislation may mean that regulators do not investigate all incidents involved in the industry.	OH-3	Legislative gaps to be closed by review and update of legislation.
UCA-14	Regulatory	HSEx	Accident investigations			Regulators do not investigate accidents in a timely manner [OH-3]		Issues over jurisdiction gaps in the legislation may mean that regulators do not investigate all incidents involved in the industry.	OH-3	Legislative gaps to be closed by review and update of legislation.
UCA-15	Industry bodies	G+, GWO etc	Safe by design guides	Industry bodies do not share safe by design guides				Lack of safe by design implementation within the industry leads to additional hazards for the workforce operating within the wind farm leading to losses.	OH-1	Development of industry specific guidance or standards for safe by design and implementation of human factors into design. Review and update of CDM guidance for the industry. Review and issue of indistry specific legislation either amending CDM or replacing with a "safety case light" approach.
UCA-16	Industry bodies	G+, GWO etc	Safe by design guides			Industry bodies share safe by design guides too late		Lack of safe by design implementation within the industry leads to additional hazards for the workforce operating within the wind farm leading to losses.	OH-1	
UCA-17	Industry bodies	G+, GWO etc	Safe by design guides				Industry bodies share safe by design guides stopped too soon	Lack of safe by design implementation within the industry leads to additional hazards for the workforce operating within the wind farm leading to losses.	OH-2	
UCA-18	Industry bodies	G+, GWO etc	Training standards / training delivery	Industry bodies do not issue adequate training standards				Industry not issuing training standards leads to inconsistent training implementation across the industry leading to losses	OH-2	
UCA-19	Industry bodies	G+, GWO etc	Training standards / training delivery			Industry bodies issue training standards too late		Industry not issuing training standards in time to keep up with requirements leads to inconsistent training implementation across the industry leading to losses	OH-2	
UCA-20	Investors	Investors	Provide safety culture leadership	Investors do not provide safety culture leadership, or require safety standards		Investors provide safety leadership, or sets standards too late.	Investors stop setting safety culture and standards.	Investors failing to provide the right safety cultural leadership to incentivise safety leads to losses.	OH-2	
UCA-21	Design	OEM	Provide turbine designs	OEMs do not provide turbine designs adequate for safe installation or maintenance.				OEMs have a key role in ensuring turbine designs are designed in a way they can be safely installed and maintained.	OH-1	
UCA-22	Standards and certification	Standards bodies	Issue design standards		Too many or conflicting design standards			Too many or conflicting design standards could create confusion.	OH-1	
UCA-23	Emergency response	MCA	Review of Emergency Response Cooperation Plan	MCA does not review ERCOP				Crown estate requires MCA to review the ERCoP as part of the site licensing requirements.		Emergency response plan periodic review and approval and ErCoP review and approval should become a statutory requirement.
UCA-24	Emergency response	MCA	Review of Emergency Response Cooperation Plan			MCA reviews ERCOP too late				
UCA-25	Emergency response	OREEF / HMC / Operators	Emergency response testing and exercises	Emergency response testing and exercise does not take place		Emergency response testing and exercise takes place too late				
UCA-26	Emergency response	HMC / RNLI / Operators	Provision of emergency response resources	HMC or Operators do not provide SAR resources		HMC or Operators provides resources too late		Operators are required to have the capability for self rescue, however in the case of a major incident HMC can be called upon for assistance in search and rescue.		
UCA-27	Developers / Operators	Developers / Operators	Provision and update of ErCoP	ERCoP is not provided or update		ERCoP is provided or updated too late		ERCoP - emergency response cooperation plan provides information to ensure the emergency response can be coordinated with the MCA and other parties. MCA provide guidance on the ERCoP requirements.		
UCA-28	Developers / Operators	Developers / Operators	Provision and update of emergency response plan	Developers / operators do not provide or do not update an emergency response plan		Developers / operators provide an emergency response plan too late		Emergency response plans are required under UK H&S legislation although the UK does not have specific emergency response legislation for the offshore wind sector. It does publish an expectations document.		
UCA-29	Developers / Operators	Developers / Operators	Provision of emergency response resources	Developers / operators do not provide an emergency response resources		Developers / operators provide emergency response resources too late		Emergency response plans are required under UK H&S legislation although the UK does not have specific emergency response legislation for the offshore wind sector. It does publish an expectations document.		
UCA-30	Developers / Operators	Developers / Operators	Management of emergency response	Developers or operators do not coordinate emergency response		Developers or operators coordinate emergency response too late		The developer or operator should have a duty holder responsible for management of the site to coordinate emergency response.		
UCA-31	Developers / Operators	Developers / Operators	Setting H&S standards	Developers / Operators do not provide suitable standards for medical fitness		Developers / Operators standards for medical fitness too late		Health or fitness screening can play an important part in technician recruitment as offshore wind work can be physically demanding.		
UCA-32	Developers	Developers	Coordination with stakeholders	Developer does not provide adequate interface with stakeholders		Developer interfaces with stakeholders too late				
UCA-33	Industry bodies / Regulators	G+, HSEx, IMCA	Issue of safety alerts	Safety alerts are not issued		Safety alerts are issued too late				
UCA-34	Developers / Operators	Developers / Operators	Worker recruitment and training	Developers / operators do not provide adequate worker recruitment and training		Developers / operators provide adequate worker recruitment and training too late				
UCA-35	Development	Developers / Designers	Manage CDM processes	Developers / designers do not manage CDM process		Developers / designers manage CDM process too late				
UCA-36	Development	Developers / Designers	Implement technical safety process	Developers designers do not implement technical safety process		Developers / designers implement technical safety process too late				
UCA-37	Developers	Developers	Managing project budget	Developer does not provide project budget for safety		Developer provides project budget for safety too late				

Bibliography

[1] Global Wind Energy Coucil, "Global wind report 2025," Report, 2025.

[2] BEIS, *Digest of uk energy statistics*, Government Document, 2022.

[3] IRENA, "World energy transitions outlook 2022," International Renewable Energy Agency, Report, 2022.

[4] HM Government, *The ten point plan for a green industrial revolution*, Government Document, 2020.

[5] WindEurope, "Offshore wind energy statistics 2021," Report, 2021.

[6] IRENA, "Irena power generation costs 2020," Report, 2020.

