Logistic Efficiencies And Naval architecture for Wind Installations with Novel Developments

Project acronym: **LEANWIND**
Grant agreement no 614020
Collaborative project
Start date: 01st December 2013
Duration: 4 years

D.6.3 - Health & Safety risk control measures and required personnel skills

Lead Beneficiary: NTUA
Due date: 30 September 2016
Delivery date: 10 April 2017
Dissemination level: Public (PU)

This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No. 614020.

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Document Information

Version	Date	Description			
		Name/ Organisation	**Prepared by**	**Reviewed by**	**Approved by**
1.0 Initial Document	07/12/2015	NTUA	K. Louzis (NTUA)	N. Ventikos (NTUA)	D. Lyridis (NTUA)
2.0 Intermediate version 1	7/10/2016	NTUA/ NMCI_CIT	K. Louzis (NTUA) C. Gebruers (NMCI_CIT)	N. Ventikos (NTUA)	D. Lyridis (NTUA)
3.0 Intermediate version 2	17/12/2016	NTUA/ MTS	K. Louzis (NTUA) K.L. Haegg (MTS)	N. Ventikos (NTUA) J. Giebhardt (FRAUNHOFER)	D. Lyridis (NTUA)
3.1 Document review	21/12/2016	NTUA	K. Louzis (NTUA)	Jan Goormachtigh (GSM) Jeroen De Neve (GSM) C. López (PLOCAN) Dissemination Committee	J. Giebhardt (FRAUNHOFER – WP6 Leader)
4.0 Final report	05/04/2017	NTUA	K. Louzis (NTUA)		Jan Arthur Norbeck (MRTK)

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List of Abbreviations

Acronym	Description
ABS	American Bureau of Shipping
APRM	Applied Policy Research Methodology
CEC	Clean Energy Council
CTV	Crew Transportation Vessel
CWIF	Caithness Windfarm Information Forum
DMA	Danish Maritime Authority
DNV-GL	Det Norske Veritas – Germanischer Lloyd
DP	Dynamic Positioning
EWEA	European Wind Energy Association
FMECA	Failure Mode, Effects, and Criticality Analysis
FSA	Formal Safety Assessment
GWO	Global Wind Organisation
HAV	Hand-Arm Vibration
HAZID	Hazard Identification
HAZOP	Hazard and Operability
HLV	Heavy Lift Vessel
HSE	Health and Safety Executive
IFC	International Finance Corporation
IJUBOA	International Jack-Up Barge Operators Association
IMO	International Maritime Organization
ISM	International Safety Management Code
JUV	Jack-Up Vessel
LOLER	Lifting Operations and Lifting Equipment Regulations
MAIB	Marine Accident Investigation Branch
MSC	Maritime Safety Committee
O&M	Operation and Maintenance
OAV	Offshore Access Vessel
OIM	Offshore Installation Managers
OSVDPA	Offshore Service Vessel Dynamic Positioning Authority
RCO	Risk Control Option
RIDDOR	Reporting of Injuries, Diseases and Dangerous Occurrences Regulations
ROV	Remote Operating Vehicle
RRR	Rapid Risk Ranking
SAR	Search and Rescue
SIMOPS	SIMultaneous OPerationS
SOLAS	Safety Of Life At Sea Convention
STCW	Standards of Training, Certification, and Watchkeeping
WBV	Whole Body Vibration
WTG	Wind Turbine Generator
WP	Work Package

Executive Summary

The work presented in this deliverable report documents the findings and results from Task 6.3 “Health and Safety Issues” of the LEANWIND Project. It is a comprehensive analysis of the existing situation regarding health and safety issues in the offshore wind industry, in terms of regulatory framework and relevant guidelines from key players of the industry, availability of health and safety specific accident databases, and the risk levels of critical accident scenarios. The main focus of the work presented in this report is to assess selected innovation categories that have been examined in the framework of the LEANWIND Project, in terms of their effect on health and safety issues. The report deals with innovations for worker access systems, lifting arrangements, and novel vessel concepts. Furthermore, the report presents an overview of existing regulations and requirements regarding training competencies of personnel involved in the O&M of Offshore Wind Farms. The report identifies gaps that need to be filled in order to cover the actual competencies required in the wind industry and proposes training requirement guidelines that will help in improving the overall level of safety for workers in Offshore Wind Farms. The report is structured in the following four sections: state of the art, health and safety related accidents, health and safety risk assessment and training requirements.

The **state of the art** section includes the analysis of the existing framework of regulations and guidelines relating to occupational health and safety in the offshore wind industry and the identification of gaps through a structured regulatory gap analysis. In addition, a brief overview of risk assessment applications in the offshore wind industry is presented. The state of the art is concluded with a review of the existing databases for occupational accidents in Offshore Wind Farms that have been identified in the context of Task 6.3. The identified data sources include the data stored by the Caithness Windfarm Information Forum, the summary statistics on injuries and fatalities provided by the G+ Offshore Wind Health and Safety Association (formerly named G9 Offshore Wind Health and Safety Association) and the reports provided by UK’s HSE.

The following section presents two characteristic case studies of actual **accidents** that have occurred in Offshore Wind Farms and relate to health and safety issues. The selected accidents involved the collapse of a crane during an offshore lifting operation and the collision of a CTV with the tower of a WTG.

The section on **health and safety risk assessment** outlines the methodology that was employed for achieving the goals of Task 6.3. The methodology follows the general guidelines set by the IMO for Formal Safety Assessments (FSAs) and comprises the following steps: 1) hazard identification, 2) risk modelling, 3) qualitative analysis, and 4) semi-quantitative analysis. The identification of hazards was based on an extensive survey of the relevant literature and distinguishes between common industrial hazards and particular hazards that are present in an Offshore Wind Farm. Risk modelling involved the construction of bow-tie models for critical accident scenarios that were selected based on existing statistics for occupational accidents. The constructed bow-tie models combine a fault tree with an event tree analysis, which means that each selected critical scenario is examined from its root causes up to the consequences that follow the accident. The qualitative analysis aimed to determine the most important events in the development of each examined accident scenario and was coupled with a high-level barrier analysis that aims to assess the effectiveness of specific existing RCOs. The semi-quantitative analysis was used for assessing the effect of selected innovation categories on the current level of

health and safety risk. The approach that was followed combined frequency and severity indices into a risk index, by employing custom risk ranking matrices. Frequency and severity were also assigned specific numerical values, based on expert judgement and logical inference, in order to calculate the relative probability of occurrence for each top event and the relative probability of each accident scenario outcome. The selected innovations were assessed by comparing the calculated likelihood of equivalent fatalities, for each accident that was examined, of a base case (current state of the art) with the one calculated for each innovation category. The calculated likelihood of equivalent fatalities for each accident scenario that was examined was also benchmarked against annual frequencies of related incidents from data provided by the G+ Offshore Wind Health and Safety Association.

The final section of the report focuses on reviewing the current state of the art regarding **training requirements and certifications** for marine crew and industrial personnel involved in the O&M of an Offshore Wind Farm. Based on the identified gaps, the report proposes specific actions that should be taken in order for training requirements and specifications to cover the actual competencies that are necessary for the personnel working at an Offshore Wind Farm.

The report concludes with interesting findings and insights based on the analysis that was presented. The most important conclusions are the following:

- The existing regulatory framework, regarding health and safety issues, needs to become more wind industry specific to cover the special set of hazards present at an Offshore Wind Farm.
- More details on health and safety related accidents and corresponding data should be made available, in order to support quantitative risk assessment studies that aim to improve the health and safety level for Offshore Wind Farms.
- The majority of innovation categories do not have an adverse effect on the level of health and safety risk, compared to the current state of the art, and therefore no specific novel RCOs are proposed in the context of this report.
- Training requirements and certifications should be made more wind industry specific to cover the actual competencies required for working at an Offshore Wind Farm, and safe behaviour courses should be combined with courses on technical skills.

Support by:

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1 Introduction

Europe has been leading the offshore wind energy industry since 1991 when the first Offshore Wind Farm was installed in Vindeby, Denmark [1], which consisted of 11 turbines, 450 kW each. Since then, the industry has been constantly growing, as documented in the annual statistics reports of WindEurope (previously known as EWEA). European wind turbines are currently (until end of 2016) distributed across 81 Offshore Wind Farms located in 10 countries, with an overall capacity of about 12.6 GW [2]. The combined capacity of European Offshore Wind Farms has more than tripled since 2010, when the installed capacity was about 3 GW. Over 80% of the installed capacity in offshore wind is located in the United Kingdom (over 5 GW), Germany (over 4 GW), and Denmark (about 1.2 GW) [3].

The latest development in the offshore wind industry, as shown Figure 1 for the time period between 2010 and 2016, has been the installation of wind farms in locations further away from the shore, and consequently in deeper waters. Especially since 2013, the trend has become clearer and more pronounced, as water depth has increased by 46% and the distance to shore by 45%, between 2013 and 2016. The need for the industry to go deeper and further away from the shore, accompanied by an increase in technical expertise, has prompted the development of novel technologies, such as floating wind turbines, which are used instead of fixed foundation structures (e.g. mono-piles, gravity foundations etc.).

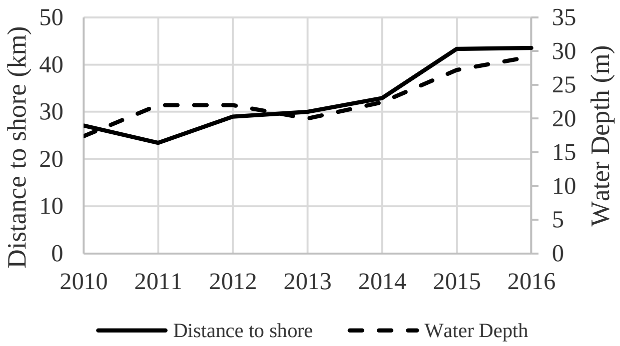


Figure 1: Timeline of developments in water depth and distance to shore for Offshore Wind Farms from 2010-2015 (Data Source: WindEurope, ex. EWEA, annual reports)

However, the expansion of the industry needs to be supported by reductions in costs for every phase of the Offshore Wind Farm life cycle, in order to increase the attractiveness and overall feasibility of the investment. Ongoing research specifically targets cost reductions. As quoted from the LEANWIND project web-site: "*The offshore wind industry has not yet applied lean principles to the logistical operations of the wind farm in all stages of the lifecycle...*". This approach highlights the need of the industry to apply "lean" principles, as originally developed by Toyota [4], to minimize wasteful use of available resources, and therefore increase optimization and efficiency across the life cycle phases of an Offshore Wind Farm installation. Towards the same goal, Barlow et al. [5] have investigated the issue of cost reductions by creating a simulation tool for modelling the logistics of the installation phase. The developed tool was used to identify specific operations that contribute to project delays due to various factors, such as uncertain environmental conditions.

1.1 Scope of Work

The main aim of this deliverable report is to evaluate the risk implications of the optimum integrated developments, as identified in Task 6.2, on health and safety issues. For developments that have unacceptably high health and safety risks, this report will propose the use of specific Risk Control Options (RCOs) to mitigate the risks to an acceptable level, if it is deemed necessary. RCOs, which may alternatively be named safety barriers, are technical or non-technical measures (RCOs) that are placed in order to either obstruct the development of initiating events into accidents or mitigate the consequences after an accident has occurred [6]. Although there is no common terminology or a commonly accepted definition for safety barriers, they could be defined as "physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents.", and also classified as preventive, controlling, or mitigating [7]. In order to achieve this goal, a structured health and safety risk assessment methodology will be outlined. Additionally, this report will document the existing framework that regulates health and safety issues in the Offshore Wind Farm industry, in order to identify any potential gaps and propose ways for improvement. This report will also document the existing accident databases that contain health and safety related incidents in Offshore Wind Farms. Finally, the report will address issues relating to the requirements for training courses that will be targeted at personnel involved in installation and O&M activities.

2 State of the Art

This Section will present the existing framework of regulations and guidelines relating to occupational health and safety in the offshore wind industry and will attempt to identify gaps through a structured regulatory gap analysis. In addition, a brief overview of risk assessment applications in the offshore wind industry is presented. The final part of this Section will present a review of the existing databases for occupational accidents in Offshore Wind Farms that have been identified in the context of Task 6.3.

2.1 Framework for regulating Health & Safety in the offshore wind industry

2.1.1 Review of existing Health & Safety Regulations

Health and Safety issues for the offshore wind industry can be classified into two broad categories, namely those arising from working on the wind turbines and those arising from working on the offshore windfarm support vessels. Currently, there are no specific regulations regarding Health and Safety for the offshore wind industry. Health and Safety aspects for offshore windfarms are governed by the general regulatory framework in effect for all land-based industrial sectors. These regulations deal with Health and Safety issues according to the various hazards the workers are being exposed to and therefore cover a wide range of industrial activities. The related activities typically span the whole spectrum of life cycle phases, such as construction, repair, and maintenance. However, the lack of a specific regulatory framework for offshore wind does not mean that the industry is not regulated. The approach that has been taken so far has been to extend the relevant regulations to explicitly cover Offshore Wind Farm installations. A good example of this practice is the Health and Safety at Work etc. Act 1974 in the UK, which has been extended to explicitly cover offshore structures and equipment with an amendment in 2001, called the 2001 Order [8]. Regarding the Health and Safety aspects of maritime operations that might take place during any phase of the offshore windfarm life-cycle (installation, operation & maintenance, decommissioning), these are governed by the existing regulatory framework that is in effect for the maritime industry. The need for the offshore wind industry to develop and adopt industry specific regulations has been pointed out by Atkinson [9] in a review of the regulatory state-of-the art. Although, for example, the offshore Oil & Gas industry operates under industry-specific regulations, some key players have a different opinion, such as the one expressed by HSE that regulations should be general enough as to be applicable to all industrial activities.

The European Union has established a general framework for occupational health and safety since 1989, with the European Framework Directive on Safety and Health at Work 89/391 [10]. This Directive establishes minimum requirements and rules with the aim to safeguard the health and safety of workers, by limiting work related accidents and occupational diseases. The application scope for the prescribed measures is any activity by both the public and private sectors (with some specific exceptions) and concerns obligations of both employers and workers. In particular, employers are mandated to provide specific means and measures for the protection of workers, which include the avoidance or management of occupational health and safety risks, appropriate training for workers and the continuous adaptation of working conditions and methods to account for relevant novel developments. Workers are also required to adapt a safe working mentality, which includes the correct use of protective equipment, the correct application of safety measures as well as informing the employer of any hazardous situations. This general framework offers a structured approach to managing and assessing occupational risks by outlining the need to evaluate hazards and risks, apply specific risk control measures against the identified risks and periodically reassess the work environment to maintain safety. The framework is complemented by various “daughter” Directives that offer guidance to specific hazards and work tasks and also address special high-risk work environments. In particular, the individual Directives describe the risk assessment process regarding these special conditions and also set measurable limits as benchmarks. The principles that are established with Directive 89/391 are applicable to every Member State and were therefore adapted and included in the relevant national legislations.

Currently, the only European-wide document that addresses occupational health and safety for the wind industry is the standard EN 50308:2004 [11]. This standard focuses on the safety aspects of the working conditions in the wind industry, related to specific work tasks and also prescribes specific protective measures to be taken against the identified hazards. However, as Lawani, Hare, and Cameron [12] have pointed out, this standard does not take into account offshore facilities. Issues not addressed in this standard will be taken into account under the revision of the document that is currently being worked on.

The following section contains a brief review of the existing health and safety regulations for a number of different European countries. It must be noted that there are no specific health and safety regulations applicable to Offshore Wind Farms, as highlighted in the health and safety guidelines published by RenewableUK [13]. As will be discussed below, various guidelines and standards that deal with specific guidance towards ensuring occupational health and safety in an Offshore Wind Farm, have been developed and published by actors in the offshore wind industry. Table 1 contains an overview of the various legislative frameworks in effect in a number of different European countries.

Country	Regulation	Year of implementation
United Kingdom	Health & Safety at Work etc. Act Management of Health & Safety at Work Regulations	1974 1999
Denmark	Working Environment Act and cooperation at the workplace Offshore Safety Act Renewable Energy Act	1975 1981 2008
Germany	Occupational Health and Safety Act	1996
Norway	Working Environment Act	1977
Netherlands	Working Conditions Act	1999
France	The Labour Code	1991
Sweden	Work Environment Act	1978

Table 1: Existing health and safety regulations per country

United Kingdom

The main regulation regarding health and safety, in effect for the UK, is the Health and Safety at Work etc. Act 1974 [14]. The main underlying principle of this piece of legislation is the allocation of responsibilities for controlling risks related to work activities to those who create the risks. The regulation takes into account both employers as well as employees as sources of risk. In particular, employers are deemed responsible for mitigating work related risks and employees are responsible for taking "*reasonable care for the health and safety of themselves and others*". Another important principle is that risks are not expected to be eliminated, but rather controlled "As Far As Reasonably Practicable" (ALARP). The ALARP principle implies that there should be a balance between the level of risk the workers are exposed to and the resources that need to be allocated towards mitigating this risk [15]. The ALARP criterion is an important part of the risk assessment process that is required by health and safety regulations because it provides a tool to evaluate the examined risks. Additionally, it must be noted that this Act does not deal with work activities related to marine operations.

The general provisions under the Health and Safety at Work etc. Act are further refined with the Management of Health & Safety at Work Regulations [16], which aim at improving health safety management by defining the specific duties that employers have in relation to their employees. The duties that are described reflect the responsibility of the employer to implement the appropriate health and safety management system and conduct "suitable and sufficient" risk assessments in order to evaluate the risks the employees are exposed to. Additionally, these regulations describe the duties of the employer relating to the application of the appropriate control measures for mitigating work related risks.

Denmark

The Working Environment Act [17] of the Danish Ministry of Employment is the main regulatory framework governing occupational health and safety. The main pillars of this Act are the proper design of the working environment, the working conditions, as well as the safety of the equipment used. This Act is applicable to all working environments, with the exemption of crews on-board ships and all military services. Although this Act is not applicable to marine operations, it does indeed deal with relevant loading and unloading ship operations. In addition, the Sandroos Advokatfirma [18] has given attention to the fact that wind farms located outside the territorial waters (12 nm from shore) are not formally covered by this Act, which only applies to onshore facilities and facilities situated within territorial waters. This presents a particular problem since Offshore Wind Farms will be situated farther from shore in the future. The Working Environment Act is complemented by the Offshore Safety Act [19], which covers health and safety issues for offshore Oil & Gas installations that are located in the Danish territorial waters and was first implemented in 1981. The latest amendments for this regulation were concluded in 2013. However, there has not been a specific amendment for the application of the Offshore Safety Act in Offshore Wind Farms [3].

The main regulation for offshore wind turbines in Denmark is the Renewable Energy Act [20], which generally deals with promoting the development of renewable energy projects. Although there are references to relevant requirements, this Act does not specifically regulate occupational health and safety. However, this Act does give the authority to the Minister of Climate and Energy to implement new and more specific regulations.

Germany

The Occupational Health and Safety Act [21], known as the "Arbeitsschutzgesetz", is the main regulation concerning occupational health and safety in Germany. It constitutes a direct transposition of the EU Directive 89/391/EEC for occupational health and safety. This piece of legislation offers an analytical description of the general duties and rights of both employers and employees regarding health and safety. Moreover, there are additional laws and regulations that complement the general regulatory framework and cover every aspect of occupational health and safety applicable to every industrial sector, as highlighted by Froneberg, et al. [22]. It is must be noted that there no specific regulations regarding Offshore Wind Farms.

Norway

The Working Environment Act [23] secures the conditions of employment as well as the working environment of employees. It is applied to all kinds of working environments, with the exemption of working on a ship. Additionally, this Act references the offshore oil and gas industry, there are no specific references to Offshore Wind Farms. Due to the fact that offshore wind installations are considered a novel application for Norwegian law, the development of a specific regulatory framework is still under consideration [24].

Netherlands

The Netherlands has already begun to formulate and implement new regulations specifically for Offshore Wind Farms, as described previously for other European countries. The main issue is that these regulations do not directly address health and safety issues but are rather concerned with providing incentives for the development of Offshore Wind Farms.

The Working Conditions Act [25] is the main regulation regarding the health and safety of the employees. The main difference of this regulation, compared to other European countries, is that it is also applicable to ships sailing under the Dutch flag. It is worth mentioning that Offshore Wind Farms are not specifically referenced in this piece of legislation.

France

The main regulation covering occupational health and safety in France is the Labour Code ("Code du Travail") [26]. This legislation covers health and safety issues including general responsibilities for the employers, the necessity of safety training, the management of hazardous substances, and specific safety measures. The Labour Code places an emphasis on the responsibilities of the employer to identify, evaluate and mitigate work-related health and safety risks, by using specific risk control measures. It must be noted that certain industries are governed by more specific regulations. In particular, the Mining Code covers mining and quarrying work activities and the Maritime Code covers maritime work activities, which in fact prescribes similar requirements to those by the IMO. It is important to note that French Labour Code gives no specific reference to the offshore wind industry.

Sweden

The Work Environment Act [27] is the main piece of legislation for occupational health and safety in Sweden and constitutes a general regulatory framework. This legislation sets broad and general goals for ensuring a safe working environment for the workers, regulates every work related environment and its main character is purely humancentric. Additionally, it must be noted that the primary responsibility for ensuring occupational health and safety is laid upon the employer.

Existing Health & Safety guidelines in the offshore wind industry

To cover the lack of industry specific regulations concerning occupational health and safety, various wind industry organizations and associations have developed specific guidelines, to be adhered to as a reference for best practice and in conjunction with applicable national and international regulations. It must be noted that the various guidelines that have been developed do not substitute the relevant requirements as set out by applicable regulations. The general outline for these guidelines includes the identification of industry specific hazards and proposing specific RCOs to mitigate them, which include the use of Personal Protective Equipment (PPE) and appropriate worker training.

RenewableUK

RenewableUK, formerly British Wind Energy Association (BWEA), have published a set of guidelines [13], which do not constitute new industry standards and requirements, but rather consider occupational health and safety of workers in offshore wind energy projects in the context of the Health and Safety at Work etc. Act 1974. The compilation of these guidelines has taken into account existing, as well as emerging, good practices of the industry and are applicable to offshore wind and marine energy projects within the territorial waters of the UK. The guidelines are divided in three parts. Part A describes the general framework for the management of occupational health and safety in the offshore wind industry, including the relevant regulations that apply to these activities, stressing the importance of health and safety management as well as risk management systems, and offering an industry specific approach to emergency response and preparedness. The significance of the lifecycle approach to risk management is highlighted by stating that "Risk management is best viewed as an ongoing process throughout the project lifecycle, both to assess and inform decisions" [8]. Furthermore, the appropriate training for ensuring the safety of the workers is prescribed. Part B examines the risks involved in an offshore wind energy project from a lifecycle perspective. This part identifies the hazards for each phase of the lifecycle and proposes specific RCOs for an effective risk management. Part C describes in detail a number of industry specific hazards, such as access, transport and logistics issues, construction and infrastructure risks, particular safety risks (e.g. confined spaces, remote working, working at height etc.), risks to the health of the workers and those related to marine and vessel management (e.g. subsea operations, vessel selection, navigational risks etc.). In general, the guidelines identify the existence of new combinations of hazards that are specifically presented in offshore wind energy projects, but hold the idea that this industry should take advantage of the relevant experience of other industrial sectors that have already addressed the individual hazards. However, special attention is given to Simultaneous Marine Operations (SIMOPS) as a peculiarity of the offshore wind industry. Due to the fact that an offshore wind energy project involves a large number of structures, which require a number of SIMOPS to take place, the risk of interference between the different operations is greater.

International Finance Corporation (IFC)

The IFC, has developed the Environmental, Health and Safety Guidelines (EHS) [28] expressed in the form of examples of Good International Industry Practice (GIIP) to be used for the appraisal of wind energy projects. The EHS Guidelines describe safety measures that can be achieved by the use of existing technologies at a reasonable cost. They deal with industry specific hazards to the environment, to the workers as well as with hazards to the health and safety of the local communities. It is important to note that a life-cycle approach is presented throughout the document. The guidelines state that occupational health and safety hazards for the different life-cycle phases of a wind energy project are generally similar to large scale industrial activities and therefore are covered by the General EHS Guidelines. The industry specific hazardous activities that are identified are: working at height, working over water, working in remote locations and lifting operations. The recommendations concerning working at height mainly involve the prevention of a fall, but also take into account the hazards from falling object and adverse weather conditions. Concerning working over water, a complete risk assessment is required for all relevant work tasks in order to ensure proper resource allocation and hazard mitigation. Concerning working in remote locations, such as offshore sites, the guidelines stress the importance of proper planning to ensure an adequate safety level. Special emphasis is given for the hazards that present during offshore lifting operations, due to the fact that they are an integral part of the construction phase of an offshore wind energy project. The additional hazards, owed to the number of different vessels and cranes used, include the sea states (affecting stability of the lifting platforms), the corrosive effect of the marine environment on the lifting points of the individual components, as well as communication problems between the involved multinational crews. Additionally, the EHS Guidelines outline various performance measures for the identified hazards. Specifically, occupational health and safety is to be benchmarked against internationally published statistics, which incurs the requirement to record all incidents as well as near-miss incidents to identify trends. The aim of an offshore wind energy project should be to reduce the number of accidents to zero, especially those that lead to lost work time, disabilities or fatalities. An additional requirement is to continuously monitor the state and development of occupational hazards and implement any improvements necessary.

<u>Clean Energy Council (CEC) - Australia</u>

The CEC, formerly Australian Wind Energy Association (AusWEA), developed a set of best practice guidelines to aid wind farm stakeholders, owners and operators to put forward a proposal for developing a wind farm project [29]. The application scope of the guidelines are onshore wind farms, although some parts may also be applicable for Offshore Wind Farms as well. Concerning offshore installations, the document states that the CEC will include relevant specific guidelines in future revisions, if deemed necessary and is due to the fact that there are currently no Offshore Wind Farms in Australia. The guidelines are organized according to each phase of the wind farm lifecycle. Since wind farm installations are considered to be workplaces, occupational health and safety issues are covered in the relevant Occupational Health and Safety regulations and are therefore not described in detail specifically for wind farms. Health and Safety issues are considered for the construction, operation and decommissioning phases of the wind farm lifecycle, but focus is given to the development of relevant management systems and not the particular hazards.

A precursor of the best practice guidelines is the document titled “Wind Farm Safety in Australia”, which was prepared by AusWEA in collaboration with the Australian Greenhouse Office [30]. This document examines various aspects of the safe operation of wind farms, such as impacts on air traffic, blade failures and the risk of fire and is mainly applicable to onshore facilities. Additionally, this document presents the various health and safety aspects of managing a wind farm, without detailing the various hazards involved. The identified general risks to the health and safety of the workers, are the following: working at height, rotating machinery, heavy machinery, high voltage electricity, hazardous weather conditions and vehicle access. The document also discusses the particular risks present at an Offshore Wind Farm installation, focusing on the possible risks stemming from the remoteness of the offshore locations and the adverse weather conditions, both for the construction and operation phases of the lifecycle.

Transportation Research Board (TRB) – U.S.A.

The Marine Board of the National Research Council (NRC) has published a report [31] on the findings of a committee, tasked with identifying industry specific health and safety risks on Offshore Wind Farms, identifying gaps in jurisdictional authority and finally with evaluating the existing regulatory framework and providing guidance for improvements. Due to the fact that there are no Offshore Wind Farms in the U.S. (as of December, 2012), this report was used to address the lack of experience of the federal government in this field. An important part of this work was to compare the hazards present in the offshore oil and gas industry, with which the federal government has years of experience, to those in the offshore wind industry. The corresponding conclusion was that while these two industries share most of the hazards, due to their offshore nature, the risks in the oil and gas industry are considered greater due to the volatility of the associated product, which increases the risk of fire and explosion on offshore platforms. Additionally, the hazards in the offshore wind industry were compared to those in the onshore wind industry. The conclusion from this comparison was that while the two industries have in common most of the hazards, since they share most the same tasks, the offshore wind industry presents additional hazards that relate to the marine environment and the adverse weather conditions that might arise. The report has documented basic facts and technical knowledge concerning wind farms and has also described the lifecycle phases of wind farm development, with a focus on Offshore Wind Farms. For each phase of the lifecycle the main work tasks have been documented and some specific tasks for an offshore installation have been examined in greater detail. The specific work tasks include working on vessels, working underwater during diving operations and working above the water on a turbine. Furthermore, the hazards during the development of a wind farm have been identified in relation to the corresponding work tasks and include, among others, slip hazards due to the weather conditions, crushing hazards from lifting operations, fall hazards from working at height and electrical hazards. Additionally, the identified hazards that are specific to Offshore Wind Farms include, access by boat and personnel transfer, commercial diving operations and emergency evacuations. For each of the described hazards, the report referenced the corresponding regulations, industry standards or guidelines that are currently in effect. It is important to note that this document was not intended to function as technical guidance, in the sense that while it documents the hazards for an Offshore Wind Farm, it does not describe specific RCOs to mitigate these risks.

WindEurope – ex. European Wind Energy Association (EWEA)

WindEurope has published a set of guidelines [32] regarding Emergency Arrangements for onshore as well as Offshore Wind Farms, which follow a high-level approach and provide best practices of the European industry on how to implement the EU Directive 89/391/EEC, Article 8, Paragraph 1. The document provides information on how to set-up and implement an emergency response system and corresponding plans for each phase of the wind farm lifecycle. In this direction, these guidelines state the importance of compiling an Emergency Response Plan (ERP) that covers all work tasks and is based on risk assessments that are project, turbine and site-specific. Additionally, the ERP needs to be regularly reviewed and updated whenever necessary. Considering offshore installations in particular, each vessel that is used for operations in an Offshore Wind Farm must also be equipped with an ERP according to the requirements of regulations from the IMO. An important part of an ERP should be the specification of the training requirements for the workers, concerning all emergency arrangements that are being used. Due to the fact that Offshore Wind Farms are inherently more complex, compared to their onshore counterparts, the relevant risks analyses must take into account additional risk factors, such as extreme weather and sea state conditions. An additional risk factor to consider that is specific to Offshore Wind Farms due to the remoteness of their locations, is the time needed for travelling to and from the installation. This is especially important when considering emergency activities such as the provision of first aid in case a work-related accident takes place. Another important point to consider, again owed to the remoteness of the locations of Offshore Wind Farms, is that workers are expected to have a high level of self-reliance, which must be ensured by providing proper and adequate training.

Irish Wind Energy Association (IWEA)

The Irish Wind Energy Association has published a set of guidelines for ensuring a high level of occupational health and safety for onshore wind energy projects [33]. These guidelines have been exclusively based on those published by RenewableUK. Although these guidelines document the health and safety hazards relating to each phase of the wind farm lifecycle extensively, it explicitly does not apply to Offshore Wind Farms. Specific guidelines are planned to be developed in the future.

Figure 2 shows summarizes the existing regulatory framework that governs health and safety for the Offshore Wind Farm industry, as outlined in the present section of the deliverable report.

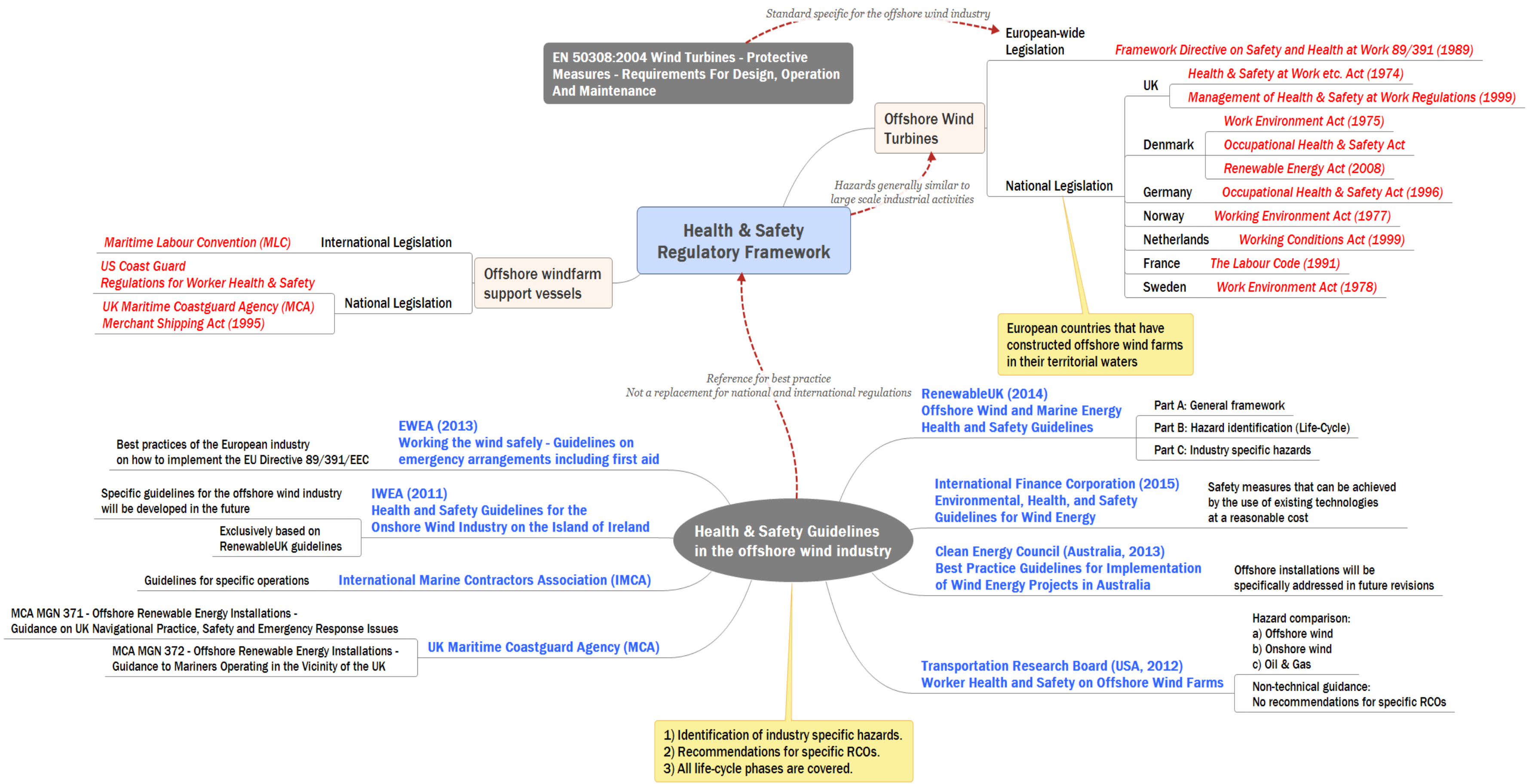


Figure 2: Overview of existing regulatory framework governing health and safety for the Offshore Wind Farm industry

2.1.2 Identification of gaps in the existing regulatory framework

An Applied Policy Research Methodology (APRM) has been adopted in the completion of this section. A broad range of distinct legislation & policy documents have been reviewed & evaluated, highlighting legislative shortfalls, & outlining areas for future research, while delivering specific recommendations.