[7] R. Soler-Bientz and S. Watson, "Preliminary assessment of the variability of uk offshore wind speed as a function of distance to the coast," *Journal of Physics: Conference Series*, vol. 749, p. 012 004, 2016. DOI: 10.1088/1742-6596/749/1/012004.

[8] S. Cavazzi and A. G. Dutton, "An offshore wind energy geographic information system (owe-gis) for assessment of the uk's offshore wind energy potential," *Renewable Energy*, vol. 87, pp. 212–228, 2016. DOI: https://doi.org/10.1016/j.renene.2015.09.021.

[9] M. J. Dvorak, C. L. Archer, and M. Z. Jacobson, "California offshore wind energy potential," *Renewable Energy*, vol. 35, no. 6, pp. 1244–1254, 2010. DOI: https://doi.org/10.1016/j.renene.2009.11.022.

[10] WindEurope, "Windeurope annual offshore statistics 2019," Report, 2019.

[11] L. Ponting, *The winds of change*, Electronic Article, 2021.

[12] T. Johnson, *Letter to offshore wind industry from health and safety executive*, Generic, Jul. 2020.

[13] E. A. for Safety and H. at Work, "Green jobs and occupational safety and health," European Agency for Safety and Health at Work, Report, 2013.

[14] U. Nations, *United nations sustainable developent goals*, Web Page, 2023.

[15] Health and Safety Executive, "Costs to britain of workplace fatalities and self-reported injuries and ill health, 2019/20," Report, 23rd November 2022 2022.

[16] C. A. Mustard and B. Yanar, "Estimating the financial benefits of employers' occupational health and safety expenditures," *Safety Science*, vol. 159, p. 106 008, 2023. DOI: `https://doi.org/10.1016/j.ssci.2022.106008`.

[17] G. van Bussel and W. Bierbooms, "The dowec offshore reference windfarm: Analysis of transportation for operation and maintenance," *Wind Engineering*, vol. 27, no. 5, pp. 381–391, 2003. DOI: `10.1260/030952403322770986`.

[18] C. Hu B; Yung, "Offshore access report," TNO, Report, 2020.

[19] TNO, "Offshore wind access report 2022," Report, 2022.

[20] Orsted, *Ørsted partners with pict offshore to develop game-changing technology for offshore wind operations and maintenance*, Press Release, 23/09/2019 2019.

[21] C. Trust, "Floating wind phase 4 summary report," Report, 2022.

[22] R. Puisa, V. Bolbot, A. Newman, and D. Vassalos, "Revealing system variability in offshore service operations through systemic hazard analysis," *Wind Energy Science*, vol. 6, no. 1, pp. 273–286, 2021. DOI: `10.5194/wes-6-273-2021`.

[23] N. Leseberg, "New drone technology uses ai to examine offshore wind turbine blades," *Insight: Non-Destructive Testing and Condition Monitoring*, vol. 66, no. 1, pp. 4–6, 2024.

[24] X. Huang, G. Wang, Y. Lu, and Z. Jia, "Study on a boat-assisted drone inspection scheme for the modern large-scale offshore wind farm," *IEEE Systems Journal*, vol. 17, no. 3, pp. 4509–4520, 2023. DOI: `10.1109/JSYST.2023.3272948`.

[25] Y. Liu, M. Hajj, and Y. Bao, "Review of robot-based damage assessment for offshore wind turbines," *Renewable and Sustainable Energy Reviews*, vol. 158, 2022. DOI: 10.1016/j.rser.2022.112187.

[26] Zelim, *Zelim unveils world's first unmanned man overboard rescue vessel at smm*, Web Page, 2024.

[27] N. Leveson, "A new accident model for engineering safer systems," *Safety Science*, vol. 42, no. 4, pp. 237–270, 2004. DOI: https://doi.org/10.1016/S0925-7535(03)00047-X.

[28] E. Hollnagel, *Resilience Engineering: Concepts and precepts*. Ashgate, 2006.

[29] T. Conklin and T. Conklin, *The 5 Principles of Human Performance: A Contemporary Update of the Building Blocks of Human Performance for the New View of Safety*. Amazon Digital Services LLC - KDP Print US, 2019, ISBN: 9781794639140.

[30] S. Dekker and T. Conklin, *Safety Differently*. CRC Press London, 2014.

[31] M. D. Cooper, "The emperor has no clothes: A critique of safety-ii," *Safety Science*, vol. 152, p. 105 047, 2022. DOI: https://doi.org/10.1016/j.ssci.2020.105047.

[32] N. G. Leveson, "Rasmussen's legacy: A paradigm change in engineering for safety," *Applied Ergonomics*, vol. 59, pp. 581–591, 2017. DOI: 10.1016/j.apergo.2016.01.015.

[33] G+ Global Offshore Wind, "G+ global offshore wind health & safety organisation 2020 incident data report," G+ Global Offshore Wind, Report, 2020.

[34] S. Asian, G. Ertek, C. Haksoz, S. Pakter, and S. Ulun, "Wind turbine accidents: A data mining study," *IEEE Systems Journal*, vol. 11, no. 3, pp. 1567–1578, 2017. DOI: 10.1109/JSYST.2016.2565818.

[35] G. Ertek, X. Chi, A. N. Zhang, and S. Asian, "Text mining analysis of wind turbine accidents: An ontology-based framework," in *5th IEEE International Conference on Big Data, Big Data 2017, December 11, 2017 - December 14,*

2017, ser. Proceedings - 2017 IEEE International Conference on Big Data, Big Data 2017, vol. 2018-January, Institute of Electrical and Electronics Engineers Inc., pp. 3233–3241. DOI: 10.1109/BigData.2017.8258305.

[36] B. K. Sovacool et al., "Balancing safety with sustainability: Assessing the risk of accidents for modern low-carbon energy systems," *Journal of Cleaner Production*, vol. 112, pp. 3952–3965, 2016. DOI: 10.1016/j.jclepro.2015.07.059.

[37] Health and Safety Executive, *Riddor - reporting of injuries, diseases and dangerous occurrences regulations 2013*, Web Page, 2022.

[38] E. Gonzalez et al., "Key performance indicators for wind farm operation and maintenance," *Energy Procedia*, vol. 137, pp. 559–570, 2017. DOI: 10.1016/j.egypro.2017.10.385.

[39] S. Pfaffel, S. Faulstich, and S. Sheng, "Recommended key performance indicators for operational management of wind turbines," vol. 1356. DOI: 10.1088/1742-6596/1356/1/012040.

[40] F. S. Torres, N. Kulev, B. Skobiej, M. Meyer, O. Eichhorn, and J. Schafer-Frey, "Indicator-based safety and security assessment of offshore wind farms," pp. 26–33. DOI: 10.1109/RWS50334.2020.9241287.

[41] H. Seyr and M. Muskulus, "Safety indicators for the marine operations in the installation and operating phase of an offshore wind farm," *Energy Procedia*, vol. 94, pp. 72–81, 2016. DOI: https://doi.org/10.1016/j.egypro.2016.09.200.

[42] I. Utne, L. Thuestad, K. Finbak, and T. Anders Thorstensen, "Shutdown preparedness in oil and gas production," *Journal of quality in maintenance engineering*, vol. 18, no. 2, pp. 154–170, 2012. DOI: 10.1108/13552511211244193.

[43] J. E. Skogdalen, I. B. Utne, and J. E. Vinnem, "Developing safety indicators for preventing offshore oil and gas deepwater drilling blowouts," *Safety science*, vol. 49, no. 8, pp. 1187–1199, 2011. DOI: 10.1016/j.ssci.2011.03.012.

[44] C. Köpke, J. Schäfer-Frey, E. Engler, C. Wrede, and J. Mielniczek, "A joint approach to safety, security and resilience using the functional resonance analysis method," 2020. DOI: `https://doi.org/10.15626/rea8.10`.

[45] O. H. Ramírez-Agudelo et al., "An expert-driven probabilistic assessment of the safety and security of offshore wind farms," *Energies*, vol. 14, no. 17, 2021. DOI: `10.3390/en14175465`.

[46] C. S. R. Alliance, "The statistical invalidity of trir as a measure of safety performance," Report, 2020.

[47] R. S. Stricoff, "Safety peformance measurement: Identifying prospective indicators with high validity," *Professional Safety*, vol. 45, no. 1, pp. 36–39, 2000.

[48] R. L. Collins, "Heinrich and beyond," *Process Safety Progress*, vol. 30, no. 1, pp. 2–5, 2011. DOI: `10.1002/prs.10422`.

[49] A. Hopkins, "Lessons from esso's gas plant explosion at longford," 2001.

[50] M. Anderson and M. Denkl, "The heinrich accident triangle - too simplistic a model for hse management in the 21st century?" In *SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production 2010, April 12, 2010 - April 14, 2010*, vol. 2, pp. 1062–1069. DOI: `10.2118/126661-ms`.

[51] J. Toellner, "Improving safety & health performance: Identifying & measuring leading indicators," *Professional Safety*, vol. 46, no. 9, pp. 42–47, 2001.

[52] D. Oswald, F. Sherratt, and S. Smith, "Problems with safety observation reporting: A construction industry case study," *Safety Science*, vol. 107, pp. 35–45, 2018. DOI: `10.1016/j.ssci.2018.04.004`.

[53] D. Oswald, "Safety indicators: Questioning the quantitative dominance," *Construction Management and Economics*, vol. 38, no. 1, pp. 11–17, 2020. DOI: `10.1080/01446193.2019.1605184`.

[54] K. Geddert, S. Dekker, and A. Rae, "How does selective reporting distort understanding of workplace injuries?" *Safety*, vol. 7, no. 3, p. 58, 2021.

[55] A. Hopkins, "Thinking about process safety indicators," *Safety Science*, vol. 47, no. 4, pp. 460–465, 2009. DOI: https://doi.org/10.1016/j.ssci.2007.12.006.

[56] W. M. Alruqi and M. R. Hallowell, "Critical success factors for construction safety: Review and meta-analysis of safety leading indicators," *J CONSTR ENG M*, vol. 145, no. 3, p. 4 019 005, 2019. DOI: 10.1061/(ASCE)CO.1943-7862.0001626.

[57] Health and Safety Executive, *Developing process safety indicators*, Electronic Book, 2006.

[58] J. Hinze, S. Thurman, and A. Wehle, "Leading indicators of construction safety performance," *Safety Science*, vol. 51, no. 1, pp. 23–28, 2013. DOI: https://doi.org/10.1016/j.ssci.2012.05.016.

[59] J. Xu, C. Cheung, P. Manu, and O. Ejohwomu, "Safety leading indicators in construction: A systematic review," *Safety Science*, vol. 139, p. 105 250, 2021. DOI: https://doi.org/10.1016/j.ssci.2021.105250.

[60] M. Grabowski, P. Ayyalasomayajula, J. Merrick, and D. McCafferty, "Accident precursors and safety nets: Leading indicators of tanker operations safety," *Maritime Policy & Management*, vol. 34, no. 5, pp. 405–425, 2007. DOI: 10.1080/03088830701585084.

[61] M. Sedgwick and A. Harley, "Bottom-line benefits through innovation in process safety kpi management," in *Hazards 25*, IChemE.

[62] Petroleum Safety Authority Norway, "Summary report 2020 trends in risk level in the petroleum activity," Report, May 2020.

[63] J.-E. Vinnem, T. Huseb, T. Aven, J. Seljelid, and O. J. Tveit, "Leading indicators for major hazard risk in offshore petroleum operations," in *8th International Conference on Probabilistic Safety Assessment and Management, PSAM 2006, May 14, 2006 - May 18, 2006*, ser. Proceedings of the 8th International Conference on Probabilistic Safety Assessment and Management, PSAM 2006, American Society of Mechanical Engineers (ASME).

[64] J. E. Vinnem, T. Aven, T. Husebø, J. Seljelid, and O. J. Tveit, "Major hazard risk indicators for monitoring of trends in the norwegian offshore petroleum sector," *Reliability Engineering & System Safety*, vol. 91, no. 7, pp. 778–791, 2006. DOI: https://doi.org/10.1016/j.ress.2005.07.004.

[65] J. E. Vinnem, "Risk indicators for major hazards on offshore installations," *Safety Science*, vol. 48, no. 6, pp. 770–787, 2010. DOI: https://doi.org/10.1016/j.ssci.2010.02.015.