2.1.2.1 Methodology Rationale

Applied policy research is a method commonly used for the analysis of government legislation and policies as a means of providing practical data over a shorter period of time. This provides policy makers with real time data allowing them to make informed decisions when implementing legislative changes.

Furthermore, this methodology is associated with the generation of data which requires specific information needs. As a research tool, it can be used in the context of theory testing or theory generation as the purpose of this method is to review and evaluate the relevance and suitability of policy documents. The basic premise of this method is to generate factual knowledge through use of the following data analysis framework:

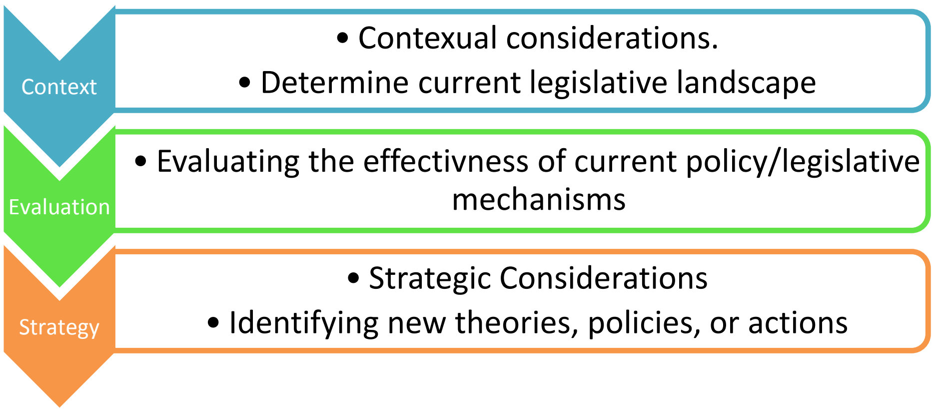


Figure 3: Applied Policy Research Methodology (APRM) Framework

In terms of practical application, the contextual aspects have been gathered through the review of relevant legislation within this area, thus setting the scene of the current legislative landscape. Evaluation has been achieved in the form of measuring the effectiveness of the current legislation by identifying "gaps" or shortfalls. The strategic considerations have been addressed through engagement with industry, highlighting shortcomings within the legislative mechanisms, & identifying and recommending a suitable course of action.

Another key feature to this methodology is the application of secondary research practices in the reviewing of policy documents in the absence of access to policy makers. The time scale and human resources allocated to this study further reinforces the rationale for the selection of this methodology, as attempting to gain access to the broad range of policy makers was simply not feasible with this study.

The contextual data, critical analysis, & strategic perspective associated with this method, highlights key micro and macro environment considerations thus providing the researcher with a 360 degree perspective of the policies under review.

2.1.2.2 Research Analysis Process

A review of **54** distinct policies (regulations), guidelines, reports and standards of relevance to Offshore Wind Farm health and safety has been completed providing a macro overview of the offshore health and safety legislative landscape. The data was analysed in order to determine the existence if any, of suitable health and safety polices, legislation, or references within generic legislation specific to the offshore windfarm industry. A grounded theory approach specific to data coding has been applied through the identification, labelling, and presentation of relevant data in order to provide structure for the study. Once reviewed, a gap analysis was conducted highlighting shortcomings within the legislative framework. These shortcomings were confirmed through use of primary research methods by engaging with industry. Specific recommendations have been outlined highlighting areas for future research and practical recommendations.

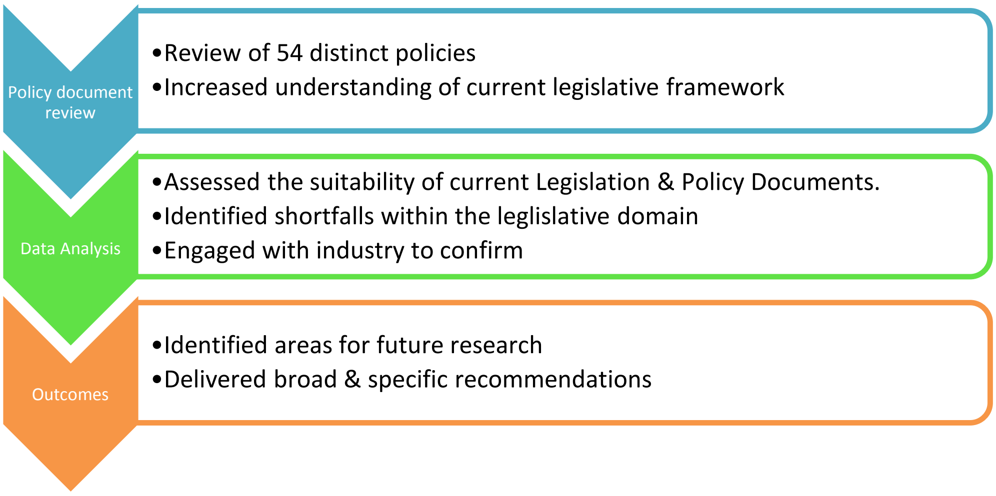


Figure 4: Research Analysis Process

2.1.2.3 Research Limitations

Further industry engagement would contribute greatly to this area. Such consultation would further investigate and determine the suitability and legislative coverage of current policies and legislation. One of the limitations associated with an applied policy research method is that it does not involve engaging with policy makers, which can restrict context determination. This limitation has been addressed by completing an extensive review of related policy documents and legislation on a global scale. By completing such an extensive review, context determination has been achieved by comparing and contrasting the broad range of data gathered throughout this study. The engagement with industry further contributed to the development of context in this case.

2.1.2.4 Material Related to Regulations, Certifications & White Papers

The identification of gaps in the existing regulatory framework has been based on **54** distinct policies (regulations), guidelines, reports and standards of relevance to Offshore Wind Farm health and safety. These have been drawn from:

- materials identified and examined in the preparation of the ***internal project report*** (under T4.5) ***Safety Assessment of O&M access with regard to human resources***
- References contained in documents identified, including in particular ***Review of Maritime and Offshore Regulations and Standards for Offshore Wind. Summary***

report on North Sea regulation and standards produced by the Danish Maritime Administration and DNV GL *as* [34]

- An internet document search
- Engagement (limited) with industry partners confirmed findings and suggested a recognition of the issues identified and an openness to considering the proposed recommendations

These materials have been classified as follows:

- Legal Nature (Figure 5)
  - Policy (i.e. regulation)
  - Guideline (i.e. non legally binding)
  - Report
  - Standard

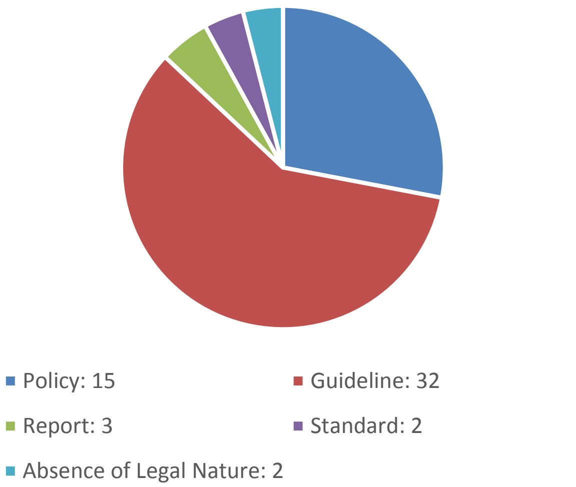


Figure 5: Materials of Legal Nature – Document Coverage

- Applicability (Figure 6)
  - National (country identified)
  - EU
  - International

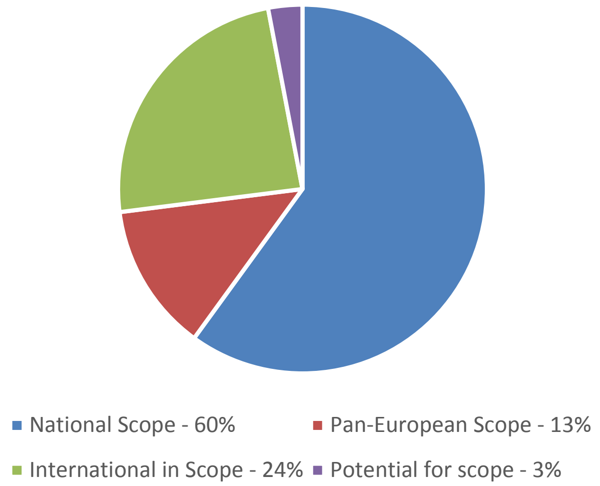


Figure 6: Applicability – Document Coverage

- Scope (Figure 7)
  - Onshore
  - Offshore
  - Generic (i.e. applies to industrial health and safety contexts in general)

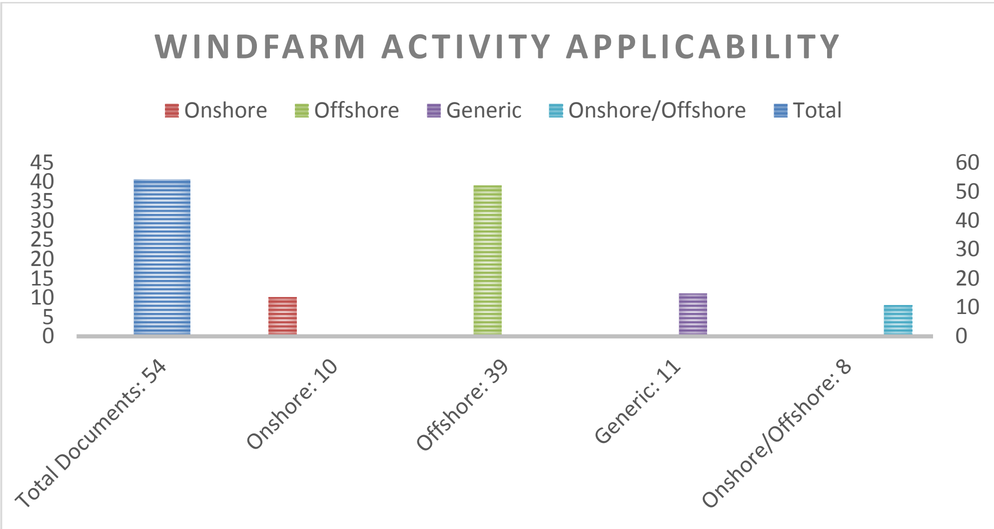


Figure 7: Legislation & Policy Document Scope – Document

Coverage (Figure 8)

- Windfarm Activity Applicability
  - Design
  - Construction
  - Installation & Commissioning
  - Operation
  - Maintenance
  - Decommissioning

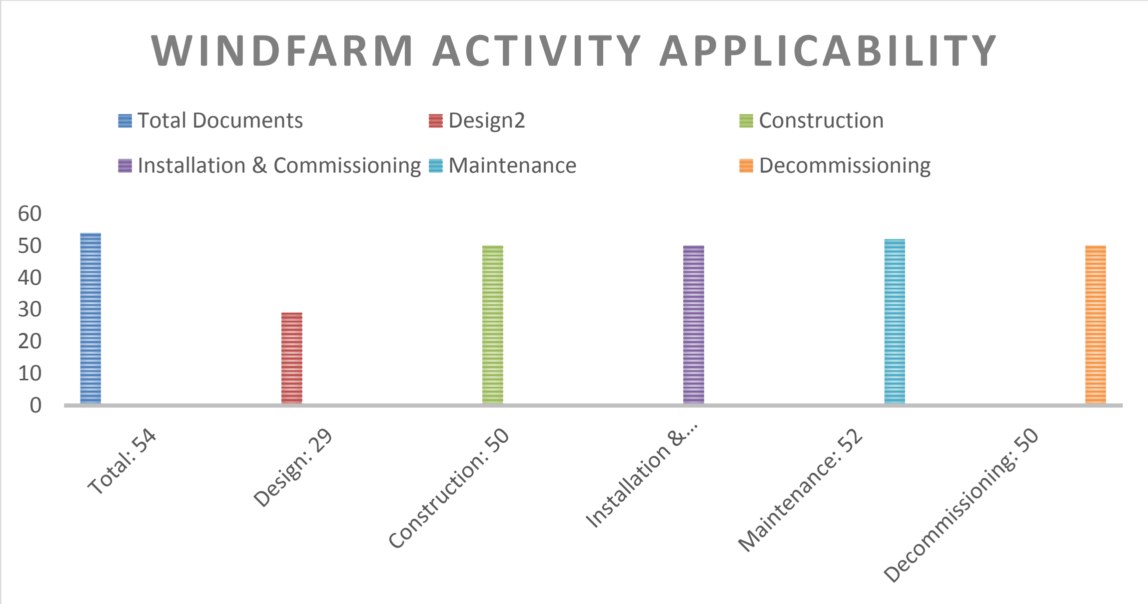


Figure 8: Windfarm Activity Applicability – Document Coverage

2.1.2.5 Evaluation - Gap Analysis:

- There are "no specific health and safety *regulations* applicable to Offshore Wind Farms"; ***Offshore Wind and Marine Energy Health and Safety Guidelines, Renewable UK*** [13]
- New offshore windfarms are being erected further out to sea in deeper waters and the complexity of the construction and maintenance of these Offshore Wind Farms is creating new diverse health and safety challenges. Much of the existing health and safety material was conceived and set down at a time when most if not all offshore windfarms were smaller and in shallower more sheltered waters and may not be sufficient to adequately address new health and safety challenges
- The national health and safety legislation for multiple countries e.g. France, the Netherlands and Norway do not make explicit reference to offshore windfarms
- As outlined in figure 6.3.4, of the 54 documents identified, 32 of them have national scope (circa 60%), only 7 of them have pan-European scope and 13 are international in scope. This suggests a lack of Offshore Wind Farm health and safety regulation in many coastal EU states
- The dearth of materials identified with pan-European scope is suggestive of a disjointed, regulatory framework without an overarching vision for comprehensive and consistent treatment of the question of Offshore Wind Farm health and safety across the European Union.
- 21 of the documents (39%) identified are either generic (i.e. apply to industry health and safety activities in general) or are written in the context of *onshore* wind health and safety
- The increase in the number of Offshore Wind Farms has seen a significant increase in the number of accidents occurring annually within the wind energy sector. There is however a significant gap in the *availability* outside industry actor organisations of accident data and details for analysis purposes. What data is available e.g. the

Incident Safety Report. G9 Offshore wind health and safety association [35] is of such a summary nature and lacking in detail to be of little utility for providing recommendations on improving health and safety

- The plethora of health and safety legislation and the fact that little of it was conceived with offshore activities in mind gives rise to sometimes less than satisfactory situations such as when a jack-up rig is jacked up, it is required to comply with shore health and safety rules, not maritime / offshore ones or when an O&M worker is on a transfer vessel maritime rules apply, when they are on a fixed structure others apply. While there does appear to be clarity in general about what legislation applies to a specific activity at a specific time, the potential for confusion about when one piece of legislation goes out of scope and another comes into effect is present
- We did not see any reference to safe working hours specifically for Offshore Wind Farm personnel. Given the very particular nature of Offshore Wind Farm O&M activities in particular (i.e. extended transit times in sometimes inclement weather) this is a matter that we suggest deserves specific attention by regulators

2.1.2.6 Strategic Considerations

Future Research

- An industry dialogue with health and safety experts and researchers should take place to find a way to make details of accidents and incidents available for analysis. This is a fundamental requirement to maintain and improve Offshore Wind Farm health and safety and is an important precursor to making any changes to existing legislation, guidelines etc. and to the introduction of any Pan-European unifying legislation, guidelines etc.
- A review to assess the continued relevance and suitability of existing regulations, guidelines etc. for larger Offshore Wind Farms further offshore should be undertaken
- The plethora of distinct pieces of legislation, guidelines, standards etc. that exist are confusing and have resulted in an overly complex landscape where offshore windfarm health and safety is concerned. There also appear to be national legislation gaps in a number of countries where Offshore Wind Farms are not covered explicitly by any legislation. It is recommended that a Europe-wide review be undertaken with the goal of consolidating existing national and pan-European legislation into a single unified body, specifically focussed on Offshore Wind Farms across Europe and with Pan-European applicability. This would address both national legislative gaps (see next) and the current complex legislative landscape.

Specific Recommendations

- In reviewing existing legislation, guidelines etc. for continued suitability and in proposing any new legislation, the issue of Offshore Wind Farm personnel working hours (particularly O&M personnel) should be explicitly considered.
- Following the development of a Pan-European body of legislation specifically for Offshore Wind Farms, each European coastal state that could possibly have

Offshore Wind Farms should adopt the Pan-European Offshore Windfarm Health & Safety Legislation

2.2 Health & Safety risk assessment in the offshore wind industry

According to a report published by the United Kingdom's HSE [36], regarding effective management of risks in the work environment, and the guidance document published by the ABS [37], regarding risk assessment applications in the marine offshore oil & gas industry, the risk assessment process consists of the following stages:

1. **Identification of the hazards** in a particular workplace, such as working at height and exposure to harmful substances.
2. Determining how often a dangerous situation occurs by applying a qualitative or quantitative methodology for **assessing the corresponding frequencies**.
3. Estimating the impact of each dangerous situation by modelling and **assessing the consequences**.
4. **Evaluation of the resulting risk** for each dangerous situation for the purpose of prioritizing the allocation of the necessary resources.

In order to conduct a comprehensive risk assessment, various techniques, either qualitative or quantitative, have been developed depending on the availability and quality of information. Some indicative examples include: literature survey or Hazard Operability (HAZOP) studies for **hazard identification**, historical records and fault tree analysis for **frequency assessment**, event trees and effect models for **consequence assessment** and risk matrices, risk indices and F-N curves for **evaluating the resulting risk.**

A survey of the relevant literature has uncovered some notable applications of comprehensive risk assessments for the offshore wind industry. [38] presented a comparison of different risk analysis techniques, applied in challenges that are unique in the offshore wind industry (i.e. collision between a vessel and a wind turbine and personnel access to the offshore installation) and discussed the application of relevant risk reducing measures. Ship collision risk for Offshore Wind Farms has been investigated in more depth by [39], who calculated ship collision frequencies by taking into account parameters such as ship traffic, navigation routes, geometry of the wind farm and the local bathymetric profile. The same study also proposed specific risk reducing measures. [40] examined the risks involved in the O&M phase of an Offshore Wind Farm by applying Failure Mode, Effects and Criticality (FMECA) analysis as well as Hazard Identification (HAZID) methods, and also suggested a number of risk control measures.

2.3 Existing accident databases

A major problem that was encountered, during the development of the methodology presented in this deliverable report, was the significant lack of accident data availability and/or access. This is partly owed to the fact that in some countries the industry is relatively new (i.e. accident reporting is not yet established) and that accident data and reports are mostly bound by confidentiality clauses. A significant source of information, as identified by [24], is the publically available accident database that has been compiled by the CWIF [41]. Another source of information are the reports from the UK's HSE [42], Offshore Injury, Ill Health and Incident Statistics, in accordance with the RIDDOR requirements, 1995. More recently, the G+ Offshore Wind Health and Safety Association (formerly G9 Offshore Wind Health and Safety Association) has released reports containing statistics for occupational health and safety accidents [43], [35].

2.3.1 Caithness Windfarm Information Forum (CWIF)

The accident database provided by the CWIF is currently the most comprehensive source of incident information available. The data is publically available from the CWIF web-site (http://www.caithnesswindfarms.co.uk/). The database includes all documented cases of wind turbine related accidents and incidents, which are either available through press reports or official information releases. In addition, it is frequently updated and the current version contains accidents and incidents up to 30 June 2016.

<u>**Database description**</u>

The database contains the following fields of information:

- Accident type
- Date
- Site/Area
- State/Country
- Turbine type
- Details
- Info source
- Web reference/link

The CWIF database contains accidents and incidents for both onshore and Offshore Wind Farms. The total number of documented cases, from 1970 up to June 30 2016, is equal to 1909. A descriptive statistical analysis that was conducted on the records of the CWIF database revealed that it contains 121 documented cases of human injuries on Offshore Wind Farms for the time period 2004 – 2016.

The majority of recorded human injuries, as shown in Figure 9, are actually near misses and comprise 45% of the total number of cases. Minor injuries and medical treatment injuries comprise 17% and 18% of the total number of cases and fatalities 8%.

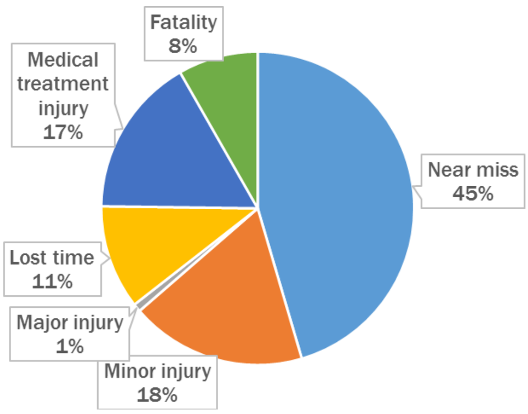


Figure 9: Distribution of human injuries per consequence type (Data source: CWIF)

Figure 10 shows the distribution of recorded human injuries according to the type of accident (i.e. construction, diving operations, dropped object during lifting operation, marine operations, operation/maintenance, transfer by vessel and vessel collision with WTG). The majority of cases (about 83%) occurred during routine O&M operations, while about 7% of documented injuries occurred during two (2) documented accidents involving a vessel that collided with a WTG. The corresponding injuries were serious enough to need medical treatment. Diving operations occupy 5% of the documented cases and it is worth mentioning that every case resulted in diver fatalities.

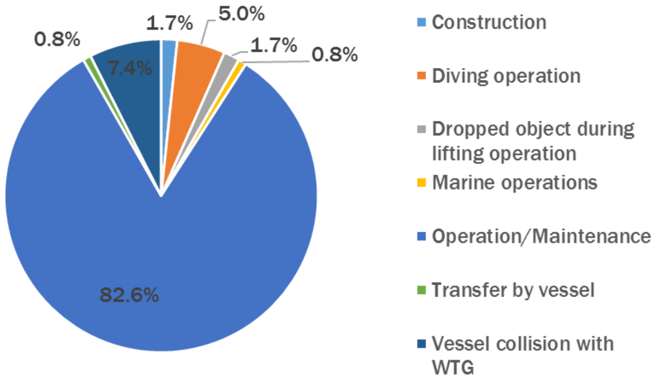


Figure 10: Distribution of human injuries per accident type (Data source: CWIF)

Figure 11 shows the yearly fluctuations in the number of documented human injuries on Offshore Wind Farms according to the particular consequence type (i.e. near miss, minor and major injuries, lost time accidents, medical treatment injuries and fatalities). It is observed that the majority of incidents, which are near misses, had an upward trend in the time period between 2004 and 2008, when the maximum number of near misses was documented. From 2008 up to 2016 there were no near misses reported. The same trend is also observed for the total number of human injuries recorded in the CWIF database. Notably, fatalities have only been documented during the time period 2009 – 2014, with the maximum number (5 cases) in 2012.

<u>Completeness</u>

CWIF states that with regard to accident numbers and frequency, the cases included in the database “may only be the tip of the iceberg”. An article from the Daily Telegraph in December 2011, which was confirmed by RenewableUK, reported that during the time period from 2006 to 2010 there had been 1500 wind turbine related accidents and incidents in the UK. Comparatively, for the same time period, the CWIF database contains only 142 wind turbine related accidents in the UK. Therefore, as stated in the CWIF web site, the database “may only represent 9% of actual accidents”.

<u>Reliability</u>

Although the CWIF database constitutes perhaps the most complete source of relevant information, its reliability can be considered quite low as the information is mostly derived from mass-media sources, which are in most cases rather vague and possibly biased.

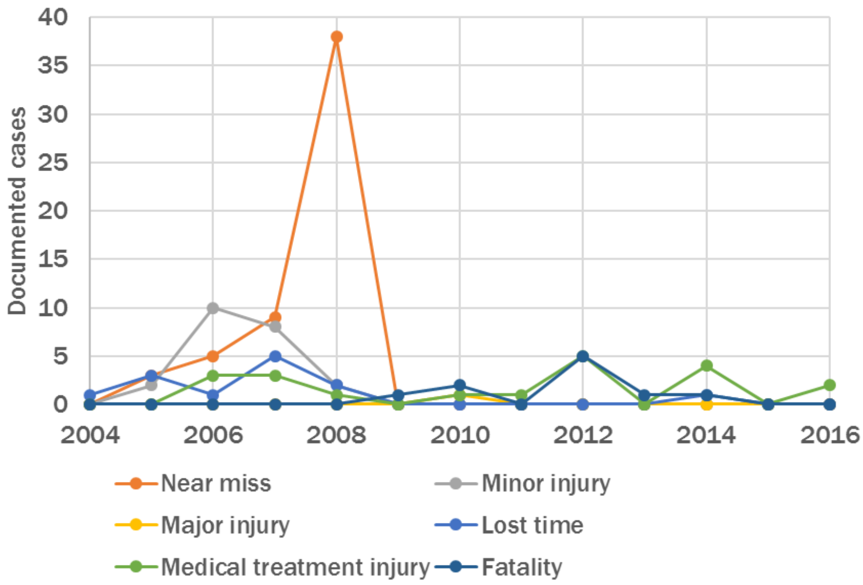


Figure 11: Yearly documented cases of human injuries per consequence type (Data source: CWIF)

2.3.2 G+ Offshore Wind Health and Safety Association

The G+ Offshore Wind Health and Safety Association (formerly G9 Offshore Wind Health and Safety Association) is a group of industry leaders that "aims at delivering world class health and safety performance across all of its activities in the offshore wind industry". This association collects, analyses and publishes Offshore Wind Farm related incident data in order to improve health and safety performance. Since 2013 the G+ has published annual incident reports that contain descriptive information from the analysis of the data they collect. It should be noted that the G+ association does not publish raw statistical accident data.

Figure 12, Figure 13 and Figure 14 provide a sample of the summary statistics that were published in the G9 2013 [43], 2014 [35] and 2015 [44] incident data reports respectively. It is observed that in 2014 about 56% more incidents have been reported compared to 2013. During the year 2015, the total number of incidents has remained relatively stable compared to 2014, showing about 2.5% increase, and compared to 2013 the number has increased by about 60%.

Key facts

616	reported incidents
0	**fatalities**
66	total **lost work days**
4	injuries to employees and contractors reported under **RIDDOR**
373	incidents occurred on **operational** sites
243	incidents occurred on **project** sites

Work process

165	**lifting operations** incidents
45	incidents occurred when **working at height**
131	incidents during **marine operations***

Incident area

281	incidents occurred on **vessels**
178	incidents occurred in the **turbine** region
124	incidents occurred **onshore**

* Marine operations comprises the following work processes: maritime operations, transfer by vessel, vessel operations, vessel mobilisation.

Figure 12: Summary statistics as presented in the G9 2013 incident data report [43]

Key facts		Work process	
959	reported incidents	228	incidents during **marine operations***
0	**fatalities**	140	**lifting operations** incidents
44	total **lost work days**	134	incidents occurred when **operating plant and machinery**
6	injuries to employees and contractors reported under **RIDDOR**	**Incident area**	
651	incidents occurred on **operational** sites	369	incidents occurred in the **turbine** region
289	incidents occurred on **project** sites	315	incidents occurred **onshore**
15	incidents occurred on **survey** sites	243	incidents occurred on **vessels**

* Marine operations comprise the following work processes: maritime operations, transfer by vessel, vessel operations, vessel mobilisation.

Figure 13: Summary statistics as presented in the G9 2014 incident data report [35]

Key facts		Work process	
983	reported incidents	194	incidents during **marine operations***2
0	**fatalities**	100	**lifting operations** incidents
41	total **lost work day** incidents	78	incidents occurred when **working at heights**
2	incidents reported under **RIDDOR***1	70	incidents occurred when **operating plant and machinery**
654	incidents occurred on **operational** sites	**Incident area**	
314	incidents occurred on **project** sites	375	incidents occurred in the **turbine** region
8	incidents occurred on **development** sites	342	incidents occurred **onshore**
		213	incidents occurred on **vessels**

*1 One incident reported under a DO where there was the potential to cause personal injury

*2 Marine operations comprise the following work processes: maritime operations, transfer by vessel, transit (vessel), vessel operations, vessel mobilisation.

Figure 14: Summary statistics as presented in the G9 2015 incident data report [44]

2.3.3 HSE – Offshore Injury, Ill Health and Incident Statistics

The HSE publishes annual reports with details of offshore accidents, dangerous occurrences and ill health. These Annual Offshore Statistics & Regulatory Activity reports analyse cases that are reported to HSE under the RIDDOR requirements. The reports include statistical information both for offshore oil & gas installations, as well as for Offshore Wind Farm installations. In particular, the reports include incidents that have occurred on offshore installations, offshore wells (and activities in connection with them), offshore pipelines, pipeline works (and certain activities in connection with pipeline works), Offshore Wind Farms and offshore diving operations. The following activities are excluded from the Offshore Statistics & Regulatory Activity reports: incidents arising from marine activities that are not directly connected with offshore operations (e.g. vessels or rigs in transit) and air transport activities (except incidents involving helicopters whilst on an offshore installation.

3 Health & Safety related accident case studies

This Section will present selected case studies of actual health and safety related accidents that have occurred in Offshore Wind Farms. Due to difficulties in gaining access to detailed information for various different accident cases, the presented cases have been limited to specific critical accident scenarios that have been identified from the available statistics and the relevant literature.

By taking into account the HSE reports as well as the CWIF data, [24] have identified the following most frequent dangerous situations for Offshore Wind Farms: falling objects during **lifting operations**, **ship collisions**, worker **access** to the installation, **working at height**, and emergency handling. Additionally, the G+ Association, in their Annual Incident Data Reports for 2013 [43] and 2014 [35], has reported that the three dangerous situations with the highest risk are the following: **lifting operations**, **working at height**, and **marine/vessel operations.** Therefore, the identified accident scenarios are considered as critical due to the fact that they may result in adverse consequences regarding occupational health and safety in Offshore Wind Farms, and can also occur in different phases of the Offshore Wind Farm life-cycle.

The selection of the case studies aims at providing insights into the identified critical accident scenarios, which were employed in the development of the risk models for the health and safety risk assessment methodology that was applied. The information for the presented case studies has been published on the web site of the MAIB (Marine Accident Investigation Branch) in the UK (www.maib.gov.uk).

3.1 Crane collapse

This accident occurred during a lifting operation in an Offshore Wind Farm of the North Sea. The crane of a JUV collapsed during the phase of assembling a WTG and the lifted object fell into the sea.

Table 2 shows the details of the accident (i.e. accident type, consequence date, location, weather conditions and sea state).

Accident details	
Accident type	Collapse of crane on JUV during a lifting operation
Consequence	No injury
Date	14/11/2003
Location	Offshore Wind Farm, UK
Day light	No
Sea state	Rough/stormy Wave Height 3m - 9m
Wind	7-9 Beaufort

Table 2: Details for the crane collapsing accident

Accident description

A JUV was anchored and above the sea surface in order to complete a lifting operation for the assembly of a WTG. The lifting operation commenced after the part of the WTG that was being lifted was secured based on the current weather conditions (i.e. wind strength and direction). At some point, wind strength increased to 30 m/s (11-12 Beaufort) and changed direction by 90°. The crane could not hold under these circumstances and collapsed. The part of the WTG that was being lifted fell into the water and no injury was reported.

3.2 Vessel collides with WTG

This accident involved the collision of an Offshore Wind Farm support vessel with a WTG test pile. The consequence was the injury of one of the workers on site.

Table 3 shows the details of the accident (i.e. accident type, consequence date, location, weather conditions and sea state).

Accident details	
Accident type	Offshore Wind Farm support vessel (18m length) collides with WTG
Consequence	Worker injured
Date	08/02/2010
Location	Offshore Wind Farm, UK
Day light	Yes
Sea state	Calm
Visibility	Good
Wind	0-3 Beaufort

Table 3: Details for the vessel collision accident

Table 4 shows the details of the injured worker (i.e. age, gender, working hours, on duty, days at sea, and type of injury).