[66] J. T. Kvaløy and T. Aven, "An alternative approach to trend analysis in accident data," *Reliability Engineering & System Safety*, vol. 90, no. 1, pp. 75–82, 2005. DOI: https://doi.org/10.1016/j.ress.2004.10.010.

[67] X. Zhen, J. E. Vinnem, Y. Han, C. Peng, and Y. Huang, "Development and prospects of major accident indicators in the offshore petroleum sector," *Process Safety and Environmental Protection*, vol. 160, pp. 551–562, 2022. DOI: https://doi.org/10.1016/j.psep.2022.02.050.

[68] P. Walaski, "The role of leading & lagging indicators in osh performance management," *Professional Safety*, vol. 65, no. 8, pp. 29–35, 2020.

[69] A. Hale, "Special issue on process safety indicators," *Safety Science*, vol. 47, no. 4, 2009. DOI: 10.1016/j.ssci.2008.07.016.

[70] J. A. Baker, "The report of the bp us refineries independent safety review panel," Report, 2007.

[71] G. S. Milligan, J. P. O'Halloran, and M. J. Tipton, "A job task analysis for technicians in the offshore wind industry," *Work*, vol. 63, pp. 537–545, 2019. DOI: 10.3233/WOR-192961.

[72] International Association of Oil and Gas Producers, "Iogp safety performance indicators - 2020 data," Report, May 2020.

[73] M. Rausand, "Accident models," pp. 137–176, 2011. DOI: 10.1002/9781118281116.ch6.

[74] J. Larouzee and J.-C. Le Coze, “Good and bad reasons: The swiss cheese model and its critics,” *Safety Science*, vol. 126, p. 104 660, 2020. DOI: https://doi.org/10.1016/j.ssci.2020.104660.

[75] H. W. Heinrich, *Industrial accident prevention: A scientific approach.* New York: McGraw-Hill, 1931.

[76] E. Hollnagel, *Safety-I and Safety-II.* CRC Press, 2014.

[77] A. Hopkins, “The limits of normal accident theory,” *Safety Science*, vol. 32, no. 2, pp. 93–102, 1999. DOI: https://doi.org/10.1016/S0925-7535(99)00015-6.

[78] K. H. Roberts and D. M. Rousseau, “Research in nearly failure-free, high-reliability organizations: Having the bubble,” *IEEE Transactions on Engineering Management*, vol. 36, no. 2, pp. 132–139, 1989. DOI: 10.1109/17.18830.

[79] J. Dwyer, N. Karanikas, and A. Sav, “Scoping review of peer-reviewed empirical studies on implementing high reliability organisation theory,” *Safety Science*, vol. 164, 2023. DOI: 10.1016/j.ssci.2023.106178.

[80] N. G. Leveson, *Engineering a Safer World : Systems Thinking Applied to Safety.* Cambridge: Cambridge: The MIT Press, 2012. DOI: 10.7551/mitpress/8179.001.0001.

[81] N. Leveson, “A systems approach to risk management through leading safety indicators,” *Reliability Engineering & System Safety*, vol. 136, pp. 17–34, 2015. DOI: https://doi.org/10.1016/j.ress.2014.10.008.

[82] N. Dulac et al., *Using system dynamics for safety and risk management in complex engineering systems*, Conference Paper, 2005. DOI: 10.1109/WSC.2005.1574392.

[83] N. Dulac, B. D. Owens, N. G. Leveson, and J. S. Carroll, “A formal modeling approach to risk management in the development of space exploration systems.”

[84] Dulac, N., et al., “Demonstration of a new dynamic approach to risk analysis for nasa’s constellation program,” MIT Complex Systems Research Laboratory Report, Report, 2007.

[85] N. Dulac, "A framework for dynamic safety and risk management modeling in complex engineering systems," Thesis, 2007.

[86] M. Couturier, "A case study of vioxx using stamp," Thesis, 2010.

[87] N. Leveson et al., "Applying system engineering to pharmaceutical safety," *Journal of Healthcare Engineering*, vol. 3, p. 689 624, 2012. DOI: `10.1260/2040-2295.3.3.391`.

[88] N. G. Leveson and J. P. Thomas, *STPA Handbook*. 2018.

[89] M. Ibrahim Shire, G. T. Jun, and S. Robinson, "The application of system dynamics modelling to system safety improvement: Present use and future potential," *Safety Science*, vol. 106, pp. 104–120, 2018. DOI: `https://doi.org/10.1016/j.ssci.2018.03.010`.

[90] R. Patriarca, M. Chatzimichailidou, N. Karanikas, and G. Di Gravio, "The past and present of system-theoretic accident model and processes (stamp) and its associated techniques: A scoping review," *Safety Science*, vol. 146, 2022. DOI: `10.1016/j.ssci.2021.105566`.

[91] Y. Zhang, C. Dong, W. Guo, J. Dai, and Z. Zhao, "Systems theoretic accident model and process (stamp): A literature review," *Safety Science*, vol. 152, 2022. DOI: `10.1016/j.ssci.2021.105596`.

[92] M. Velasco Garrido, J. Mette, S. Mache, V. Harth, and A. M. Preisser, "A cross-sectional survey of physical strains among offshore wind farm workers in the german exclusive economic zone," *BMJ Open*, vol. 8, no. 3, e020157–e020157, 2018. DOI: `10.1136/bmjopen-2017-020157`.

[93] N. Karanikas et al., "Occupational health hazards and risks in the wind industry," *Energy Reports*, vol. 7, pp. 3750–3759, 2021. DOI: `https://doi.org/10.1016/j.egyr.2021.06.066`.

[94] A. Freiberg, C. Schefter, M. Girbig, V. C. Murta, and A. Seidler, "Health effects of wind turbines in working environments – a scoping review," *Scandinavian Journal of Work, Environment and Health*, vol. 44, no. 4, pp. 351–369, 2018. DOI: `10.5271/sjweh.3711`.

[95] A. M. Preisser, R. V. McDonough, and V. Harth, "The physical performance of workers on offshore wind energy platforms: Is pre-employment fitness testing necessary and fair?" *Int Arch Occup Environ Health*, vol. 92, no. 4, pp. 513–522, 2018. DOI: 10.1007/s00420-018-1385-5.