Injured worker details	
Age	Approx. 35 – 39
Gender	Male
Working hours	3 hours
On Duty	Yes
Days at sea	1 day
Type of injury	Bone fracture

Table 4: Details of the injured worker for the vessel collision accident

<u>Accident description</u>

An 18m length support vessel was heading towards one of the WTG in the Offshore Wind Farm. At the time of the incident, the stern of the vessel was positioned about 3m away from a WTG test pile. The master of the vessel was fully aware of the obstruction. As the vessel was underway, the master accidentally caused the vessel to move astern. The master immediately realized what had happened and tried to halt the vessel. However, the vessel was already so close to the test pile that there was not enough space for manoeuvring. Consequently, the vessel collided with the test pile causing some minor damage to the hull. An indirect consequence of the incident was the injury of a worker who was on-board the vessel, as he slipped by the vibration of the impact and fell causing a bone fracture.

4 Health & Safety Risk Assessment

The Health & Safety risk assessment methodology that was applied follows the general guidelines set by the IMO for FSAs and comprises the following steps: 1) hazard identification, 2) risk modelling, 3) qualitative analysis, and 4) semi-quantitative analysis. The structure of this Section is described briefly below.

Initially, the hazards that are relevant for the different life-cycle stages of an Offshore Wind Farm have been identified from an extensive survey of the relevant literature. The results provided important insights and input for the subsequent development of the risk models.

The risk assessment methodology is based on the development of risk models in the form of bow-tie diagrams, which were constructed for specific scenarios that lead to adverse effects on occupational health and safety. These models will be subsequently used for the qualitative and semi-quantitative analysis.

The qualitative analysis of the bow-tie diagram comprises the analysis of the fault trees and event trees and will determine the events that have the most influence on the occurrence likelihood of the adverse top event and that play the most crucial part in the development of the consequences.

The semi-quantitative analysis that was conducted aimed at evaluating the effectiveness of safety barriers that have been identified from a survey of the relevant literature. The following taxonomy of safety barriers [6] has been used in the identification process:

- **Technical barriers**. The application of such measures is considered to be highly effective, since their use may either prevent a hazard from evolving into an actual accident or lower the occurrence probability of the accident. Examples of technical safety barriers include a safety valve or a smoke detector.
- **Human/Organizational barriers**. The effectiveness of such measures is considered to be average, because while they may lower the occurrence probability of an initiating event, if the initiating event does happen then they have no effect on the development and the realization of the accident. These measures usually are related to the control of an activity or process. Examples of human/organizational safety barriers include work supervision, worker training and proper equipment maintenance.
- **Fundamental barriers**. These measures are applied before the occurrence of various initiating events that might lead to an accident and therefore their effectiveness is low close to the time of the accident. These barriers are useful for improving the overall safety performance of a system by treating the underlying causes of failures that lead to the occurrence of accidents. Examples of fundamental safety barriers include work planning and maintaining the health of the workers to a high level.

The final part of this Section details the methodology that was applied and the corresponding results regarding the assessment of LEANWIND innovations. In this context, specific RCOs (where and if applicable) would be recommended with the aim to maintain or improve the health and safety risk levels in Offshore Wind Farms.

4.1 Hazard identification

Offshore Wind Farms are complex installations that incorporate various technical innovations. Consequently, they introduce a novel mix of health and safety hazards for the workers throughout all the life cycle phases. It is therefore essential to conduct a comprehensive and thorough hazard identification, to effectively support any risk assessment process. The conducted hazard identification was based on an extensive literature survey. A major source of information were relevant guidelines, which are published by various wind energy associations, concerning Health and Safety in the offshore wind industry. It must be noted that these guidelines constitute codes of best practice and generally provide an overview of the relative occupational hazards, along with proposed RCOs. Notably, one of the most comprehensive documents are the Health and Safety Guidelines published by RenewableUK [13].

The process resulted in classifying the identified hazards into two groups, one containing hazards that are common with other industrial activities (Figure 15), and another that contains hazards that are particular to Offshore Wind Farms (Figure 16). A non-exhaustive list of common industrial hazards that are present in Offshore Wind Farms include: fire, various lifting operations, working at height, confined spaces, rotating machinery etc.

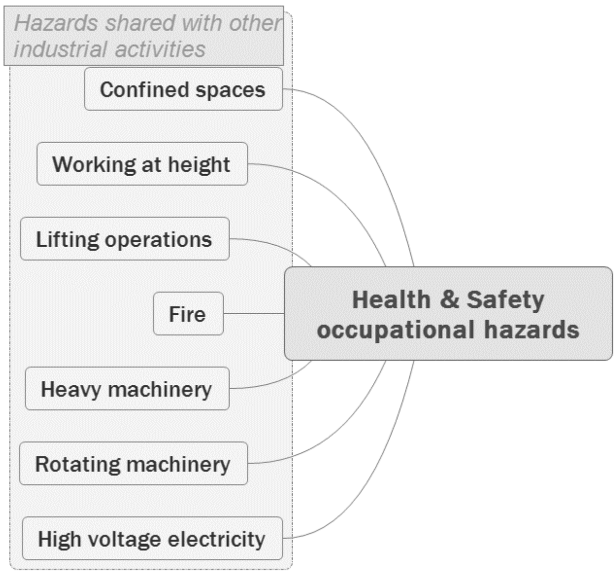


Figure 15: The common industrial hazards in Offshore Wind Farms

Additionally, hazards that are particular to Offshore Wind Farms are mainly owed to the marine environment, the weather conditions and various shipping operations which take place during the life cycle of an Offshore Wind Farm. For example, due to the fact that underwater operations are essential for every life cycle phase of an Offshore Wind Farm, the consequent exposure of the divers to the marine environment creates various health and safety hazards. Another example is the varying and often unpredictable environmental conditions (e.g. sudden changes in the sea state), to which the wind farm site can be exposed to and which introduces serious threats not only for the workers but also for the equipment and components. This parameter will play an increasing part in the mix of Offshore Wind Farm hazards, as they are installed to ever greater distances from the shore. Additionally, a large number of operations at an Offshore Wind Farm require the use of ships, resulting in the exposure of the workers to various threats related to ship operation, such as collision between ships or collision between a ship and a wind turbine. This issue becomes even more complicated when SIMOPs are in progress.

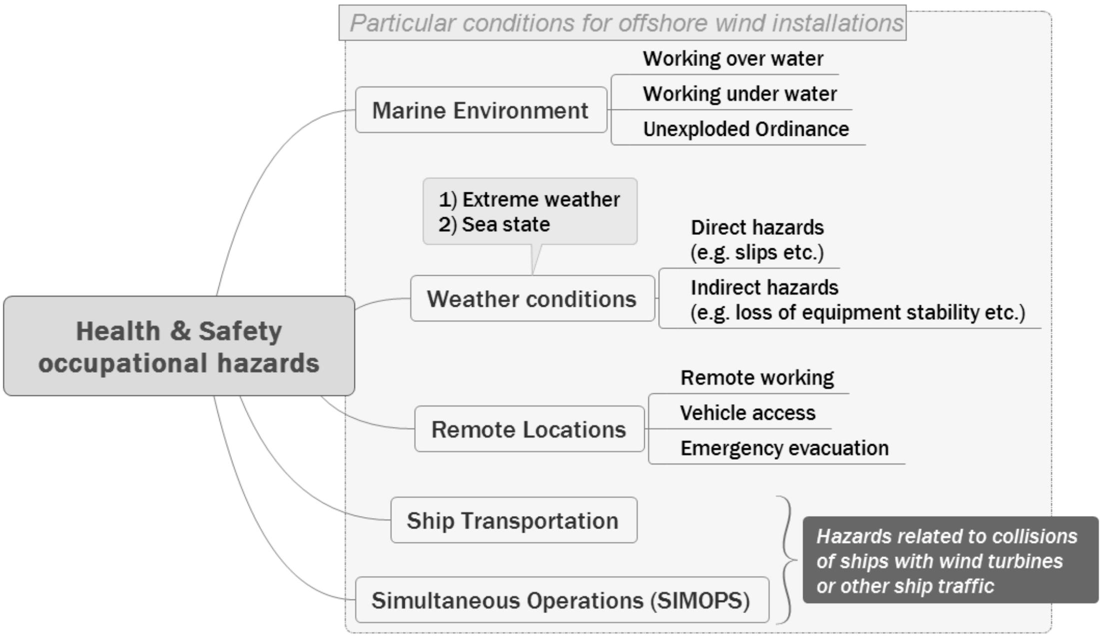


Figure 16: The particular occupational hazards in Offshore Wind Farms

Figure 17 classifies the identified hazards into the phases of the Offshore Wind Farm life cycle, according to the relevant literature [13], excluding the Project Design phase. It must be noted that, most of the identified hazards are present in more than one life cycle phase. Additionally, all identified hazards are present in the O&M phase (3), which is the phase with the longest duration, and most are shared with the Construction (2) and Decommissioning (4) phase, which are very similar in terms of work tasks.

Occupational Hazards	Lifecycle Phase				
	1	2	3	4	5
Confined spaces			•	•	
Working at height		•	•	•	
Lifting operations	•	•	•	•	
Fire	•	•	•	•	•
High voltage electricity	•	•	•	•	•
Access and Egress	•	•	•	•	
Cable laying		•	•		
Noise	•	•	•	•	•
Hazardous substances		•	•	•	•
Vibration	•	•	•	•	
Underwater operations		•	•	•	
Met-ocean conditions	•	•	•	•	
Marine operations	•	•	•	•	
Remote working	•	•	•	•	

Legend

1. Transportation
2. Construction
3. Operation and Maintenance
4. Decommissioning
5. Recycling

Figure 17: Occupational hazards per life cycle phase present in Offshore Wind Farms

4.1.1 Common Industrial Hazards

<u>Confined spaces</u>

For the reason that a large number of operations are taking place inside the pile or in the turbine the definition of confined spaces is of crucial importance. According to the Renewable UK Guidelines [13] a confined space is defined as "a place which is substantially (though not always entirely) enclosed and, secondly, there will be a reasonably foreseeable risk of serious injury from hazardous substances or conditions within the space or nearby".

When people are working in a confined space there are some hazards, which have as their main cause the limited exchange of air in the space. For instance, any hazardous substance in the air is possible to be inhaled by workers having as consequence loss of consciousness or asphyxiation. Another very important issue is the temperature inside the space which can be high because of the limited air currents. An additional hazard which arises from working in such a space is the possibility of drowning due to ingress of water, as in such a case people have restricted freedom of movement and evacuation is considered a time consuming procedure. In confined spaces every effect/consequence of another hazard (i.e. fire) is multiplied due to the fact of the limited space. Finally, difficult evacuation of injured persons multiplies the consequences of a certain event.

Work at height

An activity can be characterized that is taking place at height when there is the possibility of workers to fall and get injured or die. Work at height activities are very common in the life cycle of an Offshore Wind Farm. In particular, for every lifting operation the use of crane or derricks, which are fitted on the deck of the vessels, is obligatory. Additionally, any activity or operation that requires the use of a ladder is considered to be an activity of working at height.

The main hazards that the employees are exposed to are the following:

- Any fall from height, regarding people can result to injury or even death.
- Any object which drops from height is a potential hazard for the people who are working beneath.

Adding to the above the environment of an Offshore Wind Farm, especially the sea, the hazards which described can be more complicated because of the dynamic nature of the environment (i.e. winds, waves, sea currents).

Lifting Operations

Lifting operations are continuously taking place in the whole life cycle of offshore wind farms. From the construction phase where most of the heavy parts (e.g. rotors, pile compartments) are lifted at large heights in order to be assembled, to the maintained stage where smaller parts and appropriate equipment are lifted also. Every lifting operation requires a crane or derrick, which are fitted on the main deck of offshore installation vessels, including JUV.

The main hazard which arises in this category is the possible fall of the objects that are lifted due to any malfunction of the lifting equipment of the crane. Such an incident is possible to cause serious injuries to the people who are working beneath (i.e. on the deck of the offshore vessel), or even cause a structural damage of the ship which may lead to the sinking of the ship and consequently it poses a great threat for the lives of the crew working on the vessel.

Floating ships with fitted cranes are vulnerable to waves as their stability (e.g. draft, trim, heel) is highly dependent on the wave height as well as the weight and height of the lifted object. Moreover, the environment in these operations in Offshore Wind Farms is considered to be highly dynamic with a lot of unpredictable changes in weather and sea conditions, making the operation even more complicated.

Fire

The hazard of fire exists in almost every working environment, but in Offshore Wind Farms it has a more complicated nature. Fire poses a threat not only to human life but also endangers structural integrity. Fire in Offshore Wind Farms threatens occupational health and safety only when workers are on site. That is during the construction, maintenance and decommissioning stages. Furthermore, the possibility of fire exists in all ships which are used in Offshore Wind Farms for any activity.

Due to fire people may be faced with the following hazards:

- Burns, caused by flames or extremely hot surfaces;
- Smoke, which can be inhaled and causes unconsciousness, asphyxiation or even death;
- Toxic/hazardous emissions, which can be inhaled and caused unconsciousness, asphyxiation or even death;
- Explosions.

High Voltage (Electrical Safety)

Because of the nature of the working environment, electricity poses a threat for people who are working in Offshore Wind Farms. In particular, the presence of high voltage systems (i.e. transformers), low voltage systems (generators, various devices) and the use of some portable equipment create a lot of hazards for the workers.

The hazards which are created are the following:

- Electrical shock, which has a wide range of consequences from light injuries to death;
- Explosion;
- Fire;
- Arc flash, which may cause skin burns, eye damage and exposure to UV radiation.

Another very important issue is that any possible loss of electricity may reduce or cause various problems in a lot of systems in a farms such as communications, lighting, and lifting equipment.

Noise

The main source of noise usually are tools, generators, helicopters etc. Any exposure of people to high levels of noise can result to temporary or even permanent loss of hearing/damage. It is noted that the effect of noise can be multiplied for divers as described later on.

Vibrations

Workers may be exposed to the following types of vibrations: Harm-Arm Vibration (HAV) and Whole Body Vibration (WBV). HAVs are caused by the use of various tools and equipment, whereas WBVs are caused usually inside the offshore vessel during the transportation on site, and vice versa, because of shocks due to weather and sea state conditions.

HAVs can cause various issues on nerves, joints as well as in blood vessels. It is evident that the issues are correlated to the magnitude and the duration of the vibrations. The consequence of these issues may be temporary arm pain, which may last from a few hours up to few days. Continuous exposure to vibrations for a large period of time without the appropriate resting pauses may cause more permanent injuries such as reduced grip strength.

WBVs are highly dependent on the weather and sea state conditions (i.e. as the external conditions worsen) the shocks experienced by the people inside the vessels also worsen. Continuous exposure to WBVs may cause serious issues, such as back pain, muscle strains, physical and mental fatigue.

<u>Remote Working</u>

The tendency to build Offshore Wind Farms even further from the shore makes all activities and operations extremely complicated in terms of organizational and operational difficulties. The activities must be organized to be conducted by small groups of workers and the presence of offshore support vessels is essential for the health and safety of all people. Furthermore, taking into consideration the difficulty of the access to the Offshore Wind Farm, because of the large distance from shore, all operations must be planned in a way that people on site will be able to confront any possible undesirable incident. Therefore, the main hazard that the people are exposed to is the time needed for support to reach the Offshore Wind Farm, in case an incident occurs and the appropriate remediation equipment is not present.

4.1.2 Offshore Wind Farm-specific hazards

Apart from the common industrial hazards, Offshore Wind Farms are also endangered by the dynamic environment, where they are installed, and the nature of their structure. Almost every activity in an Offshore Wind Farm is highly dependent on the weather and met ocean conditions. In particular, sea currents, wave height, and wind speed are considered to be very important factors for every operation, because they affect every activity at any life cycle stage at an organizational and operational level. Therefore, weather conditions and sea state are of crucial importance to be predicted, despite the fact that it is not always possible.

<u>Working over water</u>

The hazards that workers are exposed to during activities that take place over the water is similar with that of working at height. The main difference is that working over water is usually more complicated because the additional effect of waves and sea currents, which increase the level of hazardous exposure compared to working at height.

<u>Working under water</u>

Subsea or under water activates are quite common in Offshore Wind Farms either in the construction or in the maintenance stage. Any activity of this kind, requires well trained personnel (i.e. divers) with long diving experience, it must be well organized and have sufficient support on the surface in order to be conducted safely. Despite the fact that there is the alternative of using Remote Operating Vehicles (ROVs) in order to minimize the potential hazards, usually the use of divers is considered to be prerequisite at all stages of the life cycle of an Offshore Wind Farm.

The possible hazards are positively correlated to the depth of the activity, because the pressure increase and the air mixture that is used by the divers to breath is more sensitive to changes. The main hazards that are present in a diving operation are the following:

- Decompression sickness;
- Strong sea currents;
- Wave height;
- Marine traffic above the activity point;
- Restricted visibility;
- Underwater noise;
- Possible entrapment of divers.

Unexploded Ordnance

Unexploded ordnance are posing a threat not only for divers and ships but also for operations in general. A large number of sea mines was released during WWI and WWII that have never been recovered and taking into account the time that they have been submerged they are considered to be extremely unstable. A sea mine may cause an explosion which can seriously damage any ship or turbine that are in the vicinity. Moreover, an explosion can result to serious injuries or death for the personnel that is also in the vicinity.

Marine operations

Any activity that needs a ship in order to be completed is exposed to hazards that have to do with navigational safety. There are two main hazards, which are listed below:

- Collision between ships;
- Collision between ship and turbine.

A lot of activities in an Offshore Wind Farm are taking place simultaneously (i.e. SIMOPS) and this increases the complexity of the operations at an organizational and operational level. The more ships and activities that are simultaneously in progress, the greater the hazard of collision. SIMOPS require strict and detailed marine coordination in order to manage the possible hazard of collisions effectively.

Ports and Mobilisation

The support vessels and equipment for an Offshore Wind Farm is located at the closest port that has the appropriate facilities. Port use is crucial throughout all stages of the life cycle of an Offshore Wind Farm. In particular, during the construction stage the turbine parts and the vessels that are required are located at port. Furthermore, during the Operation and Maintenance stage offshore support vessels and spare equipment are stored at port in case of an emergency. Therefore, the exposure to various hazards for people who are working there is inevitable. The proper organization for SIMOPS is essential in order to avoid not only congestion but also to reduce the hazard of collision between ships and between ships and quays. Apart from the hazards regarding the vessels there are also hazards for the workers, such as the following:

- Tripping into ropes, cables and chains;
- Unprotected quays or edges, which might lead to a possible fall into the sea.

- Moving Vehicles and Equipment.

4.2 Bow-Tie Models

The bow-tie diagram incorporates all possible causes and consequences, as well as the safety barriers that are used to mitigate either the propagation of faults that lead to the dangerous scenario or the magnitude of the resulting consequences [45]. The advantage of using bow-tie diagrams has been demonstrated by [46] and their utility is based on the fact that they directly correlate causes and effects in a way that is easily understandable.

The bow-tie diagrams constructed in the context of this deliverable report constitute a departure from the above mentioned definition because they combine a classic fault tree on the left side (Causes), that leads to the top event, with an event tree (Consequences) on the right side, that expands all the possible consequence combinations from the top event. As shown in Figure 18, the diagrams have been constructed as Generalized Bow-Ties to effectively cover every phase of the Offshore Wind Farm life cycle for each dangerous scenario that was examined (e.g. ship collision with the wind turbine, accident during worker access to the installation, accident during lifting operations etc.). This type of diagram is flexible enough to be used in either a qualitative or quantitative analysis, depending on the availability of information (e.g. frequencies, consequence probabilities etc.).

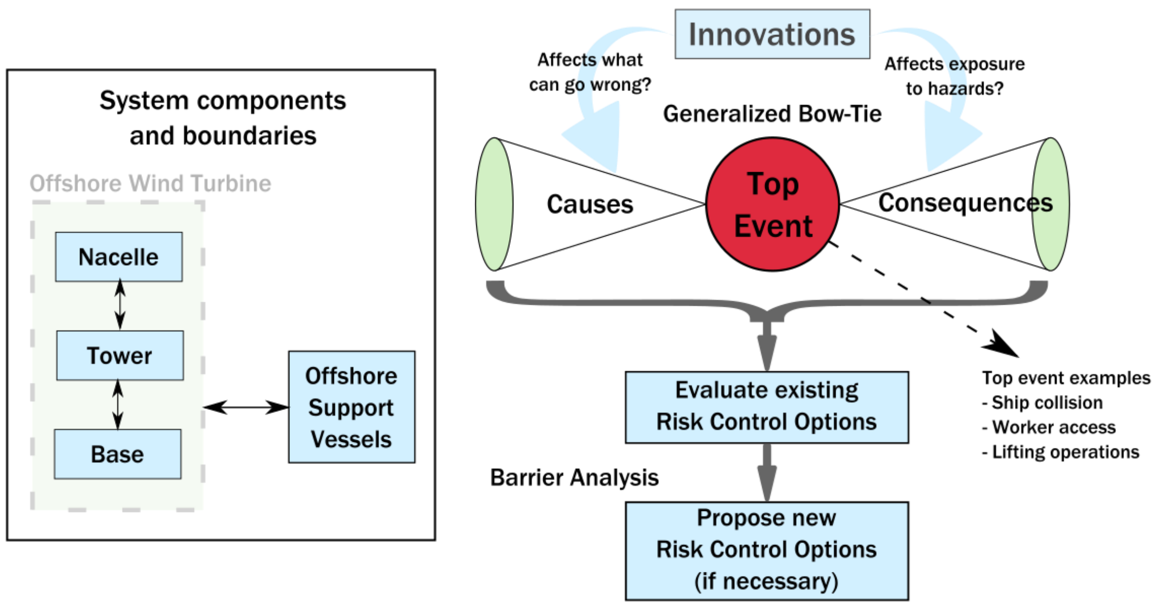


Figure 18: Outline of risk assessment methodology for occupational health and safety in Offshore Wind Farms

Each of the bow-tie diagrams that have been constructed deal with a specific accident scenario (top event). The accident scenarios have been selected on the basis of their frequency, compared to other accident scenarios, as indicated by the available statistics and the relevant literature, as described in the Section presenting actual accident case studies. The following are short descriptions of the selected critical accident scenarios that will be used for the construction of the bow-tie diagrams:

1. Object falls during offshore lifting operation (**construction phase, operation & maintenance phase**).

2. Offshore windfarm CTV collides with the WTG tower during approach (**construction phase, operation & maintenance phase**).
3. Worker loses his balance while moving from the CTV to the WTG (**operation & maintenance phase**).

The bow-tie diagrams have been constructed with a Fault Tree and Event Tree approach, in order to capture all the possible failure paths that might lead to the top event, as well as all the possible consequence paths following the top event. The construction of the bow-tie diagrams has been based on an extensive literature survey and relevant consultations with Task 6.3 partners and industry experts.

Due to the lack of quantitative failure data, the analysis of the bow-tie diagrams will be conducted on a qualitative level (e.g. minimal cut set analysis for the fault trees). Following the qualitative analysis of the bow-tie diagrams, a barrier analysis will be conducted with the aim to determine the most critical barriers that affect the development of the critical accident scenarios that have been selected.

Fault Tree Construction

The intermediate and basic events that comprise each fault tree have been derived from each of the following general categories (Figure 19): human factor failures (e.g. work related fatigue, training, work experience, worker coordination etc.), machinery failures (e.g. either due to excessive wear or insufficient maintenance etc.), Offshore Wind Farm management failures (e.g. work planning, selection of suitable work equipment, work progress monitoring etc.), and work environment characteristics (e.g. weather conditions, corrosive characteristics of the marine environment etc.).

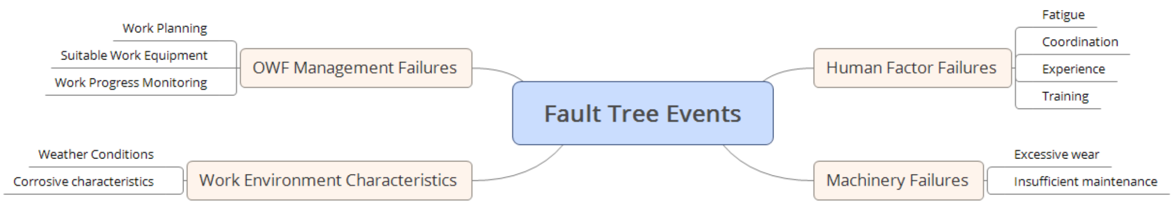


Figure 19: Categorization of intermediate and basic events of the fault tree

Event Tree Construction

The event trees of the bow-tie diagrams have been constructed in such a way as to capture all the possible consequence paths, regarding occupational health and safety, resulting after the accident has occurred. The consequences to the health and safety of Offshore Wind Farm workers have been measured on a 4-level ordinal categorical scale of increasing consequence. Below are the descriptions of each of the four consequence levels:

- **Level 0**: Near miss. The accident results in no adverse health and safety consequences.
- **Level 1**: Accident results in minor injuries for the workers involved. Minor injuries might include scratches, bruises, musculoskeletal pain, dizziness, blackouts etc.
- **Level 2**: Accident results in major injuries for the workers involved. Major injuries might include loss of consciousness, bone fractures, breathing difficulty, internal or external bleeding, paralysis etc.

- **Level 3**: Accident results in at least one fatality (e.g. due to drowning, heart attack etc.).

<u>**Placement of barriers**</u>

Selected safety barriers have been incorporated into the developed bow-tie models based on general information of barriers that are commonly used in Offshore Wind Farms that has been extracted from relevant guidelines and regulations.

4.2.1 Construction of Bow-Tie Models

4.2.1.1 Object falls during offshore lifting operation

<u>**Accident scenario description**</u>

This accident scenario involves the failure of an offshore lifting operation, occurring either during the construction or the operation & maintenance phase of the Offshore Wind Farm, that results in the fall of the object that is being lifted. The object might either be a section of the WTG (e.g. tower section or rotor blade etc.) or a piece of machinery equipment.

Lifting operations for an Offshore Wind Farm are being conducted by specialized vessels fitted with a crane on deck. Construction tasks and large maintenance tasks use one of the following vessel types: JUVs (Figure 20a), HLVs (Figure 20b), and OAVs (Figure 20c). Relatively smaller work boats (Figure 20d) may be used for small scale maintenance tasks. The particular vessel to be used in a specific work task is selected based on the weight of the object to be lifted and the final lifting height. Indicatively, for 5 MW turbines the nacelle can weigh up to 250 tons and the tower up to 350 tons, although the tower is usually not transported as a single piece but in modules. Considering that even larger turbines are being designed, these weights may be even greater. For 8 MW turbines, which are used as a benchmark throughout the LEANWIND Project, the nacelle can weigh between 400 and 500 tons and the tower may exceed 500 tons [47].

<u>**Fault Tree construction**</u>

The immediate causes that lead to an object falling during a lifting operation are the following: a) lifting equipment handling failure, b) lifting equipment mechanical failure, and c) improper lashing of object. Each of these factors are analysed below, outlining the structure of the fault tree that is shown in Figure 21.

Lifting equipment handling failure: This type of failure is attributed to the human factor. According to the HSE LOLER regulations [48], three workers must be engaged during a lifting operation. These are the crane operator, a lifting supervisor for guiding the crane operator due to the restricted visibility, and the safety manager who supervises the work task. A failure in handling the lifting equipment might either be caused by the crane operator due to either a lack of experience or work related fatigue, probably caused by extended working hours. Another factor that might lead to the occurrence of the particular accident, is a failure in the communications between the workers. This might either be caused by a technical failure in the communications equipment or interference due to adverse external conditions (e.g. high noise levels etc.).

Lifting equipment mechanical failure: The lifting equipment includes both the lifting crane and the wire rope that is used to hold the object being lifted. A mechanical failure of the lifting equipment may either be the result of overloading or a structural failure. A structural failure of the lifting equipment is a combination of excessive wear, which may be caused by either corrosion (e.g. from the effects of the marine environment etc.) or operational fatigue (e.g. excessively frequent use of the same equipment etc.), and insufficient maintenance.

(a) (b)

(c) (d)

Figure 20: Common vessel types used in Offshore Wind Farms: (a) Jack-Up Vessel (JUV) [49], (b) Heavy Lift Vessel (HLV) [50], (c) Offshore Access Vessel (OAV) [51], (d) Small work boat [52]

The combinatory effects of the aforementioned factors cause the structural failure, even though the maximum load is not exceeded, because the strength of the structures or equipment has been compromised. In case the mechanical failure is caused by overloading of the lifting equipment, either of the following three factors may lead to the occurrence of this event:

- **Unexpected change in the weather conditions.** The lifting cranes installed on JUVs may safely operate up to 20 m/s wind speed [53]. If there is, for example, a sudden gust of wind, this threshold may easily be exceeded leading to overloading of the lifting equipment.
- **Large and sudden ship movement.** This event may occur, under the influence of external factors such as large waves, either due to a failure of the DP system or a failure of the mooring system of the vessel. Due to the generic nature of the

constructed fault tree, exactly which failure occurs depends upon the system installed on the specific vessel used for the work task.

- **Excessive weight of lifted object.** This event may occur as a combination of a human error during the initial work planning stage (i.e. an initial miscalculation of the required lifting capacity or the selection of lifting equipment with insufficient lifting capacity, and a failure of the on-board overload alarm system).

Improper lashing of lifted object. This type of failure is attributed to the human factor and may be the result of either insufficient training (i.e. the workers did not know how to properly lash the lifted object) or a failure of the coordination between the workers involved in the particular work task (e.g. the workers were given false or insufficient lashing instructions for the particular task).

Event Tree Construction

Two important factors that affect the development of the events, after an object has fallen during a lifting operation, and therefore determine the health and safety consequences are the weight of the object and the height from which it falls. The combination of these will determine the impact force of the contact of the falling object with its target.

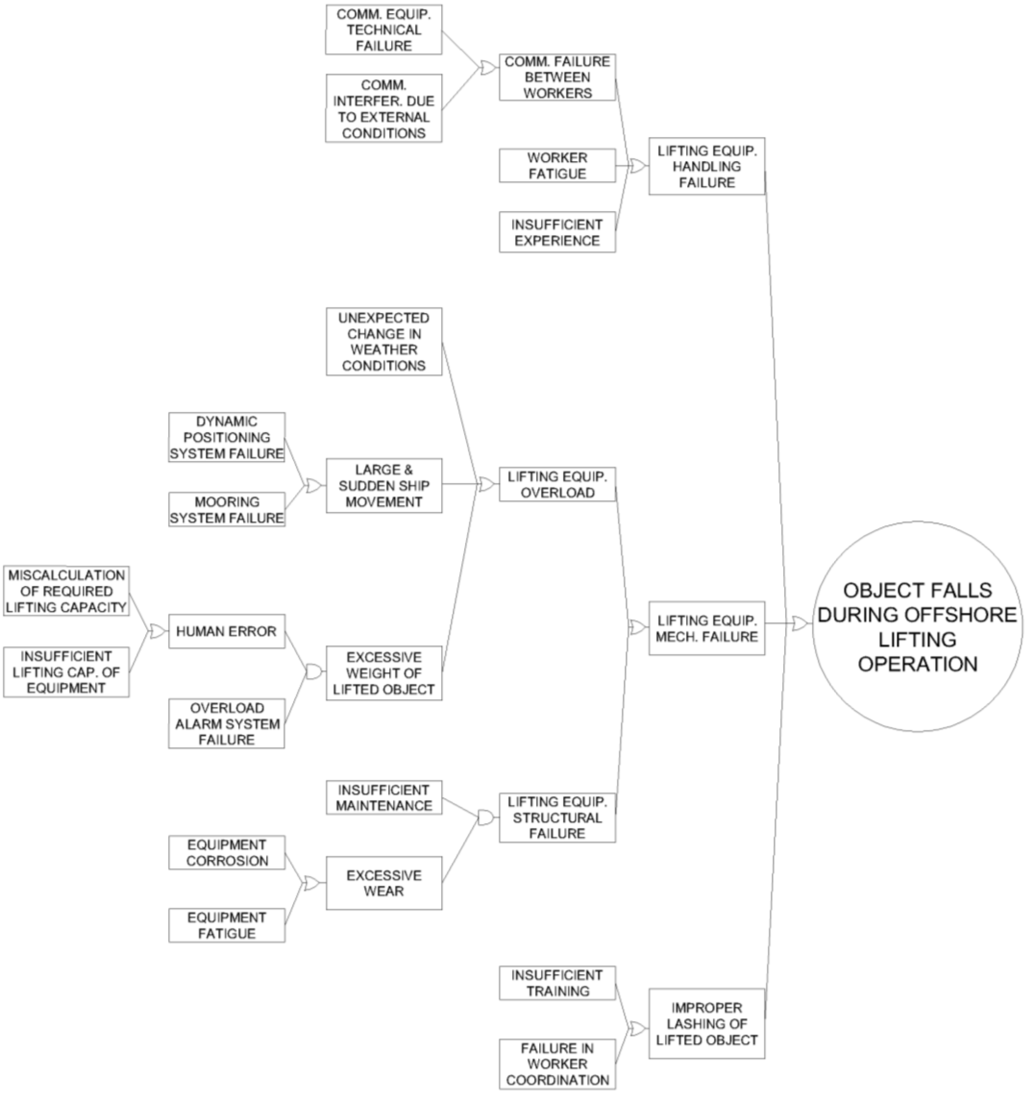


Figure 21: Fault Tree for the accident of a falling object during an offshore lifting operation

The present analysis determined that the following events affect the ultimate consequences to the health and safety of the involved workers. The nodes of the constructed event tree are binary (YES/NO) due to the high-level nature of the analysis. The constructed event tree is shown in Figure 22.

1. **Worker located in the impact area.** If a worker is situated in the impact area of the falling object, the consequences may either be direct (i.e. being struck by the falling object) or indirect (i.e. falling into the sea)
2. **Violent ship motion due to contact with falling object.** A violent ship motion may be triggered either directly by the lifted object falling onto the deck of the vessel or indirectly in case the lifted object falls in the sea near the vessel.
3. **Worker falls in the sea.** This is a direct consequence of the violent ship motion and is applicable for workers situated on the deck of the vessel or on the WTG tower.
4. **Worker wears life jacket.** According to the relevant regulations [54], every worker that is situated on the deck of a service vessel must be equipped with a life jacket. The state of the life jacket, which affects its effectiveness in case it has not been

maintained properly or not replaced, contributes to the severity of the consequences for the worker.

5. **Worker is immediately salvaged.** The amount of time taken to salvage a worker who has fallen in the sea is in some cases crucial for the consequences to health and safety. For example, if a worker suffers hypothermia the probable consequences might be inability to move, loss of consciousness and loss of life.
6. **Ship sinks due to contact with falling object.** This event has been included to capture situations when a very heavy lifted object comes into contact with the vessel and the structural damage is so severe that the vessel begins to sink.
7. **Worker embarks life raft.** A worker may not be able to embark a life raft, e.g. For example, if there is not enough time.
8. **SAR vessel operates nearby.**

The following assumptions have been applied to the construction of the event tree.

- The contact of the falling object with the vessel will not cause any other events (e.g. fire etc.) that might directly endanger the health and safety of the workers.
- The lifting cranes installed on the vessels have an operating radius that does not intersect with the bridge of the vessel. Therefore, only the workers who are situated on the deck of the vessel are endangered.
- The immediate salvage of a worker who has fallen into the sea means that the worker has been retrieved onto the deck of the vessel and therefore is not in danger of drowning.
- If a worker does not have enough time to embark a life raft, then it is assumed that the worker has fallen into the sea.

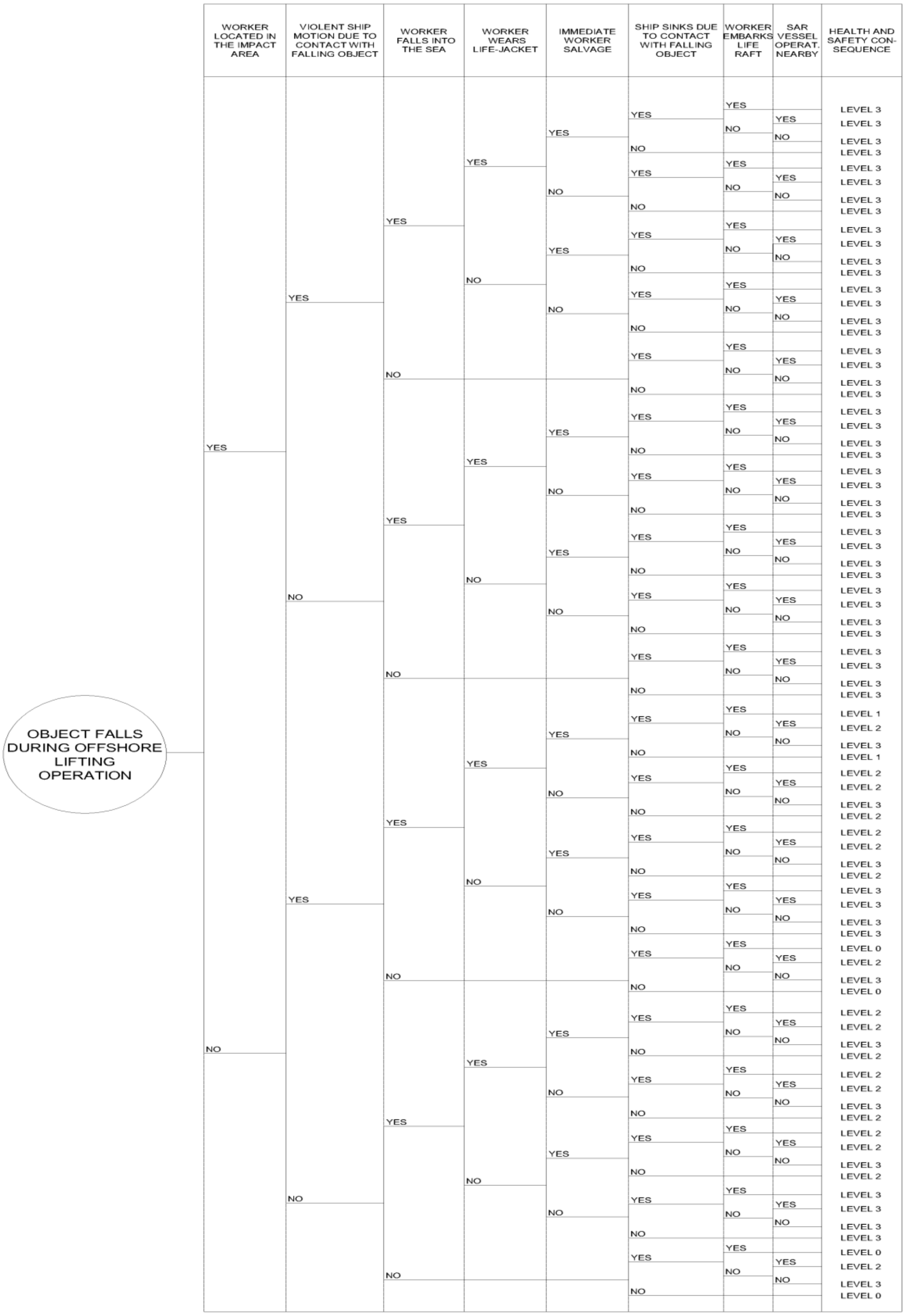


Figure 22: Event tree for the accident of a falling object during an offshore lifting operation

The constructed event tree contains 80 different scenarios that lead to varying degrees (measured on the scale mentioned previously) of health and safety consequence. As shown in Figure 23, the majority of scenarios (70%) lead to Level 3 consequences (i.e. fatality). Additionally, as shown in Figure 23, 23% of scenarios lead to Level 2 consequences, 3% of scenarios lead to Level 1 consequences and 5% of scenarios lead to Level 0 consequences. Therefore, the conclusion can be drawn that lifting operations pose serious threats to the health and safety of the involved workers, since most consequence scenarios lead to a fatality.

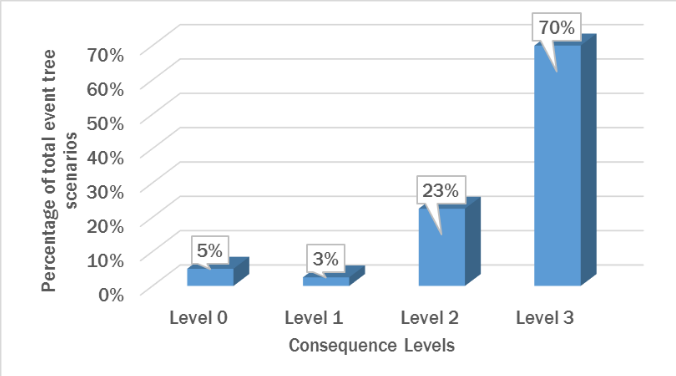


Figure 23: Distribution of consequence levels as a percentage of the total number of scenarios, for the accident of a falling object during an offshore lifting operation

4.2.1.2 CTV collides with WTG tower during approach

Accident scenario description

This accident scenario involves the collision of a vessel with the tower of an offshore WTG, during the transport of workers. This accident scenario may occur either during the construction phase, or the O&M phase, or the decommissioning phase of an Offshore Wind Farm. Transportation of workers from the shore to the Offshore Wind Farm is typically carried out either using small CTVs (L < 30 m, Figure 24a) or larger OAVs (L > 30 m, Figure 24b).

Fault Tree construction

The immediate causes that might lead to the collision of a CTV with the tower of a WTG is either a failure in the approach of the vessel or limited controllability of the vessel due to a technical failure in the navigational machinery [55]. Each of these factors are analysed below, outlining the structure of the fault tree that is shown in Figure 25.

Ship approach failure: The occurrence of this event is a combination of a failure to effectively manoeuvre the vessel and a human error in navigation. The factors that affect the effective manoeuvring of the vessel are the following:

- **An insufficient amount of time available to change course** due to either exceeding vessel speed or limited manoeuvring space (e.g. when the vessel is too close to the WTG tower), or
- **Limited manoeuvrability** due to the effect of adverse weather conditions and a lack of adequate propulsive power (e.g. in case an inappropriately powered vessel has been selected for carrying out the work task), or
- **A technical failure in the navigational equipment**, which might lead to false setting of the course. A human error in the navigation of the vessel might have been caused either by underestimating the external conditions (e.g. vessel position or

speed) due to either work related fatigue or insufficient work experience, or by distracted attention.

(a) (b)

Figure 24: Typical vessels that are used for the transportation of workers in the Offshore Wind Farm industry: (a) Crew Transfer Vessel (CTV) [56], (b) Offshore Access Vessel (OAV) [57]

Limited vessel controllability due to technical failure: The occurrence of this event is a combination of a failure of the navigational machinery (either the propulsion system or the rudder of the vessel) and insufficient maintenance.

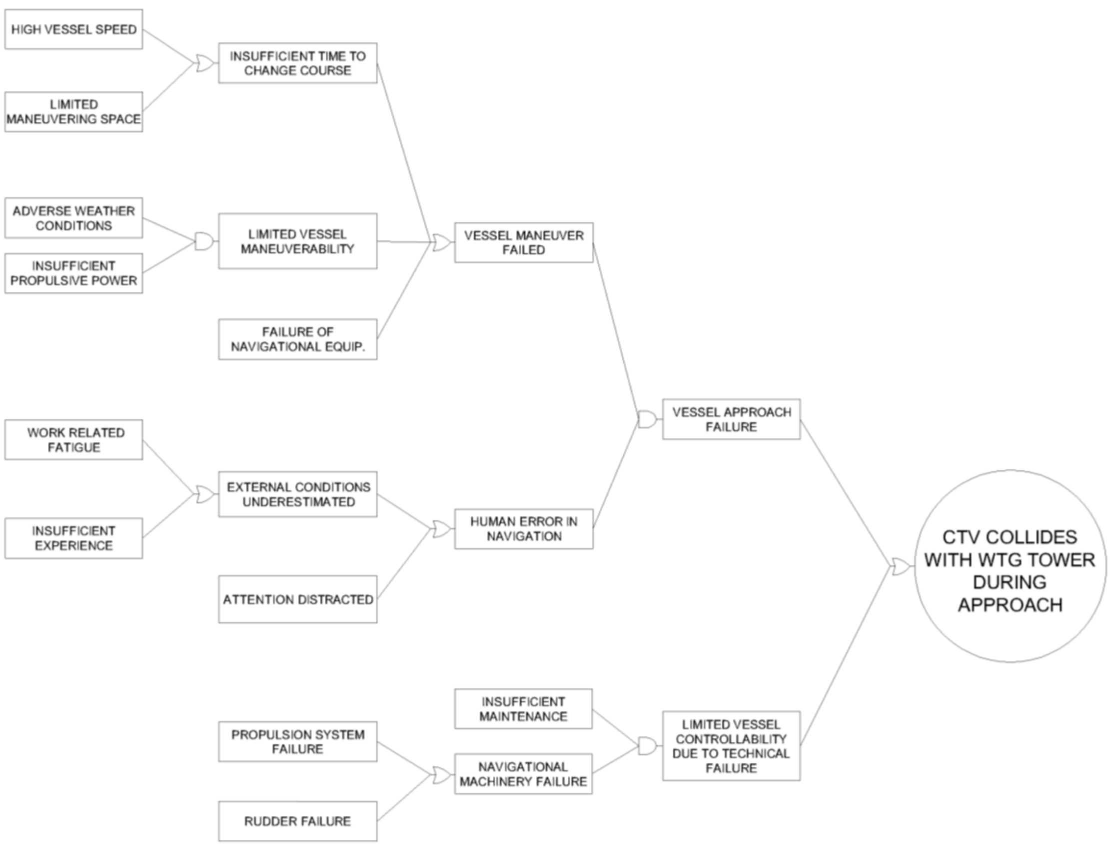


Figure 25: Fault tree for the accident of a CTV collision with a WTG tower during approach

<u>**Event Tree construction**</u>

The present analysis determined that the following events affect the ultimate consequences to the health and safety of the involved workers. The nodes of the constructed event tree are binary (YES/NO) due to the high-level nature of the analysis. The constructed event tree is shown in Figure 26.

1. **Worker in the vicinity of the collision area.** A worker who is situated in the vicinity of the collision area is exposed to the effects of the vibration caused by the collision of the vessel to the WTG tower. These effects might include slips, trips and falls, which in turn might lead to injury caused by coming into contact with a nearby object, and/or an object falling on the worker.
2. **Worker falls into the sea.** A worker who is situated on the deck of the vessel or on one of the components of the WTG might fall into the sea as a result of the vibration caused by the collision of the vessel to the WTG tower.
3. **Worker wears life-jacket.** According to the relevant regulations [54], every worker that is situated on the deck of a service vessel must be equipped with a life jacket. The state of the life jacket, which affects its effectiveness in case it has not been maintained properly or not replaced, contributes to the severity of the consequences for the worker.
4. **Immediate worker salvage.** The amount of time taken to salvage a worker who has fallen in the sea is in some cases crucial for the consequences to health and safety. For example, if a worker suffers hypothermia the probable consequences might be inability to move, loss of consciousness and loss of life.
5. **Ship sinks due to collision.** If the damage to the vessel from the collision is so severe as to cause uncontrolled flooding into the compartments, then the vessel will be evacuated, which involves all crew and passengers to gather at the designated muster stations and embark the available lifeboats.
6. **Worker embarks life raft.** If the lifeboats either cannot be lowered due to technical difficulties, or a worker could not embark a lifeboat, then the worker will rely on the available life rafts.
7. **SAR vessel operates nearby.**

The following assumptions have been applied to the construction of the event tree.

- If a worker is not in the vicinity of the collision area, then the worker will not be exposed to the danger of slipping, tripping or falling due to the vibration caused by the collision. However, the worker might fall into the sea as a result of the vibration.
- If the lifeboats either cannot be lowered due to technical difficulties, or a worker could not embark a lifeboat, then the worker is assumed to have fallen into the sea.
- The collision will not be severe enough in order to cause damage to the WTG tower, due to the fact that in many cases these collisions occur in relatively low speed and the size of the vessels involved is relatively small.

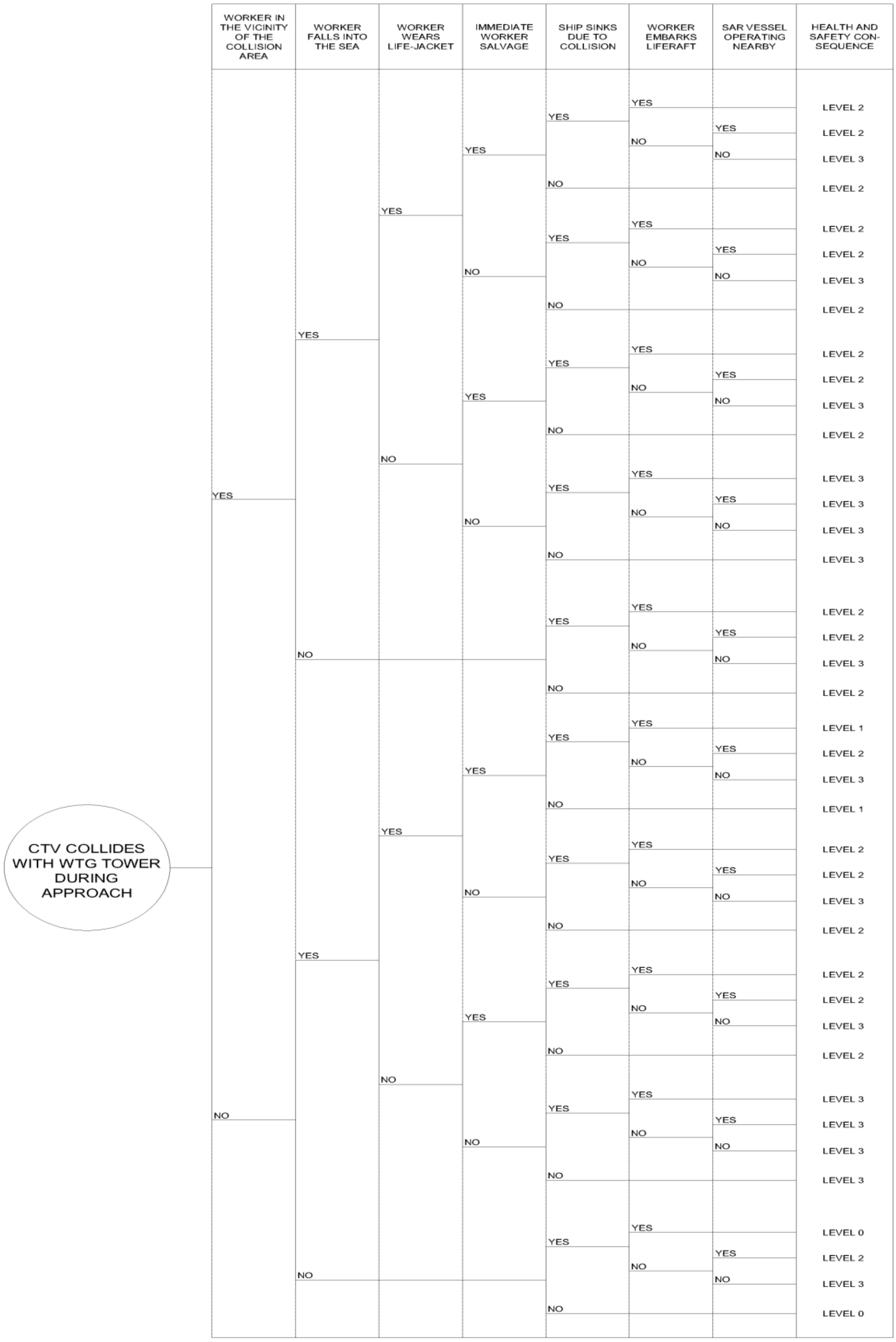


Figure 26: Event tree for the accident of a CTV collision with a WTG tower during approach

The constructed event tree contains 40 different scenarios that lead to varying degrees (measured on the scale mentioned previously) of health and safety consequence. The majority of scenarios (50%) lead to Level 2 consequences. Additionally, as shown in Figure 27, 40% of scenarios lead to Level 3 consequences, 5% of scenarios lead to Level 1 consequences and 5% of scenarios lead to Level 0 consequences. Therefore, the conclusion can be drawn that a collision of a CTV with the WTG tower is less dangerous compared to a lifting operation but still poses significant health and safety concerns for the involved workers.

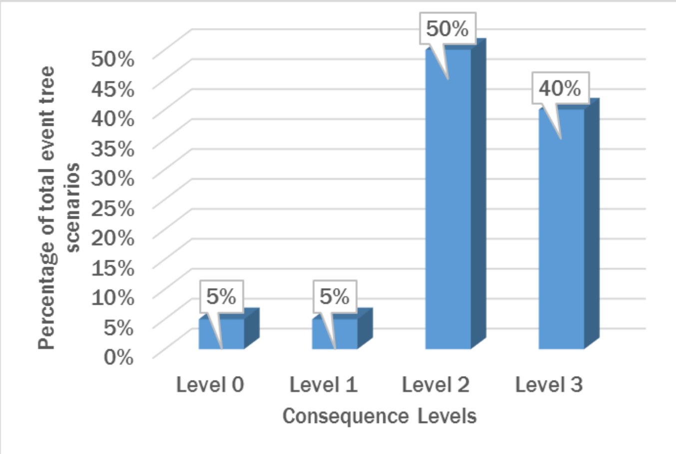


Figure 27: Distribution of consequence levels as a percentage of the total number of scenarios, for the accident of a CTV collision with a WTG tower during approach

4.2.1.3 Worker loses balance while accessing the WTG

Accident scenario description

This accident scenario involves a worker who loses his balance while accessing the WTG tower from a transport vessel. This accident scenario may occur either during the construction phase, or the O&M phase, or the decommissioning phase of the Offshore Wind Farm. Additionally, the bow-tie diagram has been constructed in such a way as to include both "bump and jump" and "walk to work" access modes. The "bump and jump" access mode (Figure 28b) constitutes common practice for near shore Offshore Wind Farms and involves using a small transport vessel, "bumping" it against special friction bars installed on the WTG, and holding it in position with forward propulsion in order to allow the worker to "jump" off the vessel and onto the WTG [58]. The motion of the transport vessel is also restricted by the friction between specifically designed bow fenders, installed on the vessel, and the friction bars on the WTG. This access mode is best suited for small and light vessels and for waves up to about 1.5m significant wave height. However, the practice of "bump and jump" becomes increasingly dangerous for Offshore Wind Farms installed further out to sea that may be in more exposed locations and in deeper waters, where it becomes more probable that significant wave heights might exceed 1.5m. The "walk to work" access mode (Figure 28a) has been developed in order to address safety concerns of far from the shore Offshore Wind Farms. This access mode involves positioning a boarding step or platform, such a gangway extending from the deck of the transport vessel, at a fixed point next to or touching the ladder on the WTG. To compensate for the six degrees of freedom of the vessel motion (i.e. pitch, roll, yaw, heave, surge and sway), such access systems continually adjust their angles using either of the following methods:

- Active positioning of the boarding platform, by using servos and an electronic control system, or

- Passive positioning of the boarding platform, by using a link with the WTG.

(a)

(b)

Figure 28: Access systems frequently used in the Offshore Wind Farm industry: (a) Walk to work [59], (b) Bump and jump [60]

Fault Tree construction

The loss of balance of a worker who is accessing the WTG from a CTV might occur under the influence of the following factors: use of improper type of access equipment, or a structural failure of the access system, or a large and sudden vessel motion. The term "access equipment" includes both Personal Protective Equipment (PPE) and access machinery, such as the gangway or the securing line for the worker. Each of these factors are analysed below, outlining the structure of the fault tree that is shown in Figure 29.

Use of improper type of access equipment. The proper access equipment is selected by the safety manager, the work task supervisor, and the worker, mostly based on factors such as the prevailing weather conditions. For example, a strong gust of wind could potentially induce vibrations to the gangway and cause the worker to lose his balance. Regarding high enough waves or rain, if the gangway is wet and the worker is not equipped with the appropriate PPEs (e.g. anti-slip boots etc.) then a slip could cause the worker to lose his balance. Therefore, the use of improper type of access equipment is a combination of adverse weather conditions and a failure in planning the particular work task.

Access system structural failure: The structural failure of a component of the access system could be a combination of insufficient maintenance and excessive wear, which could be attributed to either the corrosive effects of the marine environment or operational fatigue.

Large and sudden vessel motion: A large unexpected motion of the CTV might be induced either by a sudden change in the prevailing weather conditions (e.g. a strong gust of wind or a large wave), or a technical failure in the DPS or the mooring system of the vessel. Each of these events will cause the worker to lose balance while accessing the WTG from the CTV.

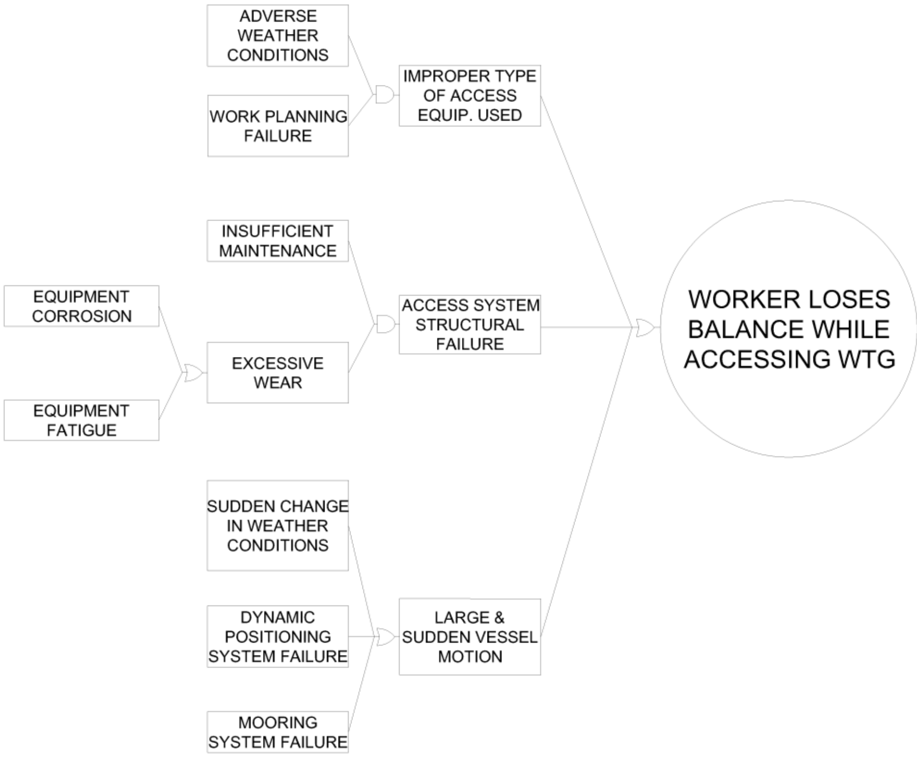


Figure 29: Fault tree for the accident of a worker losing his balance while accessing the WTG

Event Tree construction

The present analysis determined that the following events affect the ultimate consequences to the health and safety of the involved workers. The nodes of the constructed event tree are binary (YES/NO) due to the high-level nature of the analysis. The constructed event tree is shown in Figure 30.

- **Worker falls on vessel deck.** Depending on the height of the fall, the health and safety consequence to the worker may be severe.
- **Worker falls into the sea.** A worker might fall into the sea either directly after losing his balance on the gangway or after first landing on the deck of the CTV.
- **Worker wears life-jacket.** According to the relevant regulations [54], every worker that is situated on the deck of a service vessel must be equipped with a life jacket. The state of the life jacket, which affects its effectiveness in case it has not been maintained properly or not replaced, contributes to the severity of the consequences for the worker.
- **State of weather conditions.** In case the worker falls into the sea, the prevailing weather conditions is an important factor in determining the consequence level. For example, adverse weather conditions may obstruct salvaging efforts or even have direct health consequences to the worker such as hypothermia. It is noted that the normal temperature of the human body is about 37 °C and the sea water temperature for the Mediterranean is 15 – 24 °C, while the sea water temperature for the North Sea is 10 – 18 °C. Therefore, the body temperature of a worker who falls into the sea will start to diminish with a rate that depends on the sea water temperature, age, physical condition, clothing etc.

- **Immediate worker salvage.** The amount of time taken to salvage a worker who has fallen in the sea is in some cases crucial for the consequences to health and safety. For example, if a worker suffers hypothermia the probable consequences might be inability to move, loss of consciousness and loss of life.

The following assumptions have been applied to the construction of the event tree.

- The state of the prevailing weather conditions mainly refers to the sea water temperature and the prevailing wave profile.

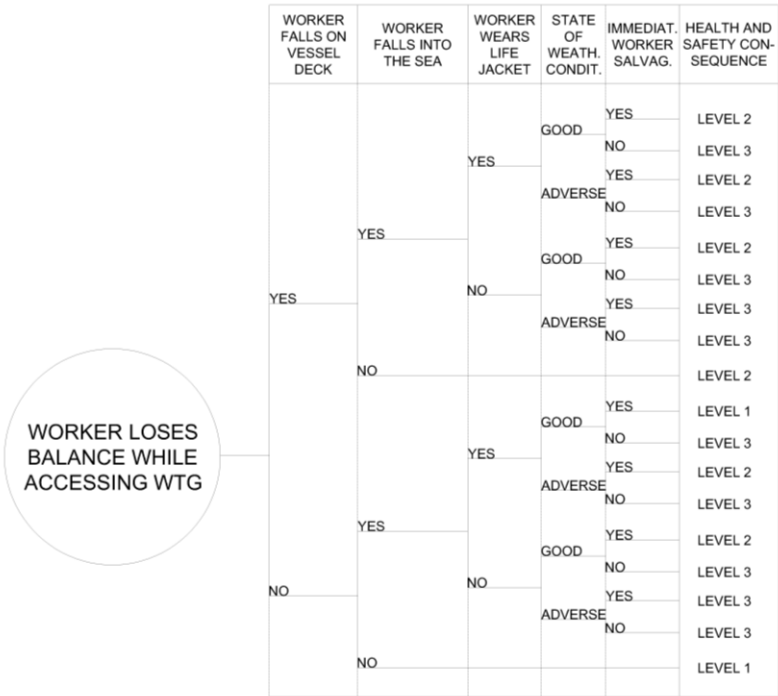


Figure 30: Event tree for the accident of a worker losing his balance while accessing the WTG

The constructed event tree contains 18 different scenarios that lead to varying degrees (measured on the scale mentioned previously) of health and safety consequence. The majority of scenarios (56%) lead to Level 3 consequences. Additionally, as shown in Figure 31, 33% of scenarios lead to Level 2 consequences, 6% of scenarios lead to Level 1 consequences and 6% of scenarios lead to Level 0 consequences. Therefore, the conclusion can be drawn that a worker losing his balance while accessing the WTG from a CTV is almost equally dangerous to a lifting operation.

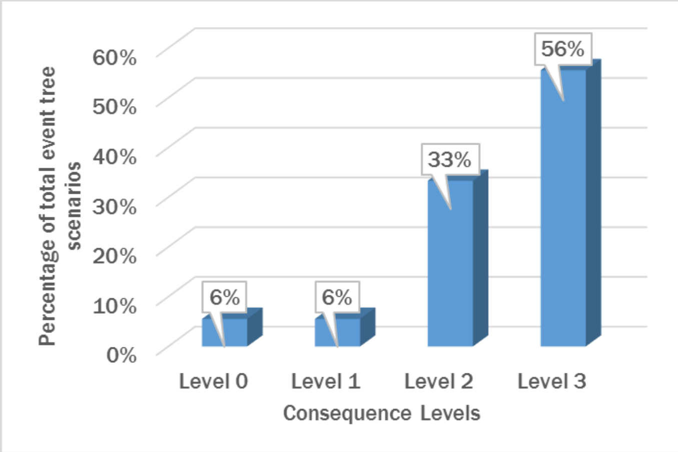


Figure 31: Distribution of consequence levels as a percentage of the total number of scenarios, for the accident of a worker losing his balance while accessing the WTG

4.3 Qualitative analysis

This Section will present the results of the qualitative analysis that was conducted on the bow-tie diagrams that were constructed. The analysis involves the analysis of both the fault trees and the event trees that comprise the bow-tie diagram. The qualitative analysis of the fault trees is based on the calculation of the minimal cut sets that aim to identify the most important basic events regarding the occurrence likelihood of the top event. The analysis of the event trees aims at identifying the events in the chain that play the most crucial part in the development of the consequences.

4.3.1 Minimal cut set analysis

A cut set is defined as a set of basic events that, when they all occur, will cause the top event (accident) to occur [61]. A cut set also links the basic events directly to the top event. A minimal cut set is a set containing the smallest possible number of basic events that, when they all occur, will cause the top event to occur. A cut set is minimal if the non-occurrence of any of the constituent basic events means the non-occurrence of the top event. The calculation of the cut sets and minimal cut sets can also be regarded as a way to simplify the structure of a given fault tree [62].

The calculation of the cut sets and the minimal cut sets gives an indication regarding the overall reliability of the system. This means that when a fault tree contains cut sets consisting of small numbers of basic events, or events that are very likely to occur then the system may be deemed unreliable. Additionally, the cut sets provide the analyst with a way to target the efforts for failure probability reduction in order to improve the overall reliability of the system. The following sections present the minimal cut sets for each fault tree of the constructed bow-tie diagrams.

4.3.1.1 Object falls during offshore lifting operation

The fault tree consists of 15 basic events, each of which has been assigned a letter of the alphabet (Figure 32) for easy representation of the minimal cut sets.