[96] J. Mette, M. Velasco Garrido, V. Harth, A. M. Preisser, and S. Mache, "Healthy offshore workforce? a qualitative study on offshore wind employees' occupational strain, health, and coping," *BMC Public Health*, vol. 18, no. 1, pp. 172–172, 2018. DOI: 10.1186/s12889-018-5079-4.

[97] F. Earle et al., "Spowtt: Improving the safety and productivity of offshore wind technician transit," 2021. DOI: 10.1002/we.2647.

[98] M. Scheu, D. Matha, M.-A. Schwarzkopf, and A. Kolios, "Human exposure to motion during maintenance on floating offshore wind turbines," *Ocean Engineering*, vol. 165, pp. 293–306, 2018. DOI: 10.1016/j.oceaneng.2018.07.016.

[99] D. Ahsan, S. Pedersen, M. R. Bang Nielsen, and J. Ovesen, "Why does the offshore wind industry need standardized hse management systems? an evidence from denmark," *Renewable Energy*, vol. 136, pp. 691–700, 2019. DOI: 10.1016/j.renene.2019.01.034.

[100] S. Pedersen and D. Ahsan, "Emergency preparedness and response: Insights from the emerging offshore wind industry," *Safety Science*, vol. 121, pp. 516–528, 2020. DOI: 10.1016/j.ssci.2019.09.022.

[101] Global Wind Organisation, "Gwo annual report 2020," Report, 2020.

[102] renewableUK, "Offshore marine health & safety guidelines," Report, 2014.

[103] E. Wifa and T. S. Hunter, "Mitigating occupational health and safety risks in the proposed australian offshore wind energy industry: Lessons from the safety case regime," *Journal of energy & natural resources law*, pp. 1–22, 2021. DOI: 10.1080/02646811.2021.1879547.

[104] W. Eddy Lenusira, "A review of the uk's offshore oil and gas safety case regulatory model: Is it worth "the hype"?" *International Energy Law Review*, no. 6, pp. 206–211, 2018.

[105] ORE Catapult, “Sparta portfolio review 2019-20,” Report, 2020.

[106] ORE Catapult, “Sparta portfolio review 2020/21,” Report, 2022.

[107] M. Martini, R. Guanche, I. J. Losada, and C. Vidal, “Accessibility assessment for operation and maintenance of offshore wind farms in the north sea: Accessibility offshore north sea,” *Wind energy (Chichester, England)*, vol. 20, no. 4, pp. 637–656, 2017. DOI: 10.1002/we.2028.

[108] N. Silva and A. Estanqueiro, “Impact of weather conditions on the windows of opportunity for operation of offshore wind farms in portugal,” *Wind engineering*, vol. 37, no. 3, pp. 257–268, 2013. DOI: 10.1260/0309-524X.37.3.257.

[109] M. O’Connor, T. Lewis, and G. Dalton, “Weather window analysis of irish west coast wave data with relevance to operations & maintenance of marine renewables,” *Renewable energy*, vol. 52, pp. 57–66, 2013. DOI: 10.1016/j.renene.2012.10.021.

[110] J. Feuchtwang and D. Infield, “Offshore wind turbine maintenance access: A closed-form probabilistic method for calculating delays caused by sea-state,” *Wind Energy*, vol. 16, no. 7, pp. 1049–1066, 2013. DOI: 10.1002/we.1539.

[111] R. T. Walker, J. van Nieuwkoop-McCall, L. Johanning, and R. J. Parkinson, “Calculating weather windows: Application to transit, installation and the implications on deployment success,” *Ocean engineering*, vol. 68, pp. 88–101, 2013. DOI: 10.1016/j.oceaneng.2013.04.015.

[112] M. N. Scheu, D. Matha, and M. Muskulus, “Validation of a markov-based weather model for simulation of o&m for offshore wind farms,” in *22nd International Offshore and Polar Engineering Conference, ISOPE-2012, June 17, 2012 - June 22, 2012*, ser. Proceedings of the International Offshore and Polar Engineering Conference, International Society of Offshore and Polar Engineers, pp. 463–468.

[113] J. Paterson, P. R. Thies, R. Sueur, J. Lonchampt, and F. D’Amico, “Assessing marine operations with a markov-switching autoregressive metocean model,” *Proceedings of the Institution of Mechanical Engineers. Part M, Journal of en-*

gineering for the maritime environment, vol. 234, no. 4, pp. 785–802, 2020. DOI: 10.1177/1475090220916084.

[114] H. Seyr and M. Muskulus, "Using a langevin model for the simulation of environmental conditions in an offshore wind farm," *Journal of Physics: Conference Series*, vol. 1104, p. 012 023, 2018. DOI: 10.1088/1742-6596/1104/1/012023.

[115] J. Browell, A. Zitrou, L. Walls, T. Bedford, and D. Infield, "Analysis of wind and wave data to assess maintenance access to offshore wind farms," in *European Safety and Reliability Association Conference*, pp. 743–750.

[116] G. Rinaldi, P. Thies, and L. Johanning, *Improvements in the O&M modelling of floating offshore wind farms*. 2020.

[117] D. Rowell, B. Jenkins, J. Carroll, and D. McMillan, "How does the accessibility of floating wind farm sites compare to existing fixed bottom sites?" *Energies*, vol. 15, no. 23, p. 8946, 2022. DOI: 10.3390/en15238946.

[118] I. Dinwoodie, V. M. Catterson, and D. McMillan, "Wave height forecasting to improve off-shore access and maintenance scheduling," IEEE. DOI: 10.1109/pesmg.2013.6672438.

[119] H. Zhang, J. Yan, S. Han, L. Li, Y. Liu, and D. Infield, "Uncertain accessibility estimation method for offshore wind farm based on multi-step probabilistic wave forecasting," *IET Renewable Power Generation*, vol. 15, no. 13, pp. 2944–2955, 2021. DOI: 10.1049/rpg2.12227.

[120] C. Gilbert, J. Browell, and D. McMillan, "Visualisation of probabilistic access forecasts for offshore operations," in *WindEurope Conference and Exhibition 2019, April 2, 2019 - April 4, 2019*, ser. Journal of Physics: Conference Series, vol. 1222, IOP Publishing Ltd. DOI: 10.1088/1742-6596/1222/1/012040.