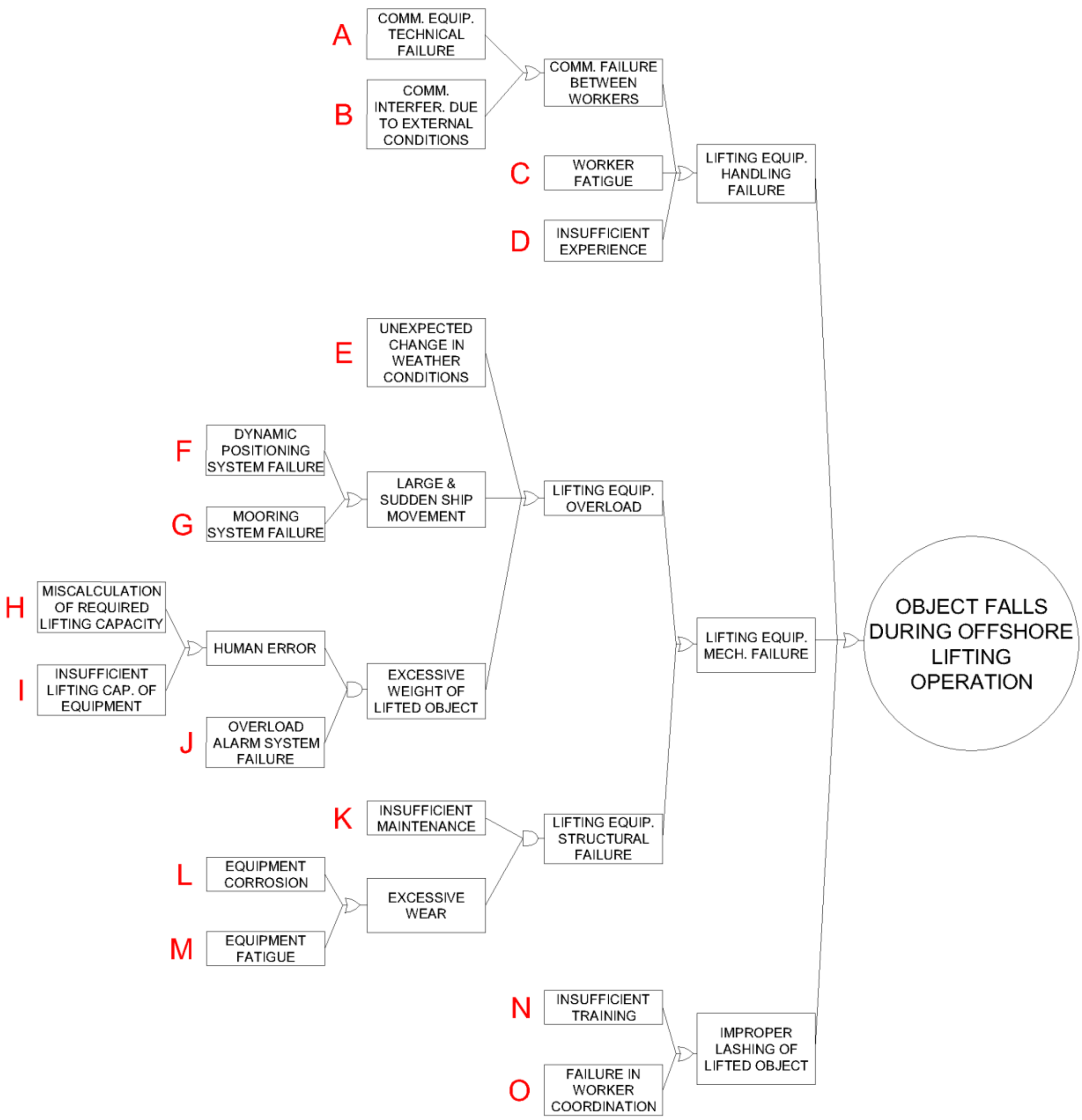


Figure 32: Fault tree with basic event codes for the accident of an object falling during an offshore lifting operation

Letter code	Event description
A	Communication equipment technical failure
B	Communication interference due to external conditions
C	Worker fatigue
D	Insufficient worker experience
E	Unexpected change in the weather conditions
F	DP system failure
G	Mooring system failure
N	Insufficient training
O	Failure in worker coordination

Table 5: 1st order minimal cut sets for the falling object during offshore lifting operation

Letter code	Event description
JH	(Overload alarm system failure) AND (Miscalculation of required lifting capacity)
JI	(Overload alarm system failure) AND (Insufficient lifting capacity of equipment)
KL	(Insufficient maintenance) AND (Equipment corrosion)
KM	(Insufficient maintenance) AND (Equipment fatigue)

Table 6: 2nd order minimal cut sets for the falling object during offshore lifting operation

The fault tree for this accident consists of **9 single event minimal cut sets** (1st order minimal cut sets) and **4 minimal cut sets, each comprising two events** (2nd order minimal cut sets), as shown in Table 5 and Table 6 respectively. Therefore, this system can be considered quite vulnerable because the occurrence of any of the 9 out of 15 total basic events will lead to the occurrence of the top event.

4.3.1.2 CTV collides with WTG tower during approach

The fault tree consists of 11 basic events, each of which has been assigned a letter of the alphabet (Figure 33) for easy representation of the minimal cut sets.

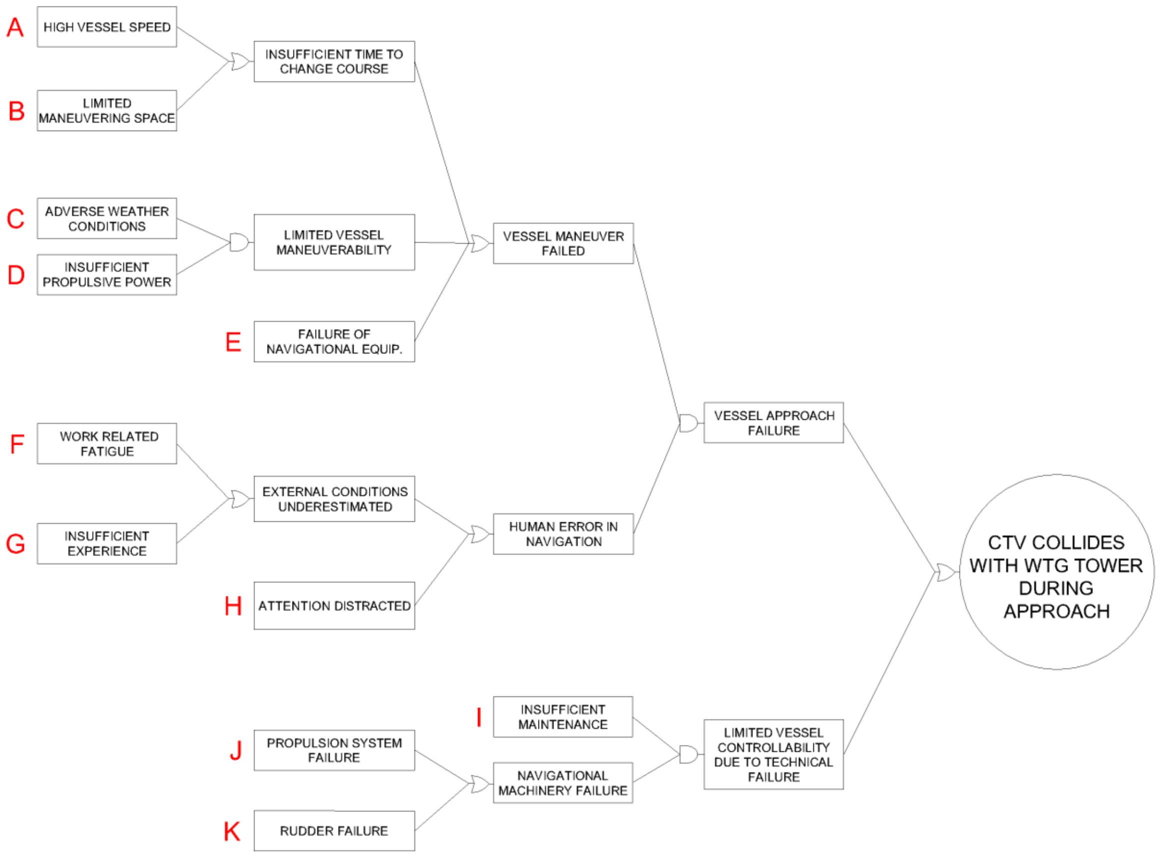


Figure 33: Fault tree with basic event codes for the accident of a CTV collision with a WTG tower during approach

Letter code	Event description
AF	(High vessel speed) AND (Work related fatigue)
AG	(High vessel speed) AND (Insufficient experience)
AH	(High vessel speed) AND (Attention distracted)
BF	(Limited manoeuvring space) AND (Work related fatigue)
BG	(Limited manoeuvring space) AND (Insufficient experience)
BH	(Limited manoeuvring space) AND (Attention distracted)
EF	(Failure of navigational equipment) AND (Work related fatigue)
EG	(Failure of navigational equipment) AND (Insufficient experience)
EH	(Failure of navigational equipment) AND (Attention distracted)
IJ	(Insufficient maintenance) AND (Propulsion system failure)
IK	(Insufficient maintenance) AND (Rudder failure)

Table 7: 2nd order minimal cut sets for the collision of a CTV with a WTG tower

Letter code	Event description
CDF	(Adverse weather conditions) AND (Insufficient propulsive power) AND (Work related fatigue)
CDG	(Adverse weather conditions) AND (Insufficient propulsive power) AND (Insufficient experience)
CDH	(Adverse weather conditions) AND (Insufficient propulsive power) AND (Attention distracted)

Table 8: 3rd order minimal cut sets for the collision of a CTV with a WTG tower

This fault tree consists of 2nd order minimal cut sets (**11 sets of basic events**) and 3rd order minimal cut sets (**3 sets of basic events**), as shown in Table 7 and Table 8 respectively. Therefore, since at least two basic events need to occur in order for the top event to occur, the collision of a CTV with the WTG is less vulnerable compared to the falling object during a lifting operation.

4.3.1.3 Worker loses balance while accessing the WTG

The fault tree consists of 8 basic events, each of which has been assigned a letter of the alphabet (Figure 34) for easy representation of the minimal cut sets.

Letter code	Event description
F	Sudden change in weather conditions
G	DP system failure
H	Mooring system failure

Table 9: 1st order minimal cut sets for a worker losing his balance while accessing the WTG

Letter code	Event description

AB	(Adverse weather conditions) AND (Work planning failure)
CD	(Insufficient maintenance) AND (Equipment corrosion)
CE	(Insufficient maintenance) AND (Equipment fatigue)

Table 10: 2nd order minimal cut sets for a worker losing his balance while accessing the WTG

This fault tree consists of **3 single event minimal cut sets** (1st order minimal cut sets) and **3 minimal cut sets, each comprising two events** (2nd order minimal cut sets), as shown in Table 9 and Table 10 respectively. Therefore, this system can be considered of average vulnerability because the occurrence of any of the 3 out of 8 total basic events will lead to the occurrence of the top event.

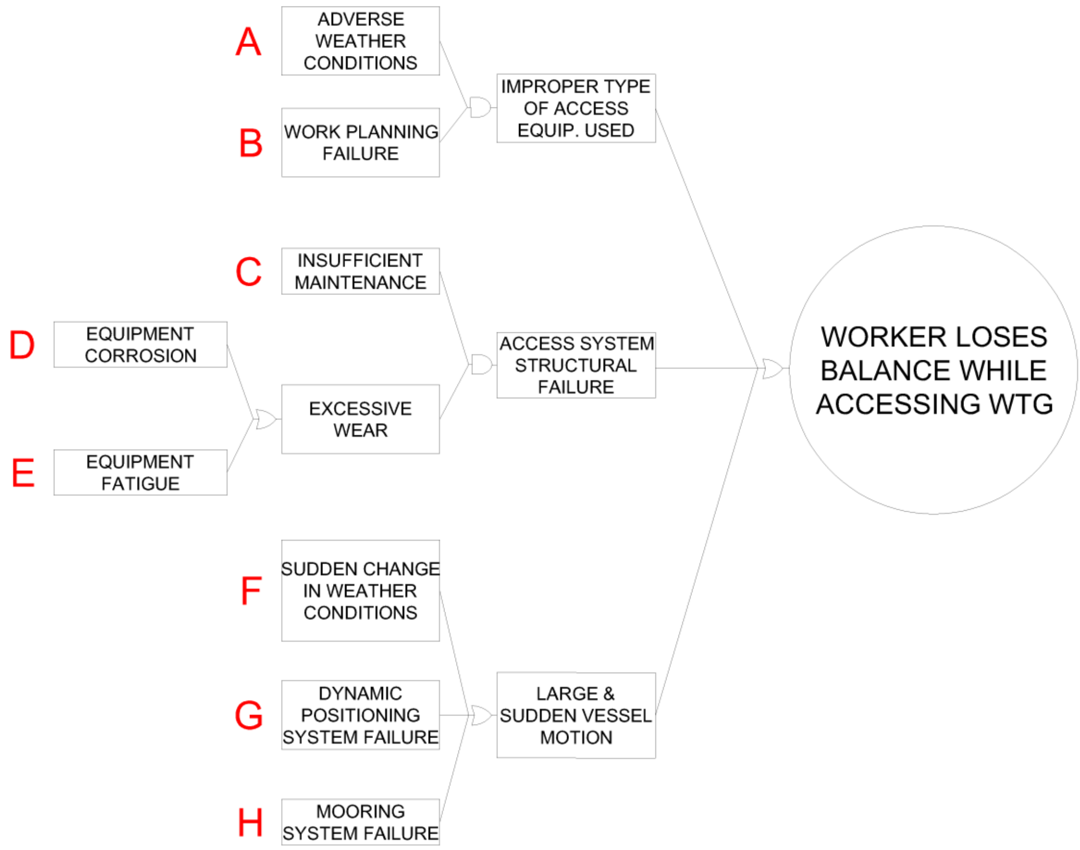


Figure 34: Fault tree with event codes for the accident of a worker losing his balance while accessing the WTG

4.3.2 Event tree analysis

The aim of this section is to determine which are the most crucial events, following the occurrence of each accident, that may lead to the worst case consequence scenario (i.e. fatality). This will be achieved by the following qualitative assessment:

1. Identify all the different paths that lead to Level 3 consequences.
2. Remove the identified paths from the event tree.
3. Examine which events have a predetermined outcome in the altered event tree.

4.3.2.1 Object falls during offshore lifting operation

Figure 35 shows the paths that lead to a Level 3 consequence are marked by red lines.

In order to avoid a fatality (Level 3 consequence), the following events need to have a predetermined outcome: **worker located in the impact area**, **immediate worker salvage**, **SAR vessel operating nearby**. outcome shows these crucial events and their desired outcome.

Event	Outcome
Worker located in the impact area	No workers are within the impact area.
Immediate worker salvage	Workers who have fallen into the sea should be immediately salvaged, in case they are not equipped with a life-jacket.
SAR vessel operating nearby	A SAR vessel is in the vicinity of the area where the lifting operation is being conducted.

Table 11: Crucial events and their desired outcome

Considering the case when workers are located in the impact area, then there is high probability that they will be directly injured by the falling object, which might result in the worst possible outcome. As previously mentioned, this is due to the fact that objects that might be lifted may reach 400 tons in weight (for 8 MW turbines) and a direct injury might be extremely severe. The second most crucial event that will determine the final level consequence, in case there are no workers within the impact area, is whether a worker who has fallen into the sea wears a life jacket and whether the worker will be salvaged immediately. Finally, in order to avoid fatalities, it is crucial that a SAR vessel is operating in the vicinity of the area where the lifting operation is being conducted.

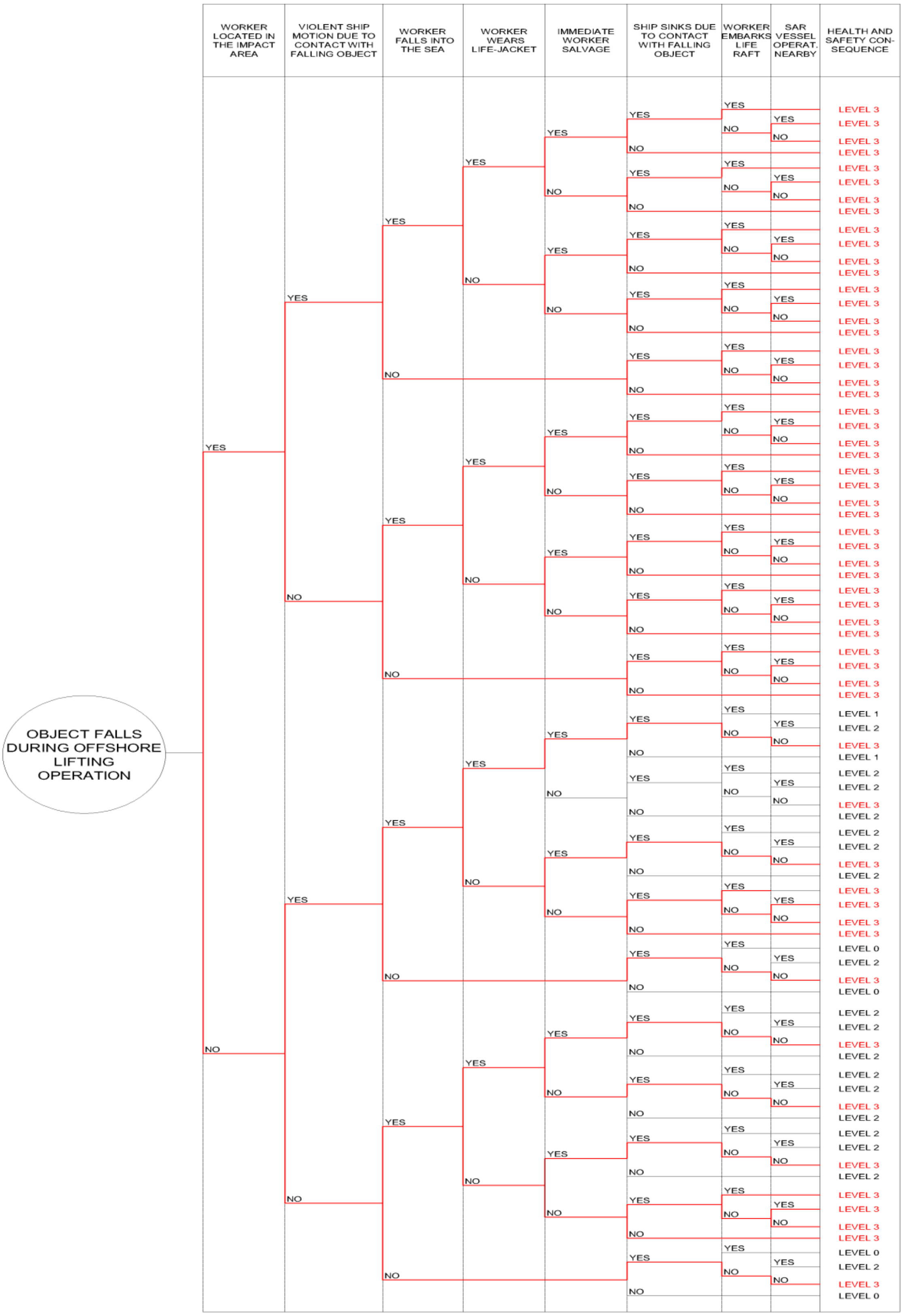


Figure 35: Event tree paths that lead to Level 3 consequences, for the accident of an object falling during an offshore lifting operation

Figure 36 shows the altered event tree after removing the identified paths from the initial event tree.

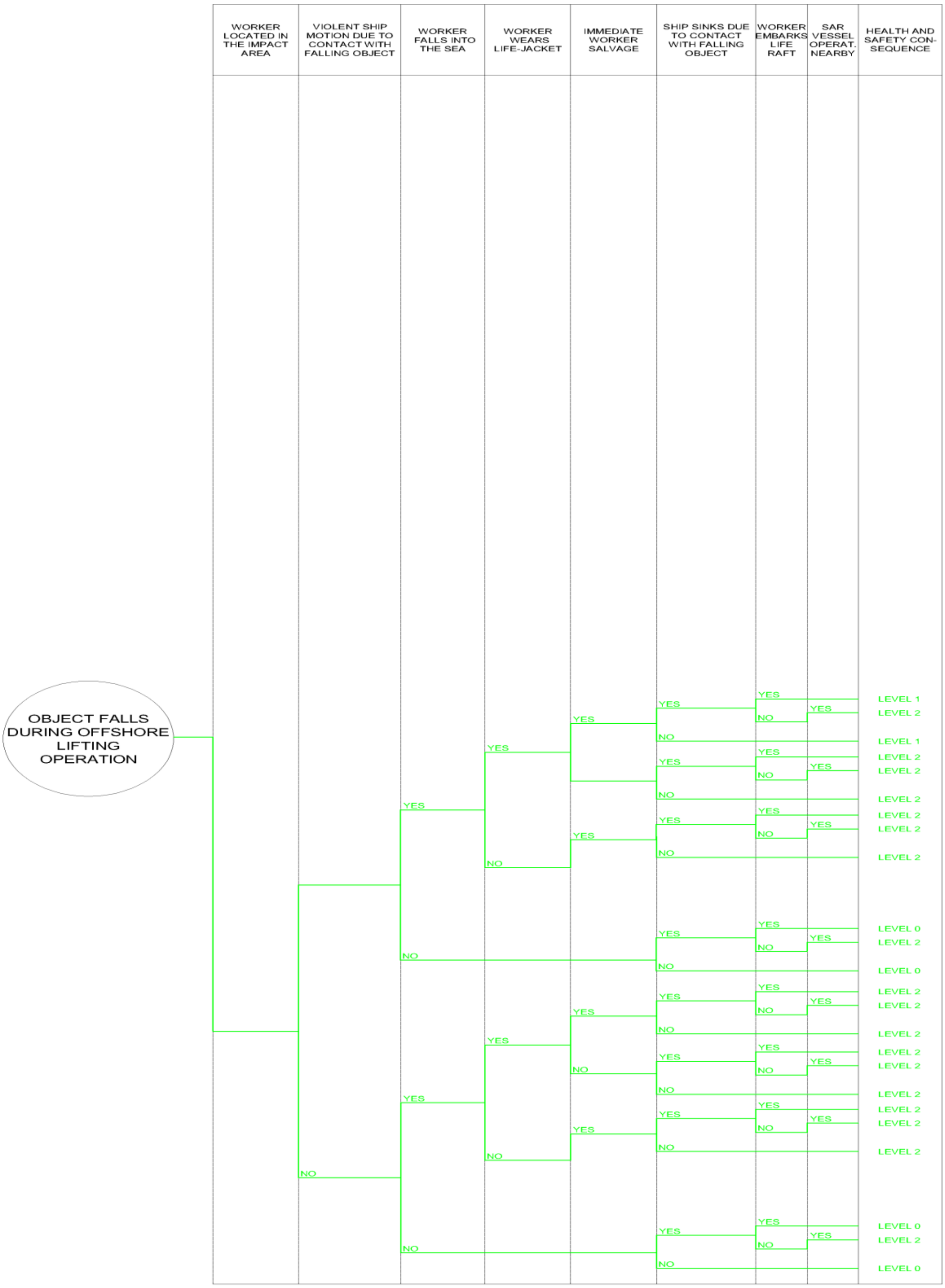


Figure 36: Event tree after removing paths that lead to Level 3 consequences, for the accident of an object falling during an offshore lifting operation

4.3.2.2 CTV collides with WTG tower during approach

Figure 37 shows the paths that lead to a Level 3 consequence are marked by red lines.

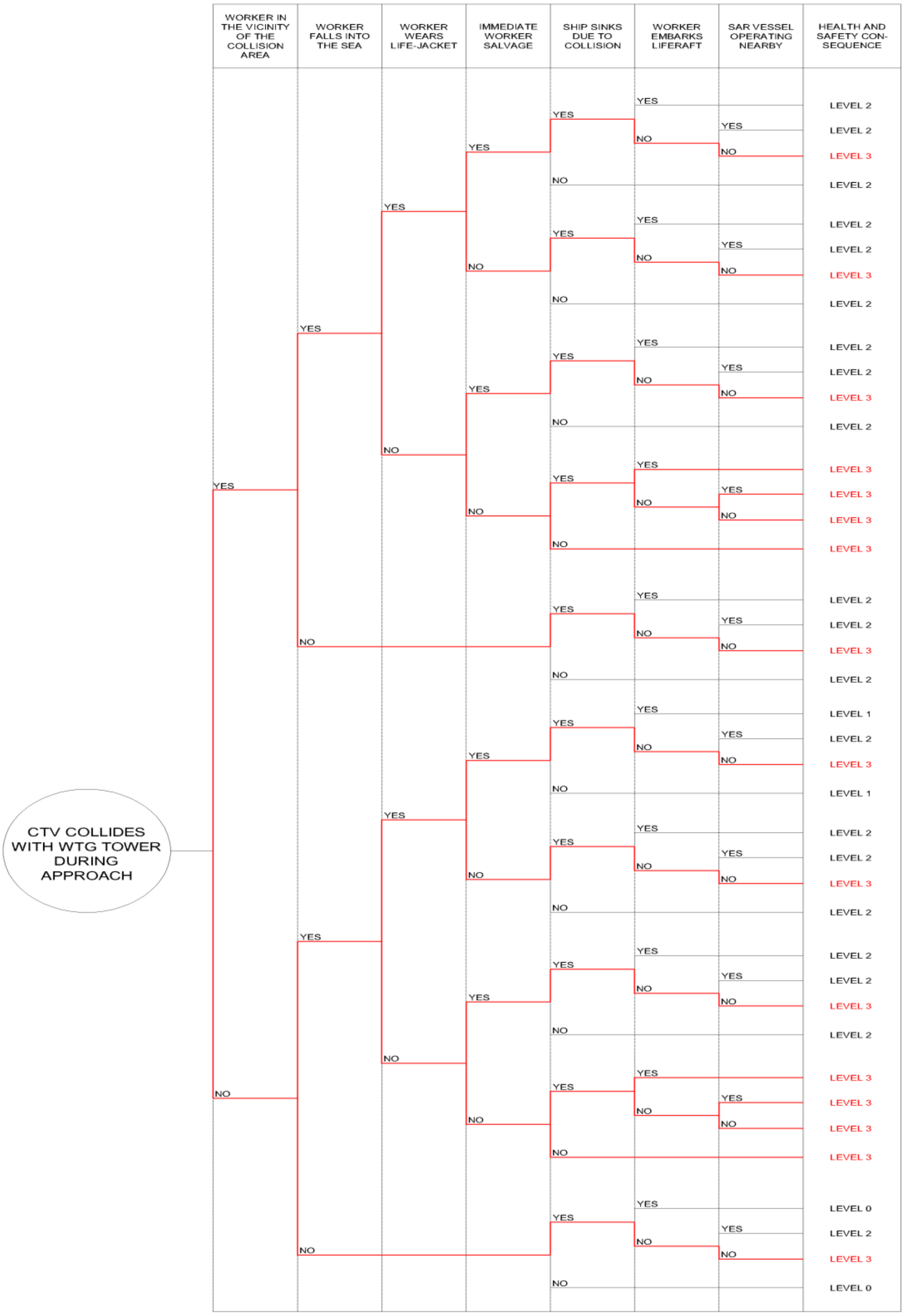


Figure 37: Event tree paths that lead to Level 3 consequences, for the accident of a CTV collision with the WTG tower during approach

Figure 38 shows the altered event tree after removing the identified paths from the initial event tree.

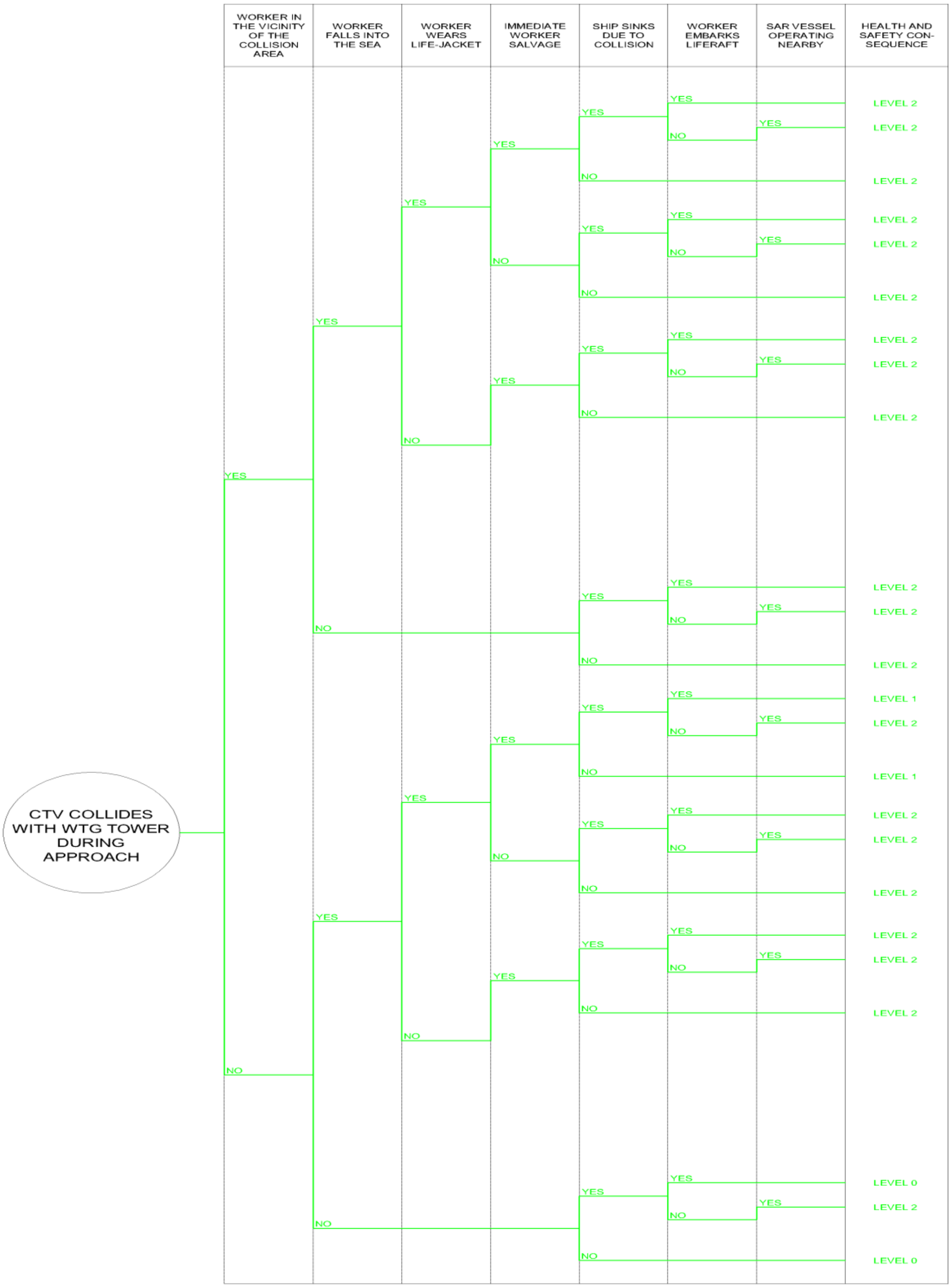


Figure 38: Event tree after removing paths that lead to Level 3 consequences, for the accident of a CTV collision with the WTG tower during approach

In order to avoid a fatality (Level 3 consequence), the following events need to have a predetermined outcome: **immediate worker salvage** and **SAR vessel operating nearby**. Table 12 shows these crucial events and their desired outcome.

Event	Outcome
Immediate worker salvage	Workers who have fallen into the sea should be immediately salvaged, in case they are not equipped with a life-jacket.
SAR vessel operating nearby	A SAR vessel is in the vicinity of the area where the collision has happened.

Table 12: Crucial events and their desired outcome

The event tree for the CTV collision with the WTG tower is very similar to the one regarding the falling of an object during a lifting operation. This means that the two event share most of the event gates and consequently 2 out of 3 crucial events are the same. The difference lies in the fact that whether a worker is located in the vicinity of the collision area is not such a crucial event, in the development of the accident to a fatality, as is the fact whether a worker is located in the impact area of the falling object. This is owed to the fact that the worker located in the vicinity of the collision area is not exposed to a high probability of Level 3 consequences (i.e. fatality), as is the case when a worker is exposed to the danger of being struck by a falling object. Therefore, the crucial events for leading to a fatality are whether the worker that has fallen into the sea (and does not wear a life jacket) will be immediately salvaged and whether there is a SAR vessel in the vicinity of the accident, with the purpose to provide assistance in case of an emergency.

4.3.2.3 Worker loses balance while accessing the WTG

Figure 39 shows the paths that lead to a Level 3 consequence are marked by red lines.

In order to avoid a fatality (Level 3 consequence), the following events need to have a predetermined outcome: **state of weather conditions** and **immediate worker salvage**. Table 13 shows these crucial events and their desired outcome.

Event	Outcome
State of weather conditions	For a worker who has fallen into the sea, the state of the weather conditions affect the consequence in conjunction with immediate worker salvage.
Immediate worker salvage	Workers who have fallen into the sea should be immediately salvaged.

Table 13: Crucial events and their desired outcomes

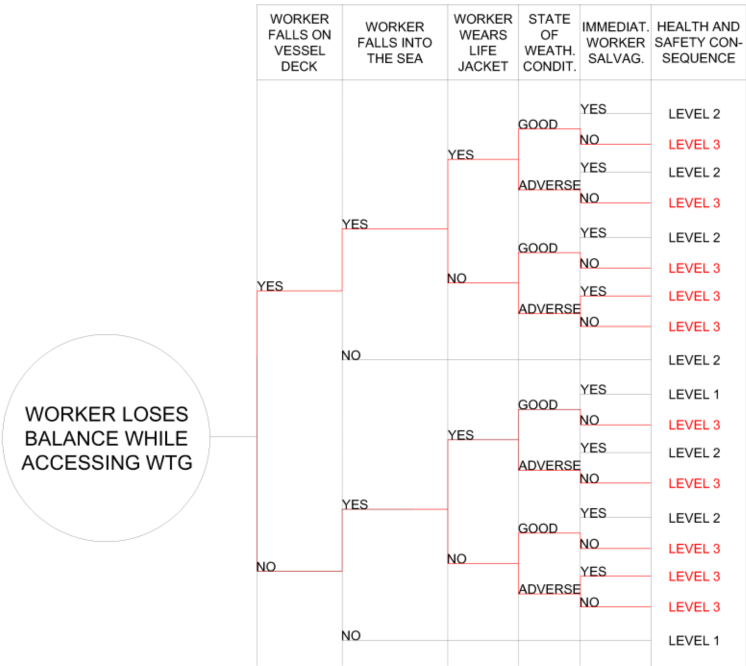


Figure 39: Event tree paths that lead to Level 3 consequences, for the accident of a worker losing his balance while accessing the WTG

Figure 40 shows the altered event tree after removing the identified paths from the initial event tree.

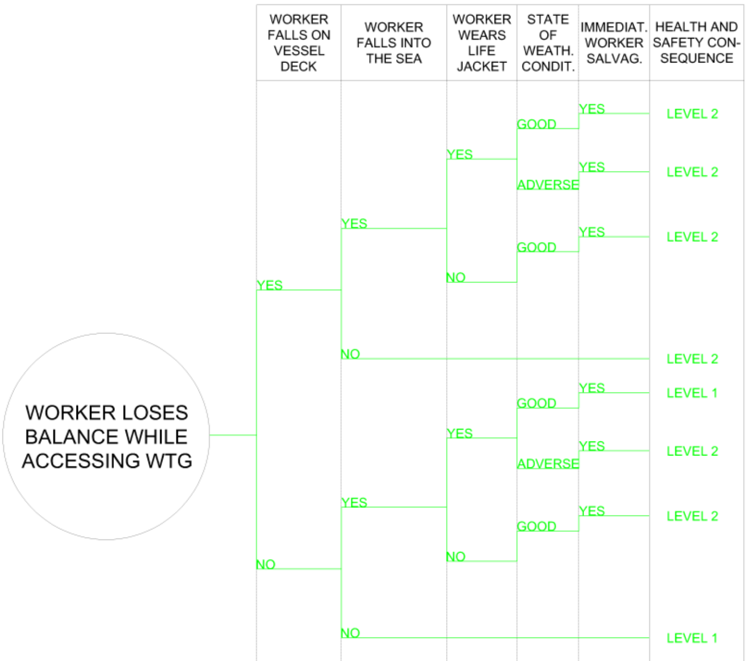


Figure 40: Event tree after removing paths that lead to Level 3 consequences, for the accident of a worker losing his balance while accessing the WTG

4.4 Barrier analysis

A particularly useful feature of the analysis of bow-tie diagrams is the inclusion of safety barriers (or RCOs). Preventative RCOs are placed in the Fault Tree part, while mitigative RCOs are placed in the Event Tree part of the bow-tie diagram. The usefulness of including safety barriers in a bow-tie diagram is illustrated by the fact that, if a specific path of events leading to the accident and also a specific path of events following the accident is examined then the effectiveness of the RCOs will become apparent from the diagram.

In the scope of the present analysis, safety barriers that are common in the Offshore Wind Farm industry have been documented from a survey of the relevant literature (i.e. regulations and guidelines) and placed on each of the three generic bow-tie diagrams that have been constructed. The following sections present the safety barriers and their placement on each of the bow-tie diagrams. The barriers were categorized in preventative measures and mitigative measures, depending on whether they are placed on the fault tree or the event tree of the bow-tie diagram respectively.

The results of the minimal cut set analysis, which was conducted for the fault trees, were used as basis for evaluating the effectiveness of the existing mitigative measures based on which minimal cut sets are affected by their implementation. This was determined by assuming that each preventative measure is being implemented with 100% effectiveness and therefore alters the structure of the fault tree. Subsequently, the minimal cut sets are calculated again for each altered fault tree. To determine which preventative measure is most effective (compared to the others), the number of resulting minimal cut sets was used as a benchmark. It is especially interesting to examine the resulting number of 1st order minimal cut sets, because they contain single basic events, the realization of any of which could lead to the occurrence of the accident (top event). Therefore, an effective preventative barrier should minimize, if not eliminate, the number of 1st order minimal cut sets.

The results of the qualitative analysis, which was conducted for the event trees (i.e. the crucial events for leading to a fatality), were used as a basis for quickly evaluating the effectiveness of the existing mitigative measures.

4.4.1 Object falls during offshore lifting operation

The following safety barriers have been derived from the HSE Lifting Operations and Lifting Equipment Regulations [48], the International Marine Contractors Association guidelines [63], and a relevant study from the Aalborg University in Denmark [64].

<u>Preventative measures</u>

- Use of colour coding for marking defective machinery equipment or equipment that is in need of maintenance.
- Monitoring the work progress and supervising the ongoing task.
- Conducting tests for the sufficient structural strength of various components (load testing).
- Inspect the lashing arrangement for the lifted object prior to commencing the lifting operation.

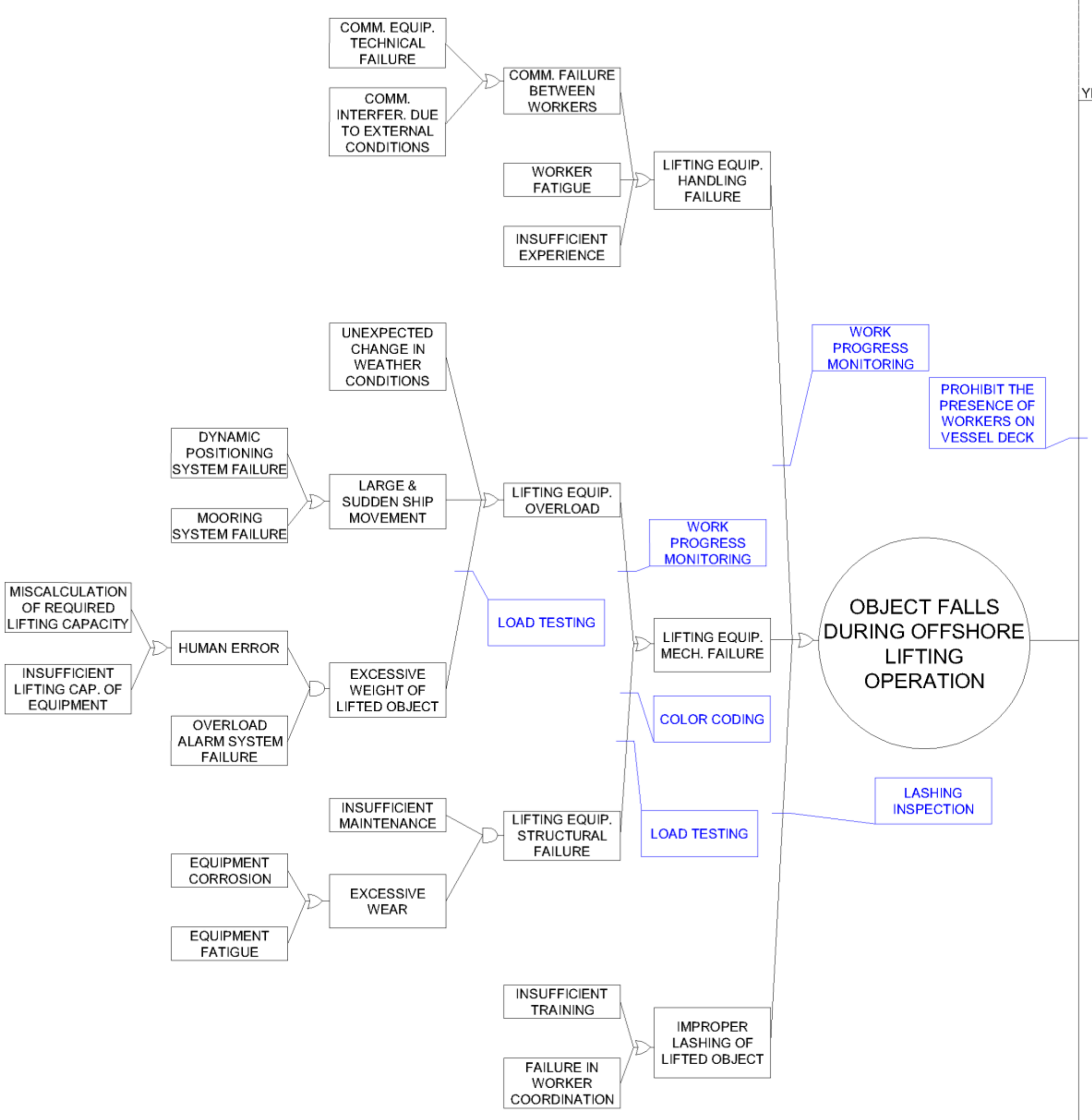
<u>Mitigative measures</u>

- Prohibit workers from being on the deck of the vessel during the lifting operation.

- A SAR vessel standing by, while the lifting operation is under way, in order to immediately provide assistance in case of an emergency.

Figure 41 shows the previously mentioned preventative and mitigative risk control measures as they have been placed on the constructed bow-tie diagram.

Consequence Level	Description
Level 0	Near miss. The accident results in no adverse health and safety consequences.
Level 1	Accident results in minor injuries for the workers involved.
Level 2	Accident results in major injuries for the workers involved.
Level 3	Accident results in fatality.



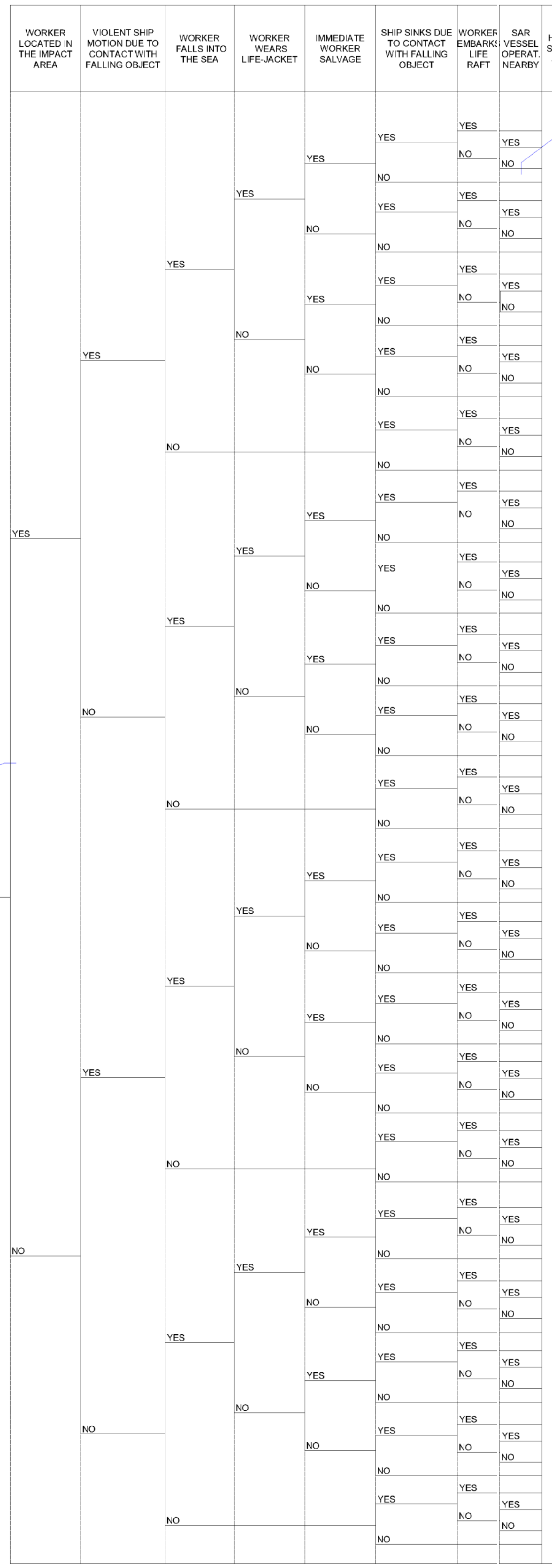


Figure 41: Bow-Tie diagram with preventative and mitigative safety measures, for the accident of an object falling during an offshore lifting operation

4.4.1.1 Effectiveness of preventative measures

The fault tree for the particular accident type consists of the following minimal cut sets:

- **9 sets** (1st order), and
- **4 sets** (2nd order).

Work progress monitoring

As shown in Figure 41, if monitoring the work progress and supervision of the ongoing task is applied with 100% effectiveness, then the following events will be averted: **handling failure of the lifting equipment** and **overload of the lifting equipment**. The resulting minimal cut sets for the altered fault tree are shown below (the event codes are retained for comparison reasons).

Letter code	Event description
N	Insufficient training
O	Failure in worker coordination

Table 14: 1st order minimal cut sets for the altered fault tree of the falling object during offshore lifting operation – Work Progress Monitoring

Letter code	Event description
KL	(Insufficient maintenance) AND (Equipment corrosion)
KM	(Insufficient maintenance) AND (Equipment fatigue)

Table 15: 2nd order minimal cut sets for the altered fault tree of the falling object during offshore lifting operation – Work Progress Monitoring

The altered fault tree consists of the following minimal cut sets:

- **2 sets** (1st order, Table 14), and
- **2 sets** (2nd order, Table 15).

Therefore, 1st order minimal cut sets are reduced by **about 78%** and 2nd order minimal cut sets are reduced by **50%**, compared to the original fault tree.

Lashing inspection

As shown in Figure 41, if the lashing arrangement is inspected prior to commencing the lifting operation with 100% effectiveness, then the following events will be averted: **improper lashing of lifted object**. The resulting minimal cut sets for the altered fault tree are shown below (the event codes are retained for comparison reasons).

Letter code	Event description
A	Communication equipment technical failure

B	Communication interference due to external conditions
C	Worker fatigue
D	Insufficient worker experience
E	Unexpected change in the weather conditions
F	DP system failure
G	Mooring system failure

Table 16: 1st order minimal cut sets for the altered fault tree of the falling object during offshore lifting operation – Lashing Inspection

Letter code	Event description
JH	(Overload alarm system failure) AND (Miscalculation of required lifting capacity)
JI	(Overload alarm system failure) AND (Insufficient lifting capacity of equipment)
KL	(Insufficient maintenance) AND (Equipment corrosion)
KM	(Insufficient maintenance) AND (Equipment fatigue)

Table 17: 2nd order minimal cut sets for the altered fault tree of the falling object during offshore lifting operation – Lashing Inspection

The altered fault tree consists of the following minimal cut sets:

- **7 sets** (1st order, Table 16), and
- **4 sets** (2nd order, Table 17).

Therefore, 1st order minimal cut sets are reduced by **about 22%** and 2nd order minimal cut sets **remain the same**, compared to the original fault tree.

<u>**Load testing**</u>

As shown in Figure 41, if tests for the sufficient structural strength of various components (load testing) are conducted with 100% effectiveness, then the following events will be averted: **excessive weight of lifted object** and **structural failure of lifting equipment**. The resulting minimal cut sets for the altered fault tree are shown below (the event codes are retained for comparison reasons).

Letter code	Event description
A	Communication equipment technical failure
B	Communication interference due to external conditions
C	Worker fatigue
D	Insufficient worker experience
E	Unexpected change in the weather conditions
F	DP system failure
G	Mooring system failure
N	Insufficient training
O	Failure in worker coordination

Table 18: 1st order minimal cut sets for the altered fault tree of the falling object during offshore lifting operation – Load Testing

Letter code	Event description

KL	(Insufficient maintenance) AND (Equipment corrosion)
KM	(Insufficient maintenance) AND (Equipment fatigue)

Table 19: 1st order minimal cut sets for the altered fault tree of the falling object during offshore lifting operation - Load Testing

The altered fault tree consists of the following minimal cut sets:

- **9 sets** (1st order, Table 18), and
- **2 sets** (2nd order, Table 19).

Therefore, 1st order minimal cut sets **remain the same** and 2nd order minimal cut sets are reduced by **50%**, compared to the original fault tree.

Table 20 summarizes the previous results regarding the effectiveness of the existing preventative measures.

Preventative measure	1st order minimal cut set reduction	2nd order minimal cut set reduction
Work progress monitoring	~78%	50%
Lashing inspection	~22%	-
Load testing	-	50%

Table 20: Summary of results for the effectiveness of the existing preventative measures

Consequently, the most effective of the existing preventative control measures is **work progress monitoring**.

4.4.1.2 Effectiveness of mitigation measures

As resulted from the analysis of the corresponding event tree, the most crucial events that play a major role in leading to Level 3 consequences are the following: **worker located in the impact area**, **immediate worker salvage**, **SAR vessel operating nearby.** The existing mitigative risk control measures are evaluated as highly effective, since they affect the development of the corresponding crucial events in a way that fatalities are averted.

4.4.2 CTV collides with WTG tower during approach

The following safety barriers have been derived from the G9 2014 incident data report [35] and the vessel safety guidelines by RenewableUK [65].

<u>Preventative measures</u>

- Permit the CTV to enter the Offshore Wind Farm 500m zone only when the weather conditions are favourably safe.
- Navigational equipment redundancies for immediately circumventing faulty equipment.
- Monitoring the course of the CTV from the Offshore Wind Farm shore-based control centre, in order to immediately warn the crew in case of an emergency.

<u>Mitigative measures</u>

- Prohibit workers from being on the deck of the vessel, before it has safely been moored.
- A SAR vessel standing by, while the transport operation is under way, in order to immediately provide assistance in case of an emergency.

Figure 42 shows the previously mentioned preventative and mitigative risk control measures as they have been placed on the constructed bow-tie diagram.

Consequence Level	Description
Level 0	Near miss. The accident results in no adverse health and safety consequences.
Level 1	Accident results in minor injuries for the workers involved.
Level 2	Accident results in major injuries for the workers involved.
Level 3	Accident results in fatality.

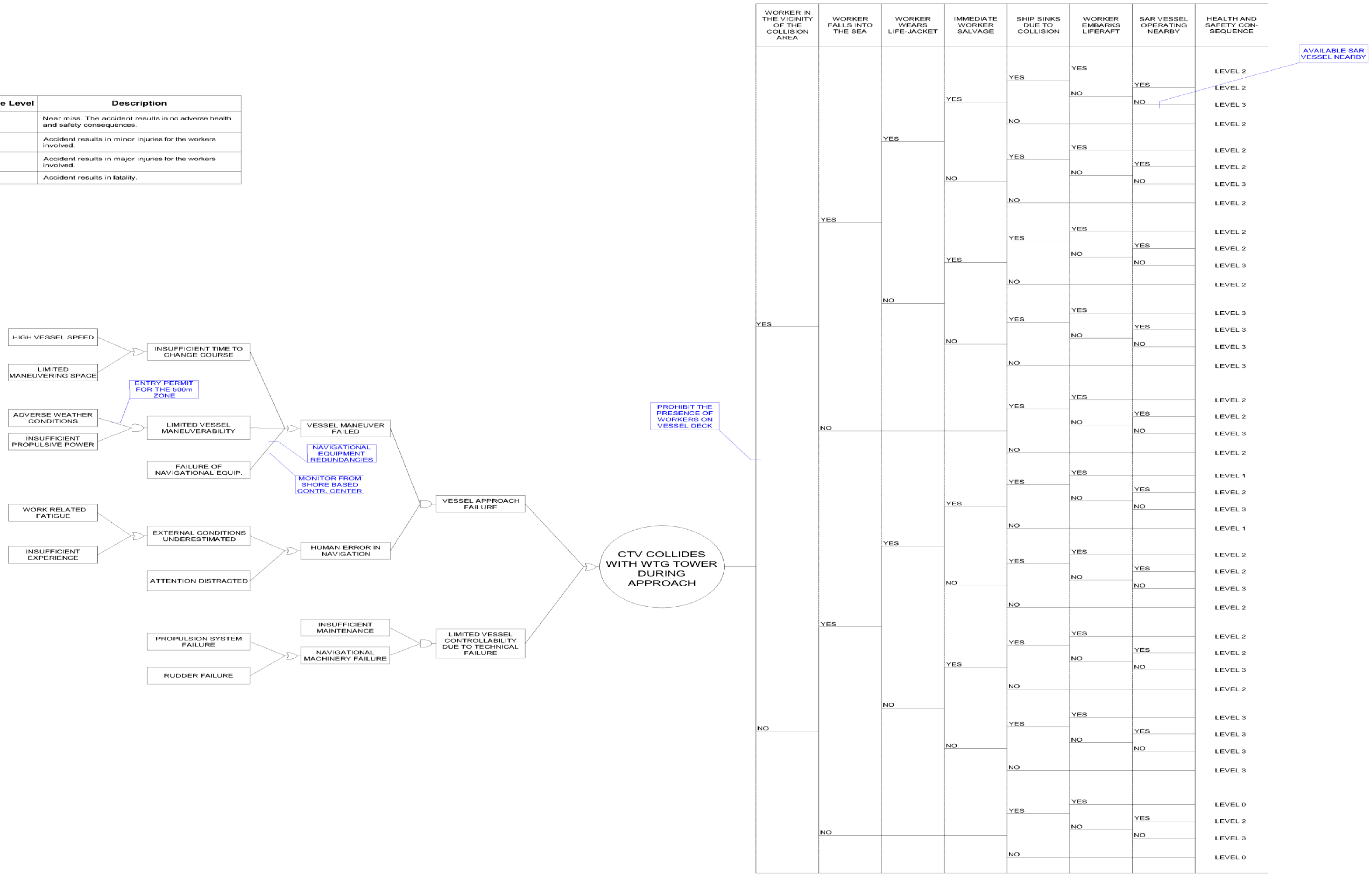


Figure 42: Bow-Tie diagram with preventative and mitigative safety measures, for the accident of a CTV collision with the WTG tower during approach

4.4.2.1 Effectiveness of preventative measures

The fault tree for the particular accident type consists of the following minimal cut sets:

- **11 sets** (2nd order), and
- **3 sets** (3rd order).

Entry permit for the 500m zone

As shown in Figure 42, if the CTV is permitted to enter the Offshore Wind Farm 500m zone only when the weather conditions are favourably safe (100% effectiveness), then the following events will be averted: **adverse weather conditions**. Due to the fact that this event is linked with an AND gate to the event "**Insufficient propulsive power**", consequently the event "**Limited vessel manoeuvrability**" will also be averted. The resulting minimal cut sets for the altered fault tree are shown below (the event codes are retained for comparison reasons).

Letter code	Event description
AF	(High vessel speed) AND (Work related fatigue)
AG	(High vessel speed) AND (Insufficient experience)
AH	(High vessel speed) AND (Attention distracted)
BF	(Limited manoeuvring space) AND (Work related fatigue)
BG	(Limited manoeuvring space) AND (Insufficient experience)
BH	(Limited manoeuvring space) AND (Attention distracted)
EF	(Failure of navigational equipment) AND (Work related fatigue)
EG	(Failure of navigational equipment) AND (Insufficient experience)
EH	(Failure of navigational equipment) AND (Attention distracted)
IJ	(Insufficient maintenance) AND (Propulsion system failure)
IK	(Insufficient maintenance) AND (Rudder failure)

Table 21: 2nd order minimal cut sets for the altered fault tree of the collision of a CTV with a WTG tower - Entry permit for the 500m zone

The altered fault tree consists of the following minimal cut sets:

- **11 sets** (2nd order, Table 21), and
- **0 sets** (3rd order).

Therefore, 2nd order minimal cut sets **remain the same** and 3rd order minimal cut sets are reduced by **100%**, compared to the original fault tree.

Navigational equipment redundancies

As shown in Figure 42, if navigational equipment redundancies for immediately circumventing faulty equipment are installed (100% effectiveness), then the following events will be averted: **failure of navigational equipment**. The resulting minimal cut sets for the altered fault tree are shown below (the event codes are retained for comparison reasons).

Letter code	Event description
AF	(High vessel speed) AND (Work related fatigue)

AG	(High vessel speed) AND (Insufficient experience)
AH	(High vessel speed) AND (Attention distracted)
BF	(Limited manoeuvring space) AND (Work related fatigue)
BG	(Limited manoeuvring space) AND (Insufficient experience)
BH	(Limited manoeuvring space) AND (Attention distracted)
IJ	(Insufficient maintenance) AND (Propulsion system failure)
IK	(Insufficient maintenance) AND (Rudder failure)

Table 22: 2nd order minimal cut sets for the altered fault tree of the collision of a CTV with a WTG tower – Navigational equipment redundancies

Letter code	Event description
CDF	(Adverse weather conditions) AND (Insufficient propulsive power) AND (Work related fatigue)
CDG	(Adverse weather conditions) AND (Insufficient propulsive power) AND (Insufficient experience)
CDH	(Adverse weather conditions) AND (Insufficient propulsive power) AND (Attention distracted)

Table 23: 3rd order minimal cut sets for the altered fault tree of the collision of a CTV with a WTG tower – Navigational equipment redundancies

The altered fault tree consists of the following minimal cut sets:

- **8 sets** (2nd order, Table 22), and
- **3 sets** (3rd order, Table 23).

Therefore, 2nd order minimal cut sets **are reduced by about 27%** and 3rd order minimal cut sets **remain the same**, compared to the original fault tree.

<u>Monitor from shore based control centre</u>

As shown in Figure 42, if the course of the CTV is monitored from the Offshore Wind Farm shore-based control centre with 100% effectiveness, then the following events will be averted: **failure of navigational equipment**. This preventative measure is placed in the same position in the fault tree as the measure "Navigational equipment redundancies". Therefore, the results are the same.

Table 24 summarizes the previous results regarding the effectiveness of the existing preventative measures.

Preventative measure	2nd order minimal cut set reduction	3rd order minimal cut set reduction
Entry permit for the 500m zone	-	100%
Navigational equipment redundancies	27%	-
Monitor from shore based control centre	27%	-

Table 24: Summary of results the effectiveness of the existing preventative measures

Consequently, the most effective of the existing preventative control measures is **entry permit for the 500m zone**.

4.4.2.2 Effectiveness of mitigation measures

As resulted from the analysis of the corresponding event tree, the most crucial events that play a major role in leading to Level 3 consequences are the following: **immediate worker salvage** and **SAR vessel operating nearby.** The existing mitigative risk control measures are evaluated as highly effective, since they affect the development of the corresponding crucial events in a way that fatalities are averted. An additional note should be made that although whether workers are located in the vicinity of the collision area is not crucial for leading to a fatality, it remains a valuable risk control measure. This is owed to the fact that workers remain in a space that protects them from various hazards such as adverse weather conditions and the effects of the impact in case the CTV is involved in a collision.

4.4.3 Worker loses balance while accessing the WTG

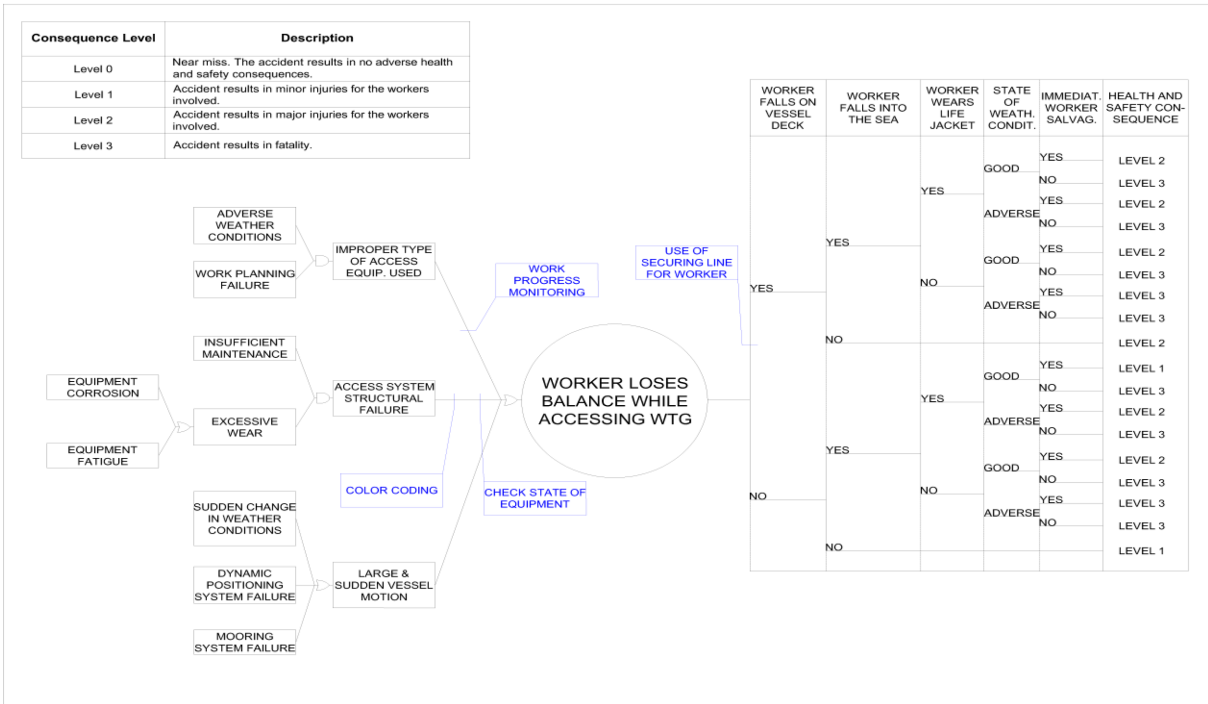


Figure 43: Bow-Tie diagram with preventative and mitigative safety measures, for the accident of a worker losing his balance while accessing the WTG

The following safety barriers have been derived from the International Marine Contractors Association guidelines [66], and the European Agency for Occupational Safety and Health [54].

<u>Preventative measures</u>

- Checking the state of the selected access equipment.
- Use of colour coding for marking defective machinery equipment or equipment that is in need of maintenance.
- Monitoring the work progress and supervising the ongoing task.

<u>Mitigative measures</u>

- Use of securing line for worker in order to prevent either the fall on the deck of the vessel or the fall into the sea after he has lost his balance on the gangway.

Figure 43 shows the previously mentioned preventative and mitigative risk control measures as they have been placed on the constructed bow-tie diagram.

4.4.3.1 Effectiveness of preventative measures

The fault tree for the particular accident type consists of the following minimal cut sets:

- **3 sets** (1st order), and
- **3 sets** (2nd order).

<u>Work progress monitoring</u>

As shown in Figure 43, if monitoring the work progress and supervision of the ongoing task are conducted with 100% effectiveness, then the following events will be averted: **improper type of access equipment used**. The resulting minimal cut sets for the altered fault tree are shown below (the event codes are retained for comparison reasons).

Letter code	Event description
F	Sudden change in weather conditions
G	DP system failure
H	Mooring system failure

Table 25: 1st order minimal cut sets for the altered fault tree of a worker losing his balance while accessing the WTG - Work progress monitoring

Letter code	Event description
CD	(Insufficient maintenance) AND (Equipment corrosion)
CE	(Insufficient maintenance) AND (Equipment fatigue)

Table 26: 2nd order minimal cut sets for the altered fault tree of a worker losing his balance while accessing the WTG - Work progress monitoring

The altered fault tree consists of the following minimal cut sets:

- **3 sets** (1st order, Table 25), and
- **2 sets** (2nd order, Table 26).

Therefore, 1st order minimal cut sets **remain the same** and 2nd order minimal cut sets **are reduced by about 33%**, compared to the original fault tree.

<u>Check state of equipment</u>

As shown in Figure 43, if the state of the selected access equipment is checked with 100% effectiveness, then the following events will be averted: **access system structural failure**. The resulting minimal cut sets for the altered fault tree are shown below (the event codes are retained for comparison reasons).

Letter code	Event description
F	Sudden change in weather conditions
G	DP system failure
H	Mooring system failure

Table 27: 1st order minimal cut sets for the altered fault tree of a worker losing his balance while accessing the WTG – Check state of equipment

Letter code	Event description
AB	(Adverse weather conditions) AND (Work planning failure)

Table 28: 2nd order minimal cut sets for the altered fault tree of a worker losing his balance while accessing the WTG – Check state of equipment

The altered fault tree consists of the following minimal cut sets:

- **3 sets** (1st order, Table 27), and
- **1 sets** (2nd order, Table 28).

Therefore, 1st order minimal cut sets **remain the same** and 2nd order minimal cut sets **are reduced by about 66%**, compared to the original fault tree.

Table 29 summarizes the previous results regarding the effectiveness of the existing preventative measures.

Preventative measure	1st order minimal cut set reduction	2nd order minimal cut set reduction
Work progress monitoring	-	33%
Check state of equipment	-	66%

Table 29: Summary of results the effectiveness of the existing preventative measures

Consequently, the most effective of the existing preventative control measures is **check state of equipment.**

4.4.3.2 Effectiveness of mitigation measures

As resulted from the analysis of the corresponding event tree, the most crucial events that play a major role in leading to Level 3 consequences are the following: **state of weather conditions** and **immediate worker salvage**. In the case of this particular accident type, the existing mitigative risk control measures have an indirect affect to the outcome of the crucial events that were determined, since the probability of a worker falling into the sea are minimized when an appropriate securing line is used.

4.5 Assessment of LEANWIND innovations

The aim of this section is to propose (where applicable) appropriate RCOs for Offshore Wind Farm innovation categories that may adversely affect occupational Health and Safety. The outlined methodology will be applied to various categories of Offshore Wind Farm innovations that have also been examined in other WPs of the LEANWIND Project. Since the presented methodology employs a high level approach, the assessment is conducted on specified innovation categories rather than specific innovative systems. To achieve this the general characteristics of the innovation categories were determined, based on information collected from the other WPs of the LEANWIND Project. The following innovation categories are considered to be within the scope of this report:

- Access Systems;
- Innovative Lifting Arrangements;
- Innovative Vessel Concepts.

This section will outline the methodology that was applied for the assessment of the innovation categories and subsequently present the results and the recommendations from the evaluation.