[121] M. L. Vinther, "Dry sea state monitoring for more efficient marine operations," in *Offshore Technology Conference Brasil*, vol. Day 1 Tue, October 29, 2019, D011S012R003. DOI: 10.4043/29952-ms.

[122] M. Konig, D. F. Gonzalez, M. Abdel-Maksoud, and A. Duster, "Numerical investigation of the landing manoeuvre of a crew transfer vessel to an offshore wind turbine," *Ships and Offshore Structures*, vol. 12, S115–S133, 2017. DOI: 10.1080/17445302.2016.1265883.

[123] D. Ferreira González, M. Lemmerhirt, M. Abdel-Maksoud, M. König, and A. Düster, "Numerical and experimental investigation regarding the landing manoeuvre of a catamaran vessel at an offshore wind turbine in waves," in *ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering*, vol. Volume 7: Ocean Engineering, V007T06A045. DOI: 10.1115/omae2015-42071.

[124] C. Gilbert, J. Browell, and D. McMillan, "A data-driven vessel motion model for offshore access forecasting," in *2019 OCEANS - Marseille, OCEANS Marseille 2019, June 17, 2019 - June 20, 2019*, ser. OCEANS 2019 - Marseille, OCEANS Marseille 2019, vol. 2019-June, Institute of Electrical and Electronics Engineers Inc. DOI: 10.1109/OCEANSE.2019.8867176.

[125] M. Wu, "Numerical analysis of docking operation between service vessels and offshore wind turbines," *Ocean engineering*, vol. 91, pp. 379–388, 2014. DOI: 10.1016/j.oceaneng.2014.09.027.

[126] O. Gaidai, X. Xu, A. Naess, Y. Cheng, R. Ye, and J. Wang, "Bivariate statistics of wind farm support vessel motions while docking," *Ships and Offshore Structures*, vol. 16, no. 2, pp. 135–143, 2021. DOI: 10.1080/17445302.2019.1710936.

[127] R. Guanche, M. Martini, A. Jurado, and I. J. Losada, "Walk-to-work accessibility assessment for floating offshore wind turbines," *Ocean Engineering*, vol. 116, pp. 216–225, 2016. DOI: https://doi.org/10.1016/j.oceaneng.2016.03.013.

[128] M. Martini, A. Jurado, R. Guanche, and I. Losada, "Probabilistic assessment of floating wind turbine access by catamaran vessel," *Energy Procedia*, vol. 94, pp. 249–260, 2016. DOI: https://doi.org/10.1016/j.egypro.2016.09.233.

[129] B. Jenkins, A. Prothero, M. Collu, J. Carroll, D. McMillan, and A. McDonald, "Limiting wave conditions for the safe maintenance of floating wind turbines,"

Journal of Physics: Conference Series, vol. 2018, no. 1, p. 012 023, 2021. DOI: 10.1088/1742-6596/2018/1/012023.

[130] G. S. Hawker and D. A. McMillan, "The impact of maintenance contract arrangements on the yield of offshore wind power plants," *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, vol. 229, no. 5, pp. 394–402, 2015. DOI: 10.1177/1748006x15594693.

[131] J. Wang, X. Zhao, and X. Guo, "Optimizing wind turbine's maintenance policies under performance-based contract," *Renewable Energy*, vol. 135, pp. 626–634, 2019. DOI: 10.1016/j.renene.2018.12.006.

[132] L. Liang, J. Xie, L. Liu, and Y. Xia, "Revenue sharing contract coordination of wind turbine order policy and aftermarket service based on joint effort," *Industrial Management and Data Systems*, vol. 117, no. 2, pp. 320–345, 2017. DOI: 10.1108/IMDS-03-2016-0088.

[133] P. Scurlock, "Standard form contracts in the offshore wind sector: A logical proposition?" *International Energy Law Review*, no. 1, pp. 13–16, 2009.

[134] BVG associates, "Contractual terms and conditions in offshore wind," Report, 2021.

[135] B. Ralph, "Construction contracts for offshore wind farms," *International Construction Law Review*, pp. 426–459, 2014.

[136] BIMCO, *Windtime contract*, Legal Rule or Regulation, 2013.

[137] G. Rinaldi, A. Garcia-Teruel, H. Jeffrey, P. R. Thies, and L. Johanning, "Incorporating stochastic operation and maintenance models into the techno-economic analysis of floating offshore wind farms," *Applied Energy*, vol. 301, p. 117 420, 2021. DOI: https://doi.org/10.1016/j.apenergy.2021.117420.

[138] R. Martin, I. Lazakis, S. Barbouchi, and L. Johanning, "Sensitivity analysis of offshore wind farm operation and maintenance cost and availability," *Renewable energy*, vol. 85, pp. 1226–1236, 2016. DOI: 10.1016/j.renene.2015.07.078.

[139] M. Shafiee, "Maintenance logistics organization for offshore wind energy: Current progress and future perspectives," *Renewable Energy*, vol. 77, pp. 182–193, 2015. DOI: 10.1016/j.renene.2014.11.045.

[140] C. Stock-Williams and S. K. Swamy, "Automated daily maintenance planning for offshore wind farms," *Renewable Energy*, vol. 133, pp. 1393–1403, 2019. DOI: 10.1016/j.renene.2018.08.112.

[141] J. Chatterjee and N. Dethlefs, "Scientometric review of artificial intelligence for operations & maintenance of wind turbines: The past, present and future," *Renewable and Sustainable Energy Reviews*, vol. 144, 2021. DOI: 10.1016/j.rser.2021.111051.

[142] H. Seyr and M. Muskulus, "Decision support models for operations and maintenance for offshore wind farms: A review," *APPL SCI-BASEL*, vol. 9, no. 2, p. 278, 2019. DOI: 10.3390/app9020278.

[143] H. Seyr and M. Muskulus, "Use of markov decision processes in the evaluation of corrective maintenance scheduling policies for offshore wind farms," *Energies*, vol. 14, no. 15, 2019. DOI: 10.3390/en12152993.

[144] S. Koukoura, M. N. Scheu, and A. Kolios, "Influence of extended potential-to-functional failure intervals through condition monitoring systems on offshore wind turbine availability," *Reliability Engineering and System Safety*, vol. 208, 2021. DOI: 10.1016/j.ress.2020.107404.