4.5.1 Assessment Methodology

The methodology that will be applied for each innovation category consists of the following steps:

1. Determine which accident types are applicable.
2. Determine whether the causes leading to the accident, or the consequences that follow the accident, or both are affected.
3. Assess the magnitude of the effect on the frequencies of the causes and the consequences.
4. Calculate the health and safety risk level and compare it to a selected base case for each innovation category.
5. Propose (where applicable) specific RCOs.

As documented in Section 2.3, the risk assessment effort presented in this deliverable report was hampered by the lack of accurate and relevant historical accident data. To overcome this problem a Rapid Risk Ranking (RRR) approach, similar to the one detailed in [67] was employed. The RRR approach was used to estimate the frequency of occurrence of both the basic events (fault trees) and the event gates (event trees) that comprise the Bow-Tie models that were constructed. This approach involves using qualitative estimations for event frequencies and assigning each one to a predetermined frequency value from a likelihood matrix. The same rationale is also applied to the estimation of consequence severities; whereby qualitative estimations are assigned to a pre-determined Equivalent Fatality value from a severity matrix. The risk level is finally assessed by combining the values of the likelihood matrix with the ones in the severity matrix, based on a risk matrix.

The matrices (Table 30 - Table 32) that were constructed for the purposes of the analysis in this deliverable report are similar to the ones described by the IMO in the FSA Guidelines [68]. The likelihood index is measured on a 0-1 scale and a specific value is assigned to each likelihood category, as shown in Table 30. It should be noted that the assigned frequencies of the likelihood index may not exactly correspond to the ones that would be calculated from the analysis of historical accident data, if such data were available, but rather give a sense of the order of magnitude and therefore may be used in the assessment of relative risk values. The severity index is measured on a logarithmic scale and therefore the assigned equivalent fatalities differ from each other by one order of magnitude.

Score	Likelihood	F	Description
5	Imminent	0.99	Event is almost certain to occur during a year of operation of an offshore wind farm.
4	Probable	0.9	Event occurs several times during a year of operation of an offshore wind farm.
3	Likely	0.5	Event occurs sometimes during a year of operation of an offshore wind farm.

2	May happen	0.1	Event is unlikely, though conceivable.
1	Unlikely	0.01	Event is extremely unlikely.

Table 30: Likelihood matrix employed in the health and safety assessment of Offshore Wind Farm innovations

Score	Severity	S (Equiv. fat.)	Description
4	Catastrophic (Level 3)	1	Accident results in at least one fatality (e.g. due to drowning, heart attack etc.).
3	Major (Level 2)	0.1	Accident results in major injuries (e.g. loss of consciousness, bone fractures, breathing difficulty, internal or external bleeding, paralysis etc.) for the workers involved.
2	Minor (Level 1)	0.01	Accident results in minor injuries (e.g. scratches, bruises, musculoskeletal pain, dizziness, blackouts etc.) for the workers involved.
1	None (Level 0)	0	Near miss. The accident results in no adverse health and safety consequences.

Table 31: Severity matrix employed in the health and safety assessment of Offshore Wind Farm innovations

Risk Index (RI)					
FI	Likelihood	Severity (SI)			
		1	2	3	4
		None	Minor	Major	Catastrophic
5	Imminent	6	7	8	9
4	Probable	5	6	7	8
3	Likely	4	5	6	7
2	May happen	3	4	5	6
1	Unlikely	2	3	4	5

Table 32: Risk matrix employed in the health and safety assessment of Offshore Wind Farm innovations

The values of the resulting Risk Index were classified into the following four categories: Negligible, Low, Moderate, High. The categories are defined based on the need for further risk reduction and the implementation of RCOs, as explained in Table 33.

Score	Risk Index	Action
2-3	Negligible	No further improvements required.
4-5	Low	Monitor existing controls.

6-7	Moderate	Further risk reduction must be considered.
8-9	High	Implement immediate control measures to prevent further harm/damage.

Table 33: Explanation of risk ranking categories

The steps used to calculate the consequence frequencies (Figure 44) for each constructed bow-tie model are the following:

1. **Qualitative evaluation of event frequencies (fault tree).** Each basic event in the fault tree is assigned a qualitative characterisation and the corresponding predetermined frequency.
2. **Calculation of top event frequency.** The predetermined frequencies are used to calculate the frequency of the top event. AND gates are calculated as the product of the frequencies of the combined events and OR gates are calculated as the sum of the frequencies of the combined events.
3. **Qualitative evaluation of event frequencies (event tree).** Each event gate in the event tree is assigned a qualitative characterisation and the corresponding predetermined frequency. Since the constructed event trees use binary event gates (i.e. YES/NO etc.), only the positive outcome of each event is evaluated. The negative outcome of each event is determined as follows: "Imminent" becomes "Unlikely", "Probable" becomes "May happen", "Likely remains "Likely".
4. **Calculation of consequence frequencies.** The calculated top event frequency is propagated through the event tree and combined with the predetermined frequencies for the event gates, the frequency of each scenario in the event tree is calculated.

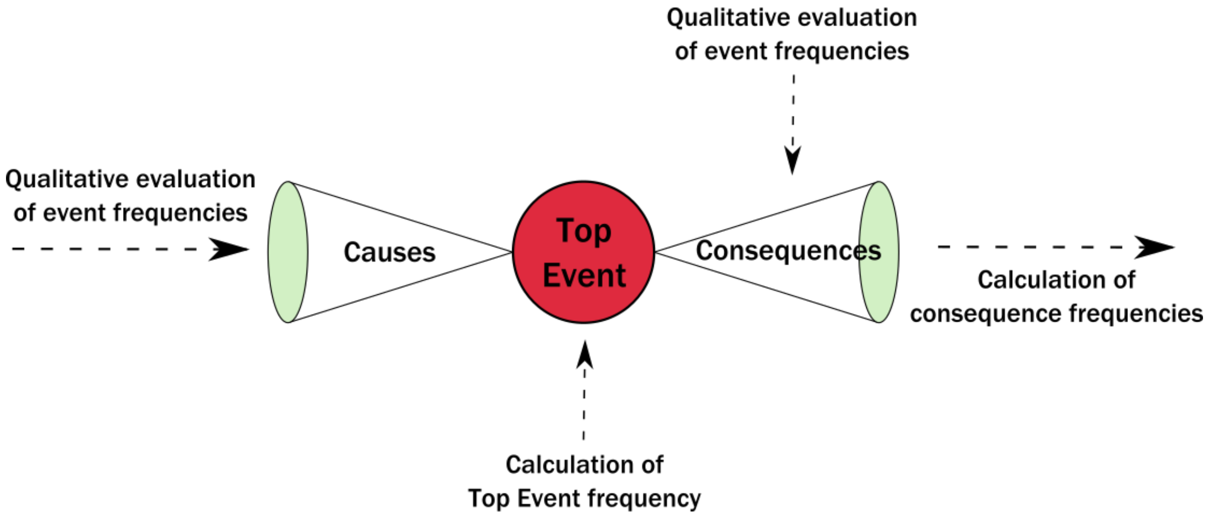


Figure 44: Steps used to calculate consequence frequencies for the constructed bow-tie diagrams

The next step of the employed methodology is the calculation of the likelihood (frequency) of equivalent fatalities. This is achieved by assigning each consequence level (category) to the corresponding Equivalent Fatalities, based on the severity matrix, and multiplying by the calculated consequence frequency. The likelihood of equivalent fatalities is used as a risk metric, combining frequency of occurrence and consequence severity. Figure 45 shows an example of these calculations for the event tree constructed for the falling object during a lifting operation. The overall risk level for each accident category is determined by summing the calculated likelihoods of equivalent fatalities for each scenario in the event tree. Additionally, the calculated values for the likelihood of equivalent fatalities are benchmarked against incident frequencies that were calculated from data provided by the G+ Offshore Wind Health and Safety Association and the CWIF database. In the context of the present report, this comparison has been used as a benchmark to evaluate the effectiveness of the constructed risk model and the affinity of the calculated probability to real world data. Subsequently, the expected impact on the frequencies of the various events in the bow-tie models was qualitatively evaluated and the likelihood calculations were conducted as previously outlined.

To serve as a comparison basis, a base case will be determined for each innovation category, which will use specific assumptions. The innovation categories will be evaluated according to how they affect occupational health and safety, using the methodology outlined in the present report.

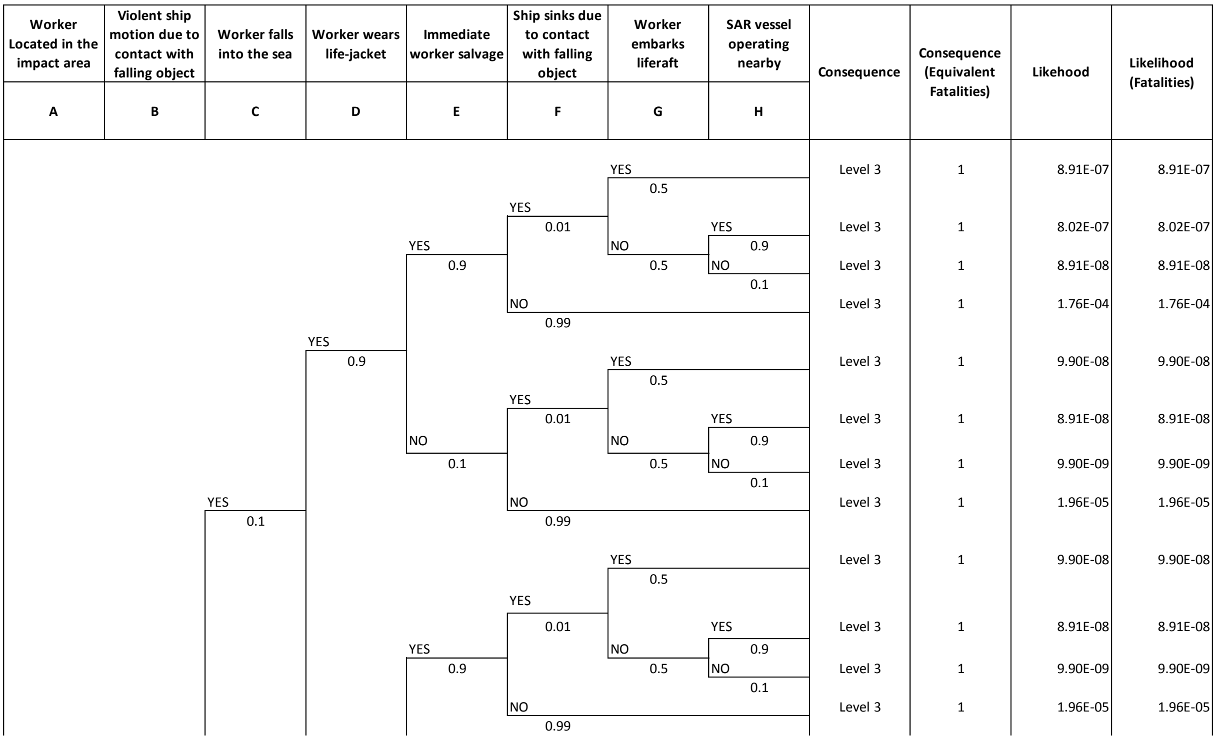


Figure 45: Example of consequence calculation for the event tree constructed for the falling object during an offshore lifting operation

The following sections present the definitions and assumptions of the base cases for each innovation category that will be examined, as well as the general features of each innovation category and how they impact the event frequencies.

4.5.2 Evaluation of Access Systems

The analysis in the present deliverable report has used information from the safety assessment of various access systems that has been conducted in the context of Task 4.5 of the LEANWIND Project [69]. The aforementioned safety assessment included the identification of various hazardous situations that arise in each access mode that has been evaluated (i.e. “bump & jump” and “walk to work”). Each identified hazard was ranked according to qualitative evaluations of the likelihood and consequence severity, based on the defined likehood and severity matrices that were previously described. Subsequently, the same ranking was conducted for each innovative solution and the average risk levels were compared, in order to evaluate the health and safety effects of each one.

The examined innovations use either the "**bump & jump**" or the "**walk to work**" access modes, but generally aim to lower the likelihood and the severity of specific hazards. The innovations were classified in the following categories:

- Vessel Hull/Seakeeping innovations;
- Passive and Active Motion Compensation innovations;
- Offshore Base concepts.

Different access systems affect the development of access related incidents and therefore the assessment will be conducted through the use of the bow-tie model for the incident "**Worker loses balance while accessing the WTG**".

4.5.2.1 Base Case

The assessment of the innovative access systems will examine the following separate base cases: "bump & jump" and "walk to work" access modes.

<u>Bump & Jump access mode</u>

Table 34 shows the qualitative evaluation of event likelihoods for the fault tree events. The frequencies of the basic events C to H were not evaluated directly, due to the fact that the available information was not enough to reliably estimate frequencies at this level of detail. Therefore, the frequencies were evaluated for the intermediate events "**Access system structural failure**" and "**Large and sudden vessel motion**", which are a combination of the aforementioned basic events.

The assumptions for the calculation of the top event frequency are listed below:

- The state of the weather conditions is equally likely to be good or adverse;
- The best estimate for the work planning failure is that it "May happen";
- The frequency for the structural failure of the access system was set to null, due to the fact that the bump & jump access mode does not involve an access system, such as a gangway;
- The frequency of a large and sudden vessel motion is set to "May happen", based on information from Task 4.5 [69].

Letter code	Event description	Likelihood	F
A	Adverse weather conditions	Likely	0.5
B	Work planning failure	May happen	0.1
C	Insufficient maintenance		
D	Equipment corrosion		
E	Equipment fatigue		
F	Sudden change in weather conditions		
G	DP system failure		
H	Mooring system failure		
C(D+E)	Access system structural failure	-	0
F+G+H	Large and sudden vessel motion	May happen	0.1

Table 34: Qualitative evaluation likelihoods of fault tree events for bump & jump access mode base case

Table 35 shows the qualitative evaluation of likelihoods for the gates of the event trees. The assumptions for the calculation of the consequence frequencies are listed below:

- The frequency of "**Worker falls on vessel deck**" is set to "Likely", based on information from Task 4.5 [69];
- The frequency of "**Worker falls into the sea**" is set to "Probable", based on information from Task 4.5 [69];
- The best estimate for the frequency of "Worker wears life-jacket" is "Probable";
- The state of the weather conditions is equally likely to be good or adverse;
- The best estimate for the frequency of "Immediate worker salvage" is "Probable".

Letter code	Event Description	Positive Outcome Likelihood	Negative Outcome Likelihood
A	Worker falls on vessel deck	Likely	Likely
B	Worker falls into the sea	Probable	May happen
C	Worker wears life-jacket	Probable	May happen
D	State of weather conditions	Likely	Likely
E	Immediate worker salvage	Probable	May happen

Table 35: Qualitative evaluation of positive and negative outcome likelihoods of event tree gates for bump & jump base case

Results

Top event	**1.50E-01**
Likelihood of equivalent fatalities	**2.94E-02**

Figure 46 shows the distribution of event tree scenarios according to their assigned risk index. For the base case of bump & jump access mode, 6% of the event tree scenarios results in **negligible risk** (i.e. risk index equal to 2 or 3) and 94% results in **low risk** (i.e. risk index equal to 4 or 5).

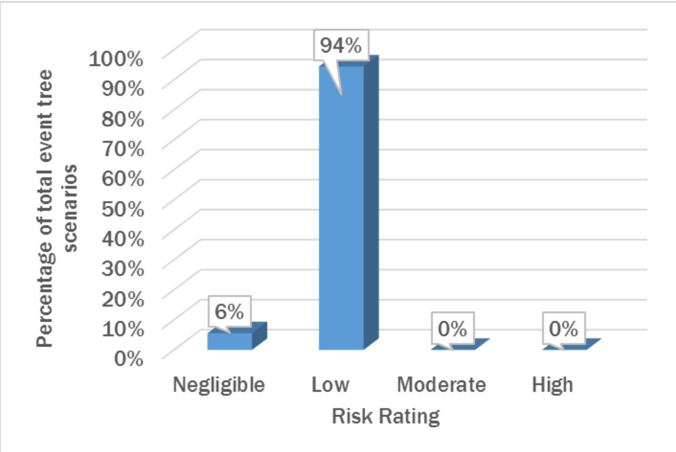


Figure 46: Distribution of event tree scenarios according to the classification of the resulting risk index (bump & jump)

Walk to Work access mode

Table 36 shows the qualitative evaluation of event likelihoods for the fault tree events. The assumptions for the calculation of the top event frequency are listed below:

- The state of the weather conditions is equally likely to be good or adverse;
- The best estimate for the work planning failure is that it "May happen";
- The frequency for the structural failure of the access system is set to "Unlikely", based on information from Task 4.5 [69];
- The frequency of a large and sudden vessel motion is set to "May happen", based on information from Task 4.5.

Letter code	Event description	Likelihood	F
A	Adverse weather conditions	Likely	0.5
B	Work planning failure	May happen	0.1
C	Insufficient maintenance		
D	Equipment corrosion		
E	Equipment fatigue		
F	Sudden change in weather conditions		
G	DP system failure		
H	Mooring system failure		
C(D+E)	Access system structural failure	Unlikely	0.01
F+G+H	Large and sudden vessel motion	May happen	0.1

Table 36 Qualitative evaluation likelihoods of fault tree events for walk to work base case

Table 37 shows the qualitative evaluation of likelihoods for the gates of the event trees. The assumptions for the calculation of the consequence frequencies are listed below:

- The frequency of "**Worker falls on vessel deck**" is set to "Likely", based on information from Task 4.5 [69];
- The frequency of "**Worker falls into the sea**" is set to "May happen", based on information from Task 4.5 [69];
- The best estimate for the frequency of "**Worker wears life-jacket**" is estimated as "Probable";
- The state of the weather conditions is equally likely to be good or adverse;
- The best estimate for frequency of "**Immediate worker salvage**" is set to "Probable".

Letter code	Event Description	Positive Outcome Likelihood	Negative Outcome Likelihood
A	Worker falls on vessel deck	Likely	Likely
B	Worker falls into the sea	May happen	Probable
C	Worker wears life-jacket	Probable	May happen
D	State of weather conditions	Likely	Likely
E	Immediate worker salvage	Probable	May happen

Table 37 Qualitative evaluation of positive and negative outcome likelihoods of event tree gates for walk to work base case

Results

Top event	**1.60E-01**
Likelihood of equivalent fatalities	**1.06E-02**

Figure 47 shows the distribution of event tree scenarios according to their assigned risk index. For the base case of walk to work access mode, 11% of the event tree scenarios results in **negligible risk** (i.e. risk index equal to 2 or 3) and 89% results in **low risk** (i.e. risk index equal to 4 or 5).

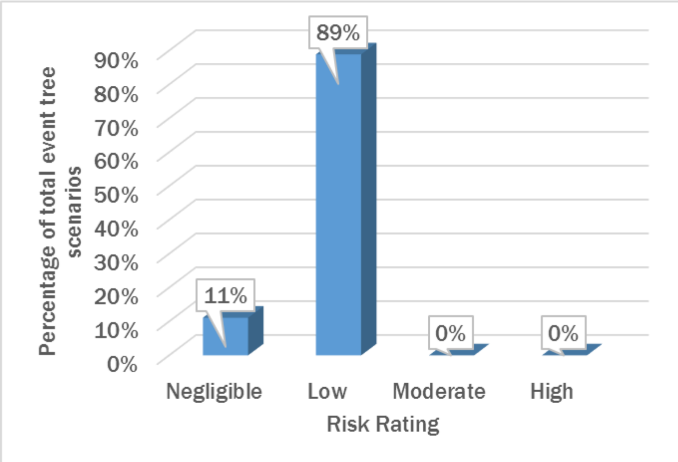


Figure 47: Distribution of event tree scenarios according to the classification of the resulting risk index (walk to work)

4.5.2.2 Vessel Hull/Seakeeping

Vessel hull and seakeeping innovations target the following optimizations: a) to minimize vessel motions during transit, consequently reducing the effects of sea motion sickness, and b) to increase stability while workers access the WTG from the vessel, consequently increasing the safety of the operation. These innovations still use either bump & jump or walk to work access modes. Therefore, each innovation group will be compared to the appropriate base case.

Bump & Jump access mode

Apart from the traditional crew transfer vessels (CTV), Bump & jump is used by the following innovative concepts [69]: *Transpar, WindServer, Wavecraft*.

Table 38 shows the qualitative evaluation of event likelihoods for the fault tree events, where exactly the same assumptions are applied as for the bump & jump base case.

Letter code	Event description	Likelihood	F
A	Adverse weather conditions	Likely	0.5
B	Work planning failure	May happen	0.1
C(D+E)	Access system structural failure	-	0
F+G+H	Large and sudden vessel motion	May happen	0.1

Table 38 Qualitative evaluation likelihoods of fault tree events – Vessel Hull/Seakeeping innovations that use bump & jump access mode

Table 39 shows the qualitative evaluation of likelihoods for the gates of the event trees. The differences in the assumptions, compared to the base case, are listed below:

- The frequency of "**Worker falls on vessel deck**" is reduced to "May happen", which reflects the fact that these innovations aim to increase vessel stability during worker access;
- The frequency of "**Worker falls into the sea**" is reduced to "May happen", for the same reason.

Letter code	Event Description	Positive Outcome Likelihood	Negative Outcome Likelihood
A	Worker falls on vessel deck	May happen	Probable
B	Worker falls into the sea	May happen	Probable
C	Worker wears life-jacket	Probable	May happen
D	State of weather conditions	Likely	Likely
E	Immediate worker salvage	Probable	May happen

Table 39 Qualitative evaluation of positive and negative outcome likelihoods of event tree gates – Vessel Hull/Seakeeping innovations that use bump & jump access mode

Results

Top event	**1.50E-01**
Likelihood of equivalent fatalities	**4.32E-03**

Figure 48 shows the distribution of event tree scenarios according to their assigned risk index. For Vessel Hull/Seakeeping innovations that use the bump & jump access mode, 6% of the event tree scenarios results in **negligible risk** (i.e. risk index equal to 2 or 3) and 94% results in **low risk** (i.e. risk index equal to 4 or 5).

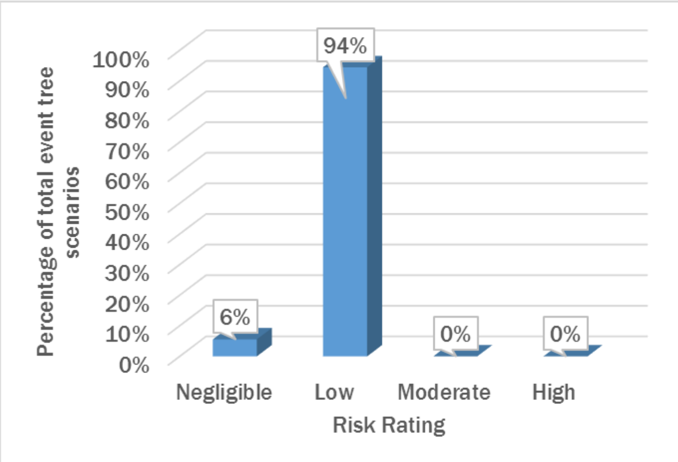


Figure 48: Distribution of event tree scenarios according to the classification of the resulting risk index (Vessel Hull/Seakeeping innovations that use bump & jump access mode)

Walk to Work access mode

Walk to work is used by the following concepts [69]: *BMT Nigel Cees XSS*.

Table 40 shows the qualitative evaluation of event likelihoods for the fault tree events. The difference in the assumptions, compared to the base case, is that the frequency of "**Large and sudden vessel motion**" is reduced to "Unlikely". This reflects the fact that these innovations aim to increase vessel stability during worker access.

Letter code	Event description	Likelihood	F
A	Adverse weather conditions	Likely	0.5
B	Work planning failure	May happen	0.1
C(D+E)	Access system structural failure	Unlikely	0.01
F+G+H	Large and sudden vessel motion	Unlikely	0.01

Table 40: Qualitative evaluation likelihoods of fault tree events – Vessel Hull/Seakeeping innovations that use walk to work access mode

Table 41 shows the qualitative evaluation of likelihoods for the gates of the event trees, where exactly the same assumptions are applied as for the walk to work base case.

Letter code	Event Description	Positive Outcome Likelihood	Negative Outcome Likelihood
A	Worker falls on vessel deck	Likely	Likely
B	Worker falls into the sea	May happen	Probable
C	Worker wears life-jacket	Probable	May happen
D	State of weather conditions	Likely	Likely
E	Immediate worker salvage	Probable	May happen

Table 41: Qualitative evaluation of positive and negative outcome likelihoods of event tree gates – Vessel Hull/Seakeeping innovations that use walk to work access mode

<u>**Results**</u>

Top event	**7.00E-02**
Likelihood of equivalent fatalities	**4.64E-03**

Figure 48 shows the distribution of event tree scenarios according to their assigned risk index. For Vessel Hull/Seakeeping innovations that use the bump & jump access mode, 11% of the event tree scenarios results in **negligible risk** (i.e. risk index equal to 2 or 3) and 89% results in **low risk** (i.e. risk index equal to 4 or 5).

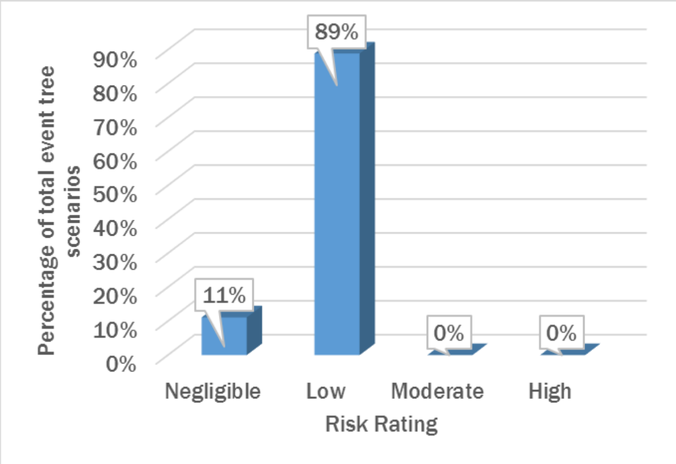


Figure 49: Distribution of event tree scenarios according to the classification of the resulting risk index (Vessel Hull/Seakeeping innovations that use walk to work access mode)

4.5.2.3 Motion Compensation

Motion compensation innovations aim to increase vessel stability during worker access by separating the hull motion from the motion of the deck or platform. Motion compensation includes both passive and active system concepts.

<u>Bump & Jump access mode</u>

Bump & jump is used by the following concepts [69]: *North Sea Logistics Pivoting Deck Vessel, Nauticraft*.

Table 42 shows the qualitative evaluation of event likelihoods for the fault tree events. The difference in the assumptions, compared to the base case, is that the frequency for "**Access system structural failure**" is set to "Unlikely", based on information from Task 4.5 [69]. This reflects the possibility of failure of the connecting system causing separation from the landing stage or the vessel.

Letter code	Event description	Likelihood	F
A	Adverse weather conditions	Likely	0.5
B	Work planning failure	May happen	0.1
C(D+E)	Access system structural failure	Unlikely	0.01
F+G+H	Large and sudden vessel motion	May happen	0.1

Table 42: Qualitative evaluation likelihoods of fault tree events – Motion compensation innovations that use bump & jump access mode

Table 43 shows the qualitative evaluation of likelihoods for the gates of the event trees. The differences in the assumptions, compared to the base case, are listed below:

- The frequency for "**Worker falls on vessel deck**" is reduced to "May happen", which reflects the fact that these innovations aim at increasing vessel stability during worker access;
- The frequency for "**Worker falls into the sea**" is reduced to "May happen", for the same reason.

Letter code	Event Description	Positive Outcome Likelihood	Negative Outcome Likelihood
A	Worker falls on vessel deck	May happen	Probable
B	Worker falls into the sea	May happen	Probable
C	Worker wears life-jacket	Probable	May happen
D	State of weather conditions	Likely	Likely
E	Immediate worker salvage	Probable	May happen

Table 43: Qualitative evaluation of positive and negative outcome likelihoods of event tree gates - Motion compensation innovations that use bump & jump access mode

Results

Top event	**1.60E-01**
Likelihood of equivalent fatalities	**4.60E-03**

Figure 50 shows the distribution of event tree scenarios according to their assigned risk index. For Vessel Hull/Seakeeping innovations that use the bump & jump access mode, 6% of the event tree scenarios results in **negligible risk** (i.e. risk index equal to 2 or 3) and 94% results in **low risk** (i.e. risk index equal to 4 or 5).

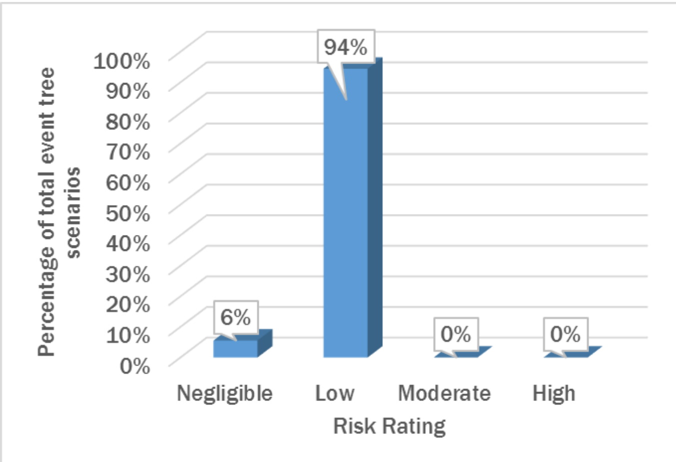


Figure 50: Distribution of event tree scenarios according to the classification of the resulting risk index (Motion compensation innovations that use bump & jump access mode)

Walk to work access mode

Walk to work is used by the following concepts [69]: *Autobrow, Windbridge*.

For the motion compensation innovations that use walk to work access mode, exactly the same assumptions are applied as for the walk to work base case, based on information from Task 4.5 [69]. Therefore, the results are exactly the same and there is no difference in the overall risk level, compared to the walk to work base case.

4.5.2.4 Summary of results

Table 44 and Table 45 summarize the results from the previous sections for the innovations that use bump & jump and those that use walk to work respectively.

	Bump & Jump

Calculated Frequencies	Base Case	Vessel Hull/Seakeeping Innovations	Motion Compensation Innovations
Top Event	1.50E-01	1.50E-01	1.60E-01
Likelihood (Fatalities)	2.94E-02	4.32E-03	4.60E-03

Table 44: Summary of calculated frequencies for access innovations that use bump & jump, compared to base case

The likelihood of equivalent fatalities for bump & jump access mode systems is in the range of 10^{-1} and 10^{-3}, in terms of order of magnitude. It is observed that both vessel hull/seakeeping and motion compensation innovations present lower expected fatalities, compared to the base case for the bump & jump access mode. The calculated likelihood of equivalent fatalities is one order of magnitude lower compared to the base case, which translates to about **85% decrease** in expected fatalities.

Calculated Frequencies	Walk to Work		
	Base	Vessel Hull/Seakeeping Innovations	Motion Compensation Innovations
Top Event	1.60E-01	7.00E-02	1.60E-01
Likelihood (Fatalities)	1.06E-02	4.64E-03	1.06E-02

Table 45: Summary of calculated frequencies for access innovations that use walk to work, compared to base case

The likelihood of equivalent fatalities for walk to work access mode systems is also in the range of 10^{-1} and 10^{-3}, in terms of order of magnitude. It is observed that vessel hull/seakeeping innovations present lower expected fatalities, compared to the base case by an order of magnitude, which translates to about **56% decrease** in expected fatalities. Regarding motion compensation innovations, the likelihood of expected fatalities are exactly the same compared to the base case as was previously stated.

When comparing the calculated likelihood of equivalent fatalities between the bump & jump and walk to work access modes, it is observed that the walk to work base case presents lower expected fatalities by about 64%. However, the innovations that employ the walk to work access mode present higher expected fatalities compared to the innovations that employ the bump & jump access mode. This could be attributed to the fact that although the walk to work access mode is generally safer, compared to bump & jump, the corresponding innovative systems often use sophisticated mechanical systems that might be more susceptible to structural failures.

For every innovative access system that was examined in this section all scenarios that are incorporated in the developed bow-tie models result in either negligible (6-11% of total number of scenarios) or low risk level (89-94% of total number of scenarios). Due to the fact that overall risk level is low, no additional RCOs is recommended to be examined. The recommended course of action would be to monitor existing controls regarding the effect of innovative access systems to health and safety issues.

In addition, the findings in this report are compatible to the corresponding results from the safety assessment that was applied in the context of Task 4.5 [69] for access systems, which also concluded that the recommended course of action would be to monitor existing controls.

The calculated likelihood of equivalent fatalities can be compared against the annual frequency of the corresponding reported incidents from the G+ Offshore Wind Health and Safety Association. Table 46 shows the data that was used to calculate the annual frequency of reported incidents during transfer by vessels, for the years 2013 – 2015, which are related to worker access incidents.

The average annual frequency of incidents during transfer by vessel for the years 2013 – 2015 is equal to **7.51E-02**. The calculated likelihood for equivalent fatalities, regarding both "walk to work" and "bump and jump" access systems is **in the same order of magnitude (2.94E-02 and 1.06E-02 respectively)** and therefore the results from the risk model are satisfactory.