[145] J. McMorland, M. Collu, D. McMillan, and J. Carroll, "Operation and maintenance for floating wind turbines: A review," *Renewable and Sustainable Energy Reviews*, vol. 163, p. 112 499, 2022. DOI: https://doi.org/10.1016/j.rser.2022.112499.

[146] S. Wallis, "Binomial confidence intervals and contingency tests: Mathematical fundamentals and the evaluation of alternative methods," *Journal of Quantitative Linguistics*, vol. 20, no. 3, pp. 178–208, 2013. DOI: 10.1080/09296174.2013.799918.

[147] G+ Global Offshore Wind, "G+ global offshore wind health & safety organisation 2022 incident data report," G+ Global Offshore Wind, Report, 2022.

[148] International Association of Oil and Gas Producers, "Iogp safety performance indicators - 2022 data," Report, May 2022.

[149] SafetyOn, "Safetyon 2022 onshore wind health and safety incident data report," Report, 2022.

[150] T. M. Probst, C. Barbaranelli, and L. Petitta, "The relationship between job insecurity and accident under-reporting: A test in two countries," *Work Stress*, vol. 27, no. 4, pp. 383–402, 2013. DOI: 10.1080/02678373.2013.850756.

[151] N. Weekes, *Four missing after south china sea offshore wind accident*, Electronic Article.

[152] Global Wind Energy Coucil, "Global wind report 2022," Report, 2022.

[153] RenewableUK, *Renewableuk wind energy projects*, Web Page, 2022.

[154] P. Atkinson, "Securing the safety of offshore wind workers," *Renewable Energy Focus*, vol. 11, no. 3, pp. 34–36, 2010. DOI: https://doi.org/10.1016/S1755-0084(10)70065-X.

[155] R. E. Löfstedt, "Reclaiming health and safety for all: An independent review of health and safety legislation," Report, 2011.

[156] *Health and safety at work etc. act 1974*, Legal Rule or Regulation, 1974.

[157] *The health and safety at work etc. act 1974 (application outside great britain) order*, Legal Rule or Regulation, 2013.

[158] Ramboll, "Floating offshore wind - application of standards, regulations, project certification and classification - risks and opportunities," Report, 2021.

[159] A. N. Beal, "Cdm regulations: 12 years of pain but little gain," *Proceedings of the Institution of Civil Engineers: Civil Engineering*, vol. 160, no. 2, pp. 82–88, 2007. DOI: 10.1680/cien.2007.160.2.82.

[160] Health and Safety Executive, "Guidance on the legislative changes introduced by the health and safety at work etc act 1974 (application outside great britain) order 2013," Report, 2013.

[161] *The management of health and safety at work regulations 1999*, Legal Rule or Regulation, 1999.

[162] *The construction (design and management) regulations 2015*, Legal Rule or Regulation, 2015.

[163] Health and Safety Executive, "A guide to the offshore installations (safety case) regulations 2005," Health and Safety Executive, Report, 2006.

[164] R. Joyce, *CDM Regulations 2015 Explained* (CDM Regulations 2015 Explained). DOI: 10.1680/cdmre.60098.

[165] A. Lee, *Five hurt at triton knoll in second serious offshore wind vessel accident*, Electronic Article.

[166] A. Buljan, *Turbine parts dropped into sea at ormonde offshore wind farm*, Electronic Article.

[167] A. Jaaskelainen, S. Tappura, and J. Pirhonen, "The path toward successful safety performance measurement," *Journal of Safety Research*, vol. 83, pp. 181–194, 2022. DOI: 10.1016/j.jsr.2022.08.014.

[168] E. D. Oguz Erkal, M. R. Hallowell, and S. Bhandari, "Formal evaluation of construction safety performance metrics and a case for a balanced approach," *Journal of Safety Research*, vol. 85, pp. 380–390, 2023. DOI: https://doi.org/10.1016/j.jsr.2023.04.005.

[169] C. Wohlin, *Guidelines for snowballing in systematic literature studies and a replication in software engineering*, Conference Paper, 2014. DOI: 10.1145/2601248.2601268.

[170] E. Sgourou, P. Katsakiori, S. Goutsos, and E. Manatakis, "Assessment of selected safety performance evaluation methods in regards to their conceptual,

methodological and practical characteristics," *Safety Science*, vol. 48, no. 8, pp. 1019–1025, 2010. DOI: 10.1016/j.ssci.2009.11.001.

[171] S. Wallis, "Binomial confidence intervals and contingency tests: Mathematical fundamentals and the evaluation of alternative methods," *Journal of Quantitative Linguistics*, vol. 20, no. 3, pp. 178–208, 2013. DOI: 10.1080/09296174.2013.799918.

[172] G+ Global Offshore Wind, "G-2021-incident-data-report," Energy Institute, Report, 2021.

[173] International Marine Contractors Association, "2021 safety statistics," International Marine Contractors Association, Report, 2021.

[174] Executive, Health and Safety, *Riddor - reporting of injuries, diseases and dangerous occurrences regulations*, Web Page, 2023.

[175] Vattenfall, "Vattenfall annual and sustainability report 2022," Vattenfall, Report, 2022.

[176] Orsted, "Orsted annual report 2022," Orsted, Report, 2022.

[177] RWE, "Rwe sustainability report 2021," RWE, Report, 2021.

[178] H. Lingard, M. Hallowell, R. Salas, and P. Pirzadeh, "Leading or lagging? temporal analysis of safety indicators on a large infrastructure construction project," *Safety Science*, vol. 91, pp. 206–220, 2017. DOI: https://doi.org/10.1016/j.ssci.2016.08.020.

[179] R. Salas and M. Hallowell, "Predictive validity of safety leading indicators: Empirical assessment in the oil and gas sector," *Journal of Construction Engineering and Management*, vol. 142, no. 10, p. 04016052, 2016. DOI: doi:10.1061/(ASCE)CO.1943-7862.0001167.

[180] G. Zwetsloot, S. Leka, P. Kines, and A. Jain, "Vision zero: Developing proactive leading indicators for safety, health and wellbeing at work," *Safety Science*, vol. 130, p. 104890, 2020. DOI: https://doi.org/10.1016/j.ssci.2020.104890.

[181] ERM, "Erm global safety survey," ERM Group, Report, 2018.

[182] A. P. Institute, *Process safety performance indicators for the refining and petrochemical industries*, Standard, 2021.

[183] R. N. Phinias, "Benefits and challenges relating to the implementation of health and safety leading indicators in the construction industry: A systematic review," *Safety Science*, vol. 163, p. 106 131, 2023. DOI: `https://doi.org/10.1016/j.ssci.2023.106131`.

[184] J.-E. Vinnem, "Use of accident precursor event investigations in the understanding of major hazard risk potential in the norwegian offshore industry," *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, vol. 227, no. 1, pp. 66–79, 2013. DOI: `10.1177/1748006X12468670`.

[185] G. A. Penaloza, C. Torres Formoso, and T. Abreu Saurin, "A resilience engineering-based framework for assessing safety performance measurement systems: A study in the construction industry," *Safety Science*, vol. 142, 2021. DOI: `10.1016/j.ssci.2021.105364`.

[186] P. O. Lloyd, *Health and safety of offshore wind farms*, Generic, 2016. DOI: `10.1016/B978-0-08-100779-2.00019-2`.

[187] G+, "G+ integrated offshore emergency response (g+ ioer)," Report, Nov. 2023.

[188] J. Gordois, *Hse letter on emergency response planning*, Personal Communication, Oct. 2024.

[189] T. Russell, *Fire strikes binhai wind farm, one missing*, Web Page, 2017.

[190] G+, "Workshop report: Escape from the nacelle in the event of a fire," Report, 2015.

[191] D. Wilkie and C. Galasso, "A probabilistic framework for offshore wind turbine loss assessment," *Renewable Energy*, vol. 147, pp. 1772–1783, 2020. DOI: `https://doi.org/10.1016/j.renene.2019.09.043`.

[192] D. Moulas, M. Shafiee, and A. Mehmanparast, “Damage analysis of ship collisions with offshore wind turbine foundations,” *Ocean Engineering*, vol. 143, pp. 149–162, 2017. DOI: `https://doi.org/10.1016/j.oceaneng.2017.04.050`.

[193] MCA, “Safety of navigation: Offshore renewable energy installations (oreis) - guidance on uk navigational practice, safety and emergency response. (mgn 654),” Report, 2008.

[194] A. Rawson and M. Brito, “Assessing the validity of navigation risk assessments: A study of offshore wind farms in the uk,” *Ocean Coastal Management*, vol. 219, p. 106 078, 2022. DOI: `https://doi.org/10.1016/j.ocecoaman.2022.106078`.

[195] E. Vind, *Data-driven detection of main shaft crack development in wind turbines*, Electronic Article, 2022.

[196] *Offshore wind turbine failure prompts calls for no sail zone*, Web Page, 2022.

[197] G+, “Wind turbine safety rules,” Report, 2021.

[198] *Darren hoadley v siemens gamesa renewable energy ltd*, Case, Nov. 2022.

[199] E. D. O. Erkal and R. Hallowell Matthew, “Moving beyond trir: Measuring monitoring safety performance with high-energy control assessments.,” *Professional Safety*, vol. 68(05), pp. 26–35, 2023.

[200] IMCA, *Uncontrolled release of walk to work gangway*, Web Page, 2019.

[201] M. Li, B. Bijvoet, K. Wu, X. Jiang, and R. R. Negenborn, “Optimal chartering decisions for vessel fleet to support offshore wind farm maintenance operations,” *Ocean Engineering*, vol. 298, p. 117 202, 2024. DOI: `https://doi.org/10.1016/j.oceaneng.2024.117202`.

[202] A. Kvitrud, G. Ersdal, and R. L. Leonhardsen, “On the risk of structural failure on norwegian offshore installations,” in *Proceedings of the Eleventh (2001) International Offshore and Polar Engineering Conference*.

[203] B. P. M. Sharples, W. T. Bennett, and J. C. Trickey, “Risk analysis of jackup rigs,” *Marine Structures*, vol. 2, no. 3, pp. 281–303, 1989. DOI: `https://doi.org/10.1016/0951-8339(89)90037-3`.

[204] G+, "Good practice guidelines for safe helicopter operations in support of the global offshore wind industry," Report, 2024.

[205] Global Wind Organisation, *Statistics publication*, Web Page, 2024.

[206] J. Rasmussen and I. Svedung, "Proactive risk management in a dynamic society," 2000.

[207] M. Perry, *Engineer who lost arm while working on north sea wind turbine wins compensation*, Web Page, 2023.

[208] G+, *Collision between crew transfer vessel and wind turbine generator*, Web Page, 2023.

[209] J. Daniel, *Sampling essentials: Practical guidelines for making sampling choices*, Electronic Book Section, 2023/09/27 2012. DOI: 10.4135/9781452272047.

[210] A. Lunde and O. Njå, "A systems thinking approach to safety in norwegian avalanche rescue operations," *Safety Science*, vol. 144, 2021. DOI: 10.1016/j.ssci.2021.105466.

[211] Oceanwinds, "Hsseq policy," Report, 2022.

[212] Orsted, "Policy for quality, health, safety and environment," Report, 2020.

[213] Vattenfall, "Health and safety policy," Report, 2021.

[214] G+ Global Offshore Wind, *Global offshore wind health and safety organisation*, Web Page, 2022.

[215] WindEurope, "Windeurope - wind energy in europe - 2022," Report, 2023.

[216] J. McMorland, "Operation and maintenance for floating wind turbines: A review," *Renewable and Sustainable Energy Reviews*, vol. 163, p. 112 499, 2022. DOI: https://doi.org/10.1016/j.rser.2022.112499.

[217] G+, "G+ safe by design workshop floating offshore wind," Report, 2022.

[218] D. Rowell, D. McMillan, and J. Carroll, "Offshore wind h&s: A review and analysis," *Renewable and Sustainable Energy Reviews*, vol. 189, p. 113 928, 2024. DOI: https://doi.org/10.1016/j.rser.2023.113928.

[219] E. Institute, "G+ floating offshore wind hazard identification (hazid)," Report, 2022.

[220] J. Forrester, ""the" model versus a modeling "process"," *System Dynamics Review*, vol. 1, pp. 133–134, 2006. DOI: 10.1002/sdr.4260010112.