Type of human injury	2015			2014			2013		
	Total	Trans. by vessel	Freq.	Total	Trans. by vessel	Freq.	Total	Trans. by vessel	Freq.
Hazards	450	-	-	97	15	-	102	20	-
Near hits	336	-	-	655	63	-	345	30	-
First aid	70	-	-	95	12	-	61	4	-
Medical treatment injuries	54	-	-	54	2	-	30	0	-
Restricted work days	32	-	-	14	1	-	12	1	-
Lost work days	41	-	-	44	8	-	66	2	-
Fatalities	0	-	-	0	0	-	0	0	-
Reported Incidents	**983**	**27**	**2.75E-02**	**959**	**101**	**1.05E-01**	**616**	**57**	**9.25E-02**

Table 46: Data from the G+ Offshore Wind Health and Safety Association that was used to calculate annual frequencies for access related incidents.

4.5.3 Evaluation of Lifting Arrangements

Novel lifting arrangements may be classified in the following two categories (in the context of Task 3.4 of the LEANWIND Project): a) stand-alone lifting tools, and b) turbine installation vessel concepts.

The general characteristics of novel stand-alone lifting tools, which have an effect on the events of the constructed bow-tie models are summarized below:

- Less manual handling and working at height;
- Increased operational wind limit to reduce weather downtime.

The general characteristics of novel turbine installation vessels, which have an effect on the events of the constructed bow-tie models are summarized below:

- Turbines are transported and installed fully assembled.

Different lifting arrangements affect the development of incidents regarding falling objects during lifting operations and therefore the assessment will be conducted through the use of the bow-tie model for the incident "**Object falls during offshore lifting operation**".

4.5.3.1 Base Case

Table 47 shows the qualitative evaluation of event likelihoods for the fault tree events. The frequencies of the basic events A- O were not evaluated directly, due to the fact that the available information was not enough to reliably estimate frequencies at this level of detail. Therefore, the frequencies were evaluated for the intermediate events "**Improper lashing of lifted object**", "**Lifting equipment handling failure**", "**Lifting equipment overload**" and "**Lifting equipment structural failure**", which are a combination of all the aforementioned basic events.

The assumptions, which were based on expert judgement and logical inferences due to lack of appropriate data, for the calculation of the consequence frequencies are listed below:

- The frequency of "**Improper lashing of lifted object**" is set to "Unlikely";
- The frequency of "**Lifting equipment handling failure**" is set to "May happen";
- The frequency of "**Lifting equipment overload**" is set to "May happen";
- The frequency of "**Lifting equipment structural failure**" is set to "Unlikely".

Letter code	Event description	Likelihood	F
N+O	Improper lashing of lifted object	Unlikely	0.01
A+B+C+D	Lifting equipment handling failure	May happen	0.1
E+F+G+J(H+I)	Lifting equipment overload	May happen	0.1
K(L+M)	Lifting equipment structural failure	Unlikely	0.01

Table 47: Qualitative evaluation likelihoods of fault tree events for the lifting arrangements base case

Table 48 shows the qualitative evaluation of likelihoods for the gates of the event trees. The assumptions for the calculation of the consequence frequencies are listed below:

- Whether a worker is located in the impact area is estimated to "May happen";
- The frequency of "**Violent ship motion due to contact with falling object**" is estimated to "May happen";
- The frequency of "**Worker falls into the sea**" is estimated as "May happen";
- The best estimate for the frequency "**Worker wears life-jacket**" is "Probable";
- The best estimate for the frequency "**Immediate worker salvage**" is "Probable";
- The frequency of "**Ship sinks due to contact with falling object**" is estimated as "Unlikely";
- Whether a worker embarks a life raft is equally likely to be true or false;
- Whether a SAR vessel is operating nearby is set to be "Likely".

Letter code	Event Description	Positive Outcome Likelihood	Negative Outcome Likelihood
A	Worker located in the impact area	May happen	Probable

B	Violent ship motion due to contact with falling object	May happen	Probable
C	Worker falls into the sea	May happen	Probable
D	Worker wears life-jacket	Probable	May happen
E	Immediate worker salvage	Probable	May happen
F	Ship sinks due to contact with falling object	Unlikely	Imminent
G	Worker embarks life raft	Likely	Likely
H	SAR vessel operating nearby	Probable	May happen

Table 48: Qualitative evaluation of positive and negative outcome likelihoods of event tree gates for the lifting arrangements base case

Results

Top event	**2.20E-01**
Likelihood of equivalent fatalities	**2.42E-02**

Figure 51 shows the distribution of event tree scenarios according to their assigned risk index. For the lifting arrangements base case, 6% of event tree scenarios results in **negligible risk** (i.e. risk index equal to 2 or 3), 93% results in **low risk** (i.e. risk index equal to 4 or 5) and 1% of event tree scenarios results in **moderate risk** (i.e. risk index equal to 4 or 5).

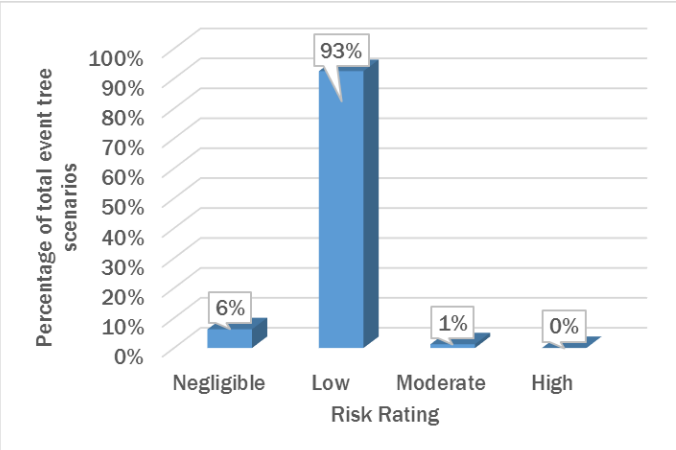


Figure 51: Distribution of event tree scenarios according to the classification of the resulting risk index (Lifting arrangements base case)

4.5.3.2 Stand-alone lifting tools

The estimated impacts, compared to the base case, of **less manual handling and working at height** on the events of the bow-tie models are listed below:

- The frequency of "**Lifting equipment handling failure**" is reduced by one level.

The estimated impacts, compared to the base case, of **increased operational wind limits** on the events of the bow-tie models are listed below:

- The frequency of "**Lifting equipment overload**" is reduced by one level;
- The frequency of "**Worker falls into the sea**" is increased by one level.

Table 49 shows the qualitative evaluation of event likelihoods for the fault tree events.

Letter code	Event description	Likelihood	F
N+O	Improper lashing of lifted object	Unlikely	0.01
A+B+C+D	Lifting equipment handling failure	Unlikely	0.01
E+F+G+J(H+I)	Lifting equipment overload	Unlikely	0.01
K(L+M)	Lifting equipment structural failure	Unlikely	0.01

Table 49: Qualitative evaluation likelihoods of fault tree events for the stand-alone lifting tools

Table 50 shows the qualitative evaluation of likelihoods for the gates of the event trees.

Letter code	Event Description	Positive Outcome Likelihood	Negative Outcome Likelihood
A	Worker located in the impact area	May happen	Probable
B	Violent ship motion due to contact with falling object	May happen	Probable
C	Worker falls into the sea	Likely	Likely
D	Worker wears life-jacket	Probable	May happen
E	Immediate worker salvage	Probable	May happen
F	Ship sinks due to contact with falling object	Unlikely	Imminent
G	Worker embarks life raft	Likely	Likely
H	SAR vessel operating nearby	Probable	May happen

Table 50: Qualitative evaluation of positive and negative outcome likelihoods of event tree gates for the stand alone lifting tools

<u>Results</u>

Top event	**4.00E-02**
Likelihood of equivalent fatalities	**5.86E-03**

Figure 52 shows the distribution of event tree scenarios according to their assigned risk index. For the lifting arrangements base case, 7.5% of event tree scenarios results in **negligible risk** (i.e. risk index equal to 2 or 3), and 92.5% results in **low risk** (i.e. risk index equal to 4 or 5).

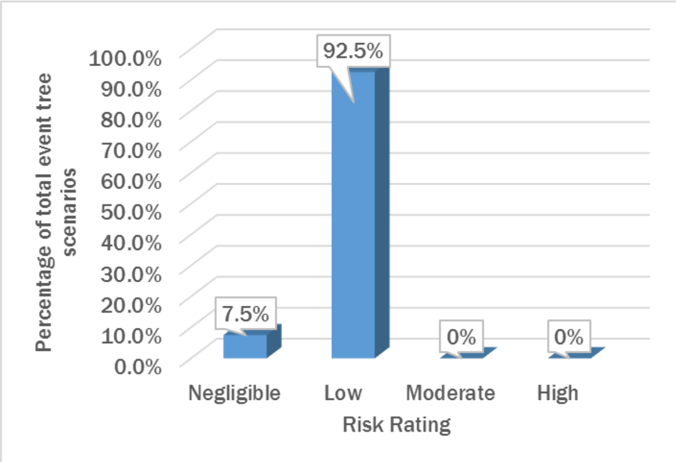


Figure 52: Distribution of event tree scenarios according to the classification of the resulting risk index (Stand-alone lifting tools)

4.5.3.3 Turbine installation vessel concepts

The estimated impacts, compared to the base case, of the fact that **turbines are transported and installed fully assembled** on the events of the bow-tie models are listed below:

- The frequency of "**Violent ship motion due to contact with falling object**" is increased by one level;
- The frequency of "**Ship sinks due to contact with falling object**" is increased by level;
- The frequency of "**Worker falls into the sea**" is increased by one level.

Due to the lack of relevant information, the assumptions regarding the fault tree event frequencies are exactly the same in the base case.

Table 51 shows the qualitative evaluation of likelihoods for the gates of the event trees.

Letter code	Event Description	Positive Outcome Likelihood	Negative Outcome Likelihood
A	Worker located in the impact area	May happen	Probable
B	Violent ship motion due to contact with falling object	Likely	Likely
C	Worker falls into the sea	Likely	Likely
D	Worker wears life-jacket	Probable	May happen
E	Immediate worker salvage	Probable	May happen
F	Ship sinks due to contact with falling object	May happen	Probable
G	Worker embarks life raft	Likely	Likely
H	SAR vessel operating nearby	Probable	May happen

Table 51: Qualitative evaluation of positive and negative outcome likelihoods of event tree gates for the turbine installation vessel concepts

Results

Top event	**2.20E-01**
Likelihood of equivalent fatalities	**3.07E-02**

Figure 53 shows the distribution of event tree scenarios according to their assigned risk index. For the lifting arrangements base case, 6% of event tree scenarios results in **negligible risk** (i.e. risk index equal to 2 or 3), and 94% results in **low risk** (i.e. risk index equal to 4 or 5).

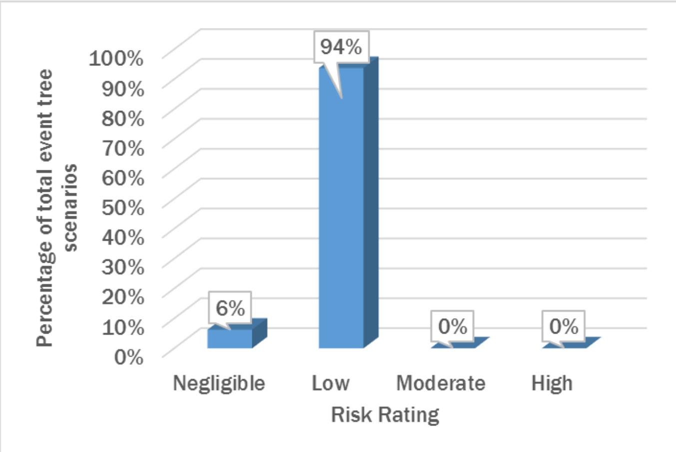


Figure 53: Distribution of event tree scenarios according to the classification of the resulting risk index (Turbine installation vessel concepts)

4.5.3.4 Summary of results

Table 52 summarizes the results from the previous sections regarding lifting arrangement innovations.

Calculated Frequencies	Base Case	Stand-alone lifting tools	Turbine installation vessel concepts
Top Event	2.20E-01	4.00E-02	2.20E-01
Likelihood (Fatalities)	2.42E-02	5.86E-03	3.07E-02

Table 52: Summary of calculated frequencies for lifting arrangement innovations, compared to the base case

The likelihood of equivalent fatalities for the lifting arrangements are in the range of 10^{-1} and 10^{-3}, in terms of order of magnitude. It is observed that the use of innovative stand-alone lifting tools lowers the likelihood of expected fatalities by one order of magnitude, which translates to about **76% decrease** in expected fatalities.

However, the use of innovative turbine installation vessel concepts **increases** the likelihood of expected fatalities by about **27%.** This result could be attributed to the fact that the transportation and installation of fully assembled turbines introduce some additional hazards to the process, which are related to the increased weight of the objects being transported and handled. In turn, this translates to more severe consequences in case such an object falls during a lifting operation.

Regarding the overall risk levels these are practically constant across all the examined cases (i.e. base case, stand-alone lifting tools and turbine installation vessel concepts innovations) and comprise negligible (6 – 7.5% of the total number of scenarios) and low (92.5 - 94% of the total number of scenarios) risk levels. Due to the fact that overall risk level is low, no additional RCOs is recommended to be examined. The recommended course of action would be to monitor existing controls regarding the effect of innovative lifting arrangements to health and safety issues.

The calculated likelihood of equivalent fatalities can be compared against the annual frequency of the corresponding reported incidents from the G+ Offshore Wind Health and Safety Association. Table 53 shows the data that was used to calculate the annual frequency of reported incidents that were caused by dropped objects during lifting operations, for the years 2014 – 2015, which are related to worker access incidents. It should be noted that the 2013 edition of the G+ summary statistics did not report dropped objects during lifting operations separately from incidents during lifting operations in general and therefore the corresponding data were not utilized for the comparison.

The average annual frequency of incidents that were caused by dropped objects during lifting operations for the years 2014 – 2015 is equal to **3.04E-02**. The calculated likelihood for equivalent fatalities is **in the same order of magnitude (2.42E-02)** and therefore the results from the risk model are satisfactory.

Type of human injury	2015			2014		
	Total	Dropped objects	Freq.	Total	Dropped objects	Freq.
Hazards	450	-	-	97	3	-
Near hits	336	-	-	655	27	-
First aid	70	-	-	95	0	-
Medical treatment injuries	54	-	-	54	1	-
Restricted work days	32	-	-	14	0	-
Lost work days	41	-	-	44	0	-
Fatalities	0	-	-	0	0	-
Reported Incidents	**983**	**28**	**2.85E-02**	**959**	**31**	**3.23E-02**

Table 53: Data from the G+ Offshore Wind Health and Safety Association [35, 44] that was used to calculate annual frequencies for lifting arrangement related incidents.

4.5.4 Evaluation of Vessel Concepts

The information in this section has been drawn from Tasks 3.3 [70] and 4.5 [69] of the LEANWIND Project, where innovative vessel concepts regarding both installation vessels and Operation & Maintenance Vessels have been studied. The general characteristics of novel vessel concepts, which have an effect on the events of the constructed bow-tie models are summarized below:

- Increased vessel size for transporting more/heavier cargo and more workers;
- Increased speed for reducing transfer times;

- Less susceptible to wave motion to increase safety during worker access.

Different vessel concepts affect the development of incidents regarding collisions and therefore the assessment will be conducted through the use of the bow-tie model for the incident "**CTV collides with WTG tower during approach**".

4.5.4.1 Base Case

Table 54 shows the qualitative evaluation of event likelihoods for the fault tree events. The frequencies of the basic events J and K were not evaluated directly, due to the fact that the available information was not enough to reliably estimate frequencies at this level of detail. Therefore, the frequencies were evaluated for the intermediate event "**Navigational machinery failure**", which is a combination of the aforementioned basic events.

The assumptions, which were based on expert judgement and logical inferences due to lack of appropriate data, for the calculation of the top event frequency are listed below:

- The frequency of high vessel speed is set to "May happen";
- The frequency of limited manoeuvring space is set to "Unlikely";
- The state of the weather conditions is equally likely to be good or adverse;
- The frequency of insufficient propulsive power is set to "May happen";
- The best estimate for navigational equipment failure is that it "May happen";
- The best estimate for work related fatigue is that it "May happen";
- The best estimate for insufficient experience is that it "May happen";
- The best estimate for distracted attention is that it "May happen";
- The best estimate for insufficient maintenance is that it is "Unlikely";
- The frequency of navigational machinery failure is set to "May happen".

Letter code	Event description	Likelihood	F
A	High vessel speed	May happen	0.1
B	Limited manoeuvring space	Unlikely	0.01
C	Adverse weather conditions	Likely	0.5
D	Insufficient propulsive power	May happen	0.1
E	Failure of navigational equipment	May happen	0.1
F	Work related fatigue	May happen	0.1
G	Insufficient experience	May happen	0.1
H	Attention distracted	May happen	0.1
I	Insufficient maintenance	Unlikely	0.01
J+K	Navigational machinery failure	May happen	0.1

Table 54: Qualitative evaluation likelihoods of fault tree events for the innovative vessel concepts base case

Table 55 shows the qualitative evaluation of likelihoods for the gates of the event trees. The assumptions, which were based on expert judgement and logical inferences due to lack of appropriate data, for the calculation of the consequence frequencies are listed below:

- The frequency for "**Worker in the vicinity of the collision area**" is set to "May happen";
- The frequency for "**Worker falls into the sea**" is set to "Unlikely";
- The best estimate for "**Worker wears life-jacket**" is "Probable";
- The best estimate for "**Immediate worker salvage**" is "Probable";
- The frequency for "**Ship sinks due to collision**" is set to "May happen";
- The frequency for "**Worker embarks life raft**" is set to "Likely";
- The frequency for "**SAR vessel operating nearby**" is set to "Probable".

Letter code	Event Description	Positive Outcome Likelihood	Negative Outcome Likelihood
A	Worker in the vicinity of the collision area	May happen	Probable
B	Worker falls into the sea	Unlikely	Imminent
C	Worker wears life-jacket	Probable	May happen
D	Immediate worker salvage	Probable	May happen
E	Ship sinks due to collision	May happen	Probable
F	Worker embarks life raft	Likely	Likely
G	SAR vessel operating nearby	Probable	May happen

Table 55: Qualitative evaluation of positive and negative outcome likelihoods of event tree gates for the innovative vessel concepts base case

Results

Top event	**7.90E-02**
Likelihood of equivalent fatalities	**1.53E-03**

Figure 54 shows the distribution of event tree scenarios according to their assigned risk index. For the lifting arrangements base case, 10% of event tree scenarios results in **negligible risk** (i.e. risk index equal to 2 or 3) and 90% results in **low risk** (i.e. risk index equal to 4 or 5).

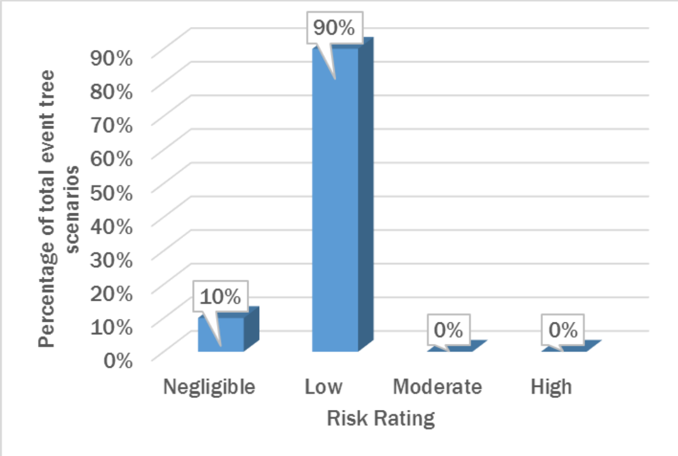


Figure 54: Distribution of event tree scenarios according to the classification of the resulting risk index (Innovative vessel concepts base case)

4.5.4.2 Innovative Concepts

The estimated impacts, compared to the base case, of **increased vessel size** on the events of the bow-tie models are listed below:

- The frequency of "**Limited manoeuvring space**" is increased by one level;
- The frequency of "**Worker in the vicinity of the collision area**" is reduced by one level;
- The frequency of "**Ship sinks due to collision**" is reduced by one level.

The estimated impacts, compared to the base case, of **increased vessel speed** on the events of the bow-tie models are listed below:

- The frequency of "**Insufficient propulsive power**" is reduced by one level.

The estimated impacts, compared to the base case, of **reduced susceptibility to wave motions** on the events of the bow-tie models are listed below:

- The frequency of "**Navigational machinery failure**" is reduced by one level.

Table 56 shows the qualitative evaluation of event likelihoods for the fault tree events.

Letter code	Event description	Likelihood	F
A	High vessel speed	May happen	0.1
B	Limited manoeuvring space	May happen	0.1
C	Adverse weather conditions	Likely	0.5
D	Insufficient propulsive power	Unlikely	0.01
E	Failure of navigational equipment	May happen	0.1
F	Work related fatigue	May happen	0.1
G	Insufficient experience	May happen	0.1
H	Attention distracted	May happen	0.1
I	Insufficient maintenance	Unlikely	0.01

Letter code	Event description	Likelihood	F
J+K	Navigational machinery failure	Unlikely	0.01

Table 56: Qualitative evaluation likelihoods of fault tree events for the innovative vessel concepts

Table 57 shows the qualitative evaluation of event likelihoods for the event gates of the event trees.

Letter code	Event Description	Positive Outcome Likelihood	Negative Outcome Likelihood
A	Worker in the vicinity of the collision area	Unlikely	Imminent
B	Worker falls into the sea	Unlikely	Imminent
C	Worker wears life-jacket	Probable	May happen
D	Immediate worker salvage	Probable	May happen
E	Ship sinks due to collision	Unlikely	Imminent
F	Worker embarks life raft	Likely	Likely
G	SAR vessel operating nearby	Probable	May happen

Table 57: Qualitative evaluation of positive and negative outcome likelihoods of event tree gates for the innovative vessel concepts

Results

Top event	**9.16E-02**
Likelihood of equivalent fatalities	**2.11E-04**

Figure 55 shows the distribution of event tree scenarios according to their assigned risk index. For the lifting arrangements base case, 10% of event tree scenarios results in **negligible risk** (i.e. risk index equal to 2 or 3) and 90% results in **low risk** (i.e. risk index equal to 4 or 5).

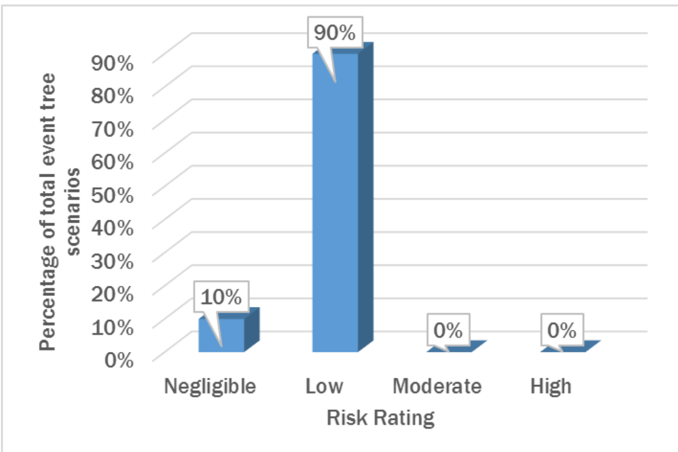


Figure 55: Distribution of event tree scenarios according to the classification of the resulting risk index (Innovative vessel concepts)

4.5.4.3 Summary of results

Table 58 summarizes the results from the previous sections regarding the innovative vessel concepts.

Calculated Frequencies	Base Case	Innovative vessel concepts
Top Event	7.90E-02	9.16E-02
Likelihood (Fatalities)	1.53E-03	2.11E-04

Table 58: Summary of calculated frequencies for the innovative vessel concepts, compared to the base case

The likelihood of equivalent fatalities for the innovative vessel concepts are in the range of 10^{-3} and 10^{-4}, in terms of order of magnitude. It is observed that the use of innovative vessels lowers the likelihood of expected fatalities by one order of magnitude, which translates to about **86% decrease** in expected fatalities.

Regarding the overall risk levels these are constant across all the examined cases (i.e. base case and innovative vessel concepts) and comprise negligible (10% of the total number of scenarios) and low (90% of the total number of scenarios) risk levels. Due to the fact that overall risk level is low, no additional RCOs is recommended to be examined. The recommended course of action would be to monitor existing controls regarding the effect of innovative vessel concepts to health and safety issues.

The calculated likelihood of equivalent fatalities can be compared against the annual frequency of the corresponding reported incidents from the CWIF database. It should be noted that the published G+ summary statistics did not specifically distinguish injuries related to vessel collisions and therefore the CWIF database was used instead. Table 59 shows the data that was used to calculate the annual frequency of reported incidents that were caused by vessel collisions with the tower of a WTG, for the years 2004 – 2016.

Type of human injury	Total	Vessel collision with WTG	Frequency
Near miss	55	0	-
Minor injury	22	0	-
Major injury	1	0	-
Lost time	13	0	-
Medical treatment injury	20	9	-
Fatality	10	0	-
Reported incidents	**121**	**9**	**6.20E-03**

Table 59: Reported human injuries for the years 2004-2016 from the CWIF accident database.

The average annual frequency of incidents that were caused by vessel collisions with the tower of a WTG for the years 2004 – 2016 is equal to **6.20E-03**. The calculated likelihood for equivalent fatalities is **in the same order of magnitude (1.53E-03)** and therefore the results from the risk model are satisfactory.

5 Training requirements

This Section presents a review of the current state of the art regarding training requirements and certifications for marine crew and industrial personnel involved in the O&M of an Offshore Wind Farm. Based on the identified gaps, specific actions are proposed for improving training requirements and specifications in order to cover the actual competencies that are necessary for the personnel working at an Offshore Wind Farm.

5.1 Competence

The need for competent crew and people to work in the offshore wind industry is growing together with the development of more and more complex offshore windfarms.

The requirements for a structured Competence Management System is of vital importance to any company involved in the development, installation, operation and decommissioning phase of an offshore windfarm. Several systems are available and pros and cons of these will not be included in this report.

For developing of training programs and in order to develop and assess the competency of an individual, it is necessary to define the meaning of 'competency', as it is required to have a common goal for any training being provided. Research in literature for definition of 'competent', will give several results. Competence is a diffuse term with several meanings, depending on the organisation and tasks to be carried out.

The British HSE has defined competence to be *"the combination of training, skills, experience and knowledge that a person has and their ability to apply them to perform a task safely"*. HSE also states that *"Other factors, such as attitude and physical ability, can also affect someone's competence"*. For training purposes, we can simplify the meaning of competence even further:

Competence is a combination of:

- <u>Knowledge and skill:</u> The person carrying out a task must have the correct knowledge and skill to carry out the task safely and efficiently.
- <u>Behaviour or attitude:</u> The person carrying out a task must have the correct behaviour or attitude to use his or her knowledge and skill correctly to carry out a task safely.
- <u>Ability</u>: The person carrying out a task must have the ability to carry out a task safely. This covers among other things, the personal physical and mental state, but also requires the correct tools to be available for the task.

All training requirements will focus on giving the participants the knowledge or skills for performing a task or focus on changing the behaviour of an individual or of a group, to act more safely and efficiently.

5.2 Existing regulations and requirements on competencies

Several regulations and requirements exists for the marine environment operation. In the report *Review of Maritime and Offshore Regulations and Standards for Offshore Wind* [34], which was developed by DNV-GL for the DMA, these regulations have been summarised. This report gives a good reference to existing requirements and this will as such not be repeated, but the report will be used as reference to discuss a few of the areas of competence.

5.2.1 Marine Crew Competencies

Marine crew competencies are covered by the STCW Convention [71]. Flag States will issue Certificate of Competence according to the requirements in the Convention.

5.2.1.1 ISM

The International Safety Management Code (ISM) has been implemented in the SOLAS convention for all vessels covered by the convention [72]. Chapter 8 of the ISM code has requirements, for all shipping companies operating vessels covered by the convention, to establish procedures, identify, describe and respond to potential emergency shipboard situations. Furthermore, it is the requirement for any company to establish procedures for key shipboard operations concerning the safety of the ship and the prevention of pollution. The various tasks involved should be defined and assigned to qualified personnel, as described in Chapter 7 of the Code.

5.2.1.2 Self-elevating units

The STCW framework does not fully cover the operation of self-elevating units. Typically, the requirements from STCW, combined with the requirements for Offshore Installation Managers (OIM) as stated in IMO Resolution A.1079(28), are often regarded as minimum standard of competence. The International Jack-Up Barge Operators Association (IJUBOA) has developed a competence framework for operators on Self-elevating units (Figure 56).

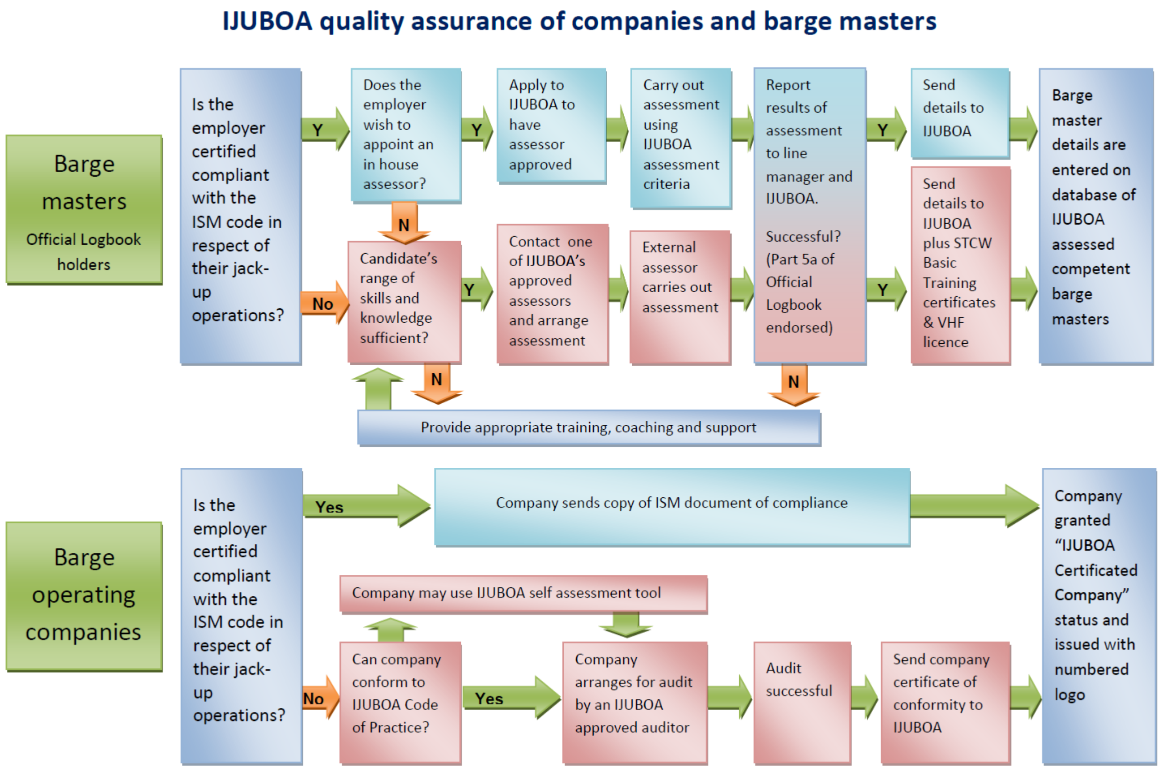


Figure 56: The International Jack-Up Barge Operators Association (IJUBOA) competence framework for operators on Self-elevating units [73].

5.2.1.3 Dynamic Positioning (DP) Operators

DP operators training is not regulated by STCW, but DP schemes have been developed by the offshore industry during several decades. Today, the following DP schemes exists:

- The Nautical Institute DP Scheme [74].
- DNV-GL DP Scheme [75]
- Offshore Service Vessel Dynamic Positioning Authority (OSVDPA) Scheme [76].

None of the schemes today are developed with offshore wind industry in mind. The most common used scheme is the one from The Nautical Institute. Figure 57 shows the route of DP education for a DP operator.

This scheme requires a total of 120 days in operation on DP, in addition to 2 shore based courses. Each day in operation on DP must be minimum 2 hours. Due to the operation of an offshore wind mill installation vessel, it is very difficult for an officer on-board to obtain a DP certificate under the schemes. This results in the risk of DP operators to be educated in other offshore sectors which again can result in different competencies than the ones required by a DP operator on-board an Offshore Wind Installation Vessel.

5.2.1.4 Crane Operators

Offshore crane training is defined by the construction and use of offshore cranes. These cranes were originally crawler cranes modified to a pedestal type crane with all the inherent dangers this implied.

Offshore cranes are now normally constructed to norms and standards, such as EN 13852-1, DNV-GL 2-22, API 2C or may be classed as such due to the construction of the vessel. As rigs and ships belong under the maritime regulations and flag state regulations there are no demands for certification of crane operators but there will always be a demand that the employer ensures competence. The certification types used today, G5, Stage 3 and API 2D are therefore all based on the use of cranes on-board drilling or production units as a method of ensuring this competence.

Wind industry cranes are also classed along with the vessel and may have many of the same construction features of an offshore crane but the use of these cranes is vastly different. This means that the contents and method of certification using the existing programs is almost impossible to achieve and the training outcomes have very little relevance to the wind industry.

What is happening at present is that offshore crane certification is being used as a guideline in the wind industry and persons certified using these guidelines will now be eligible to operate cranes in the offshore industry for which they have no training or practical capability.

The route that must be followed in order to obtain a DP Operator certificate (LIMITED and UNLIMITED):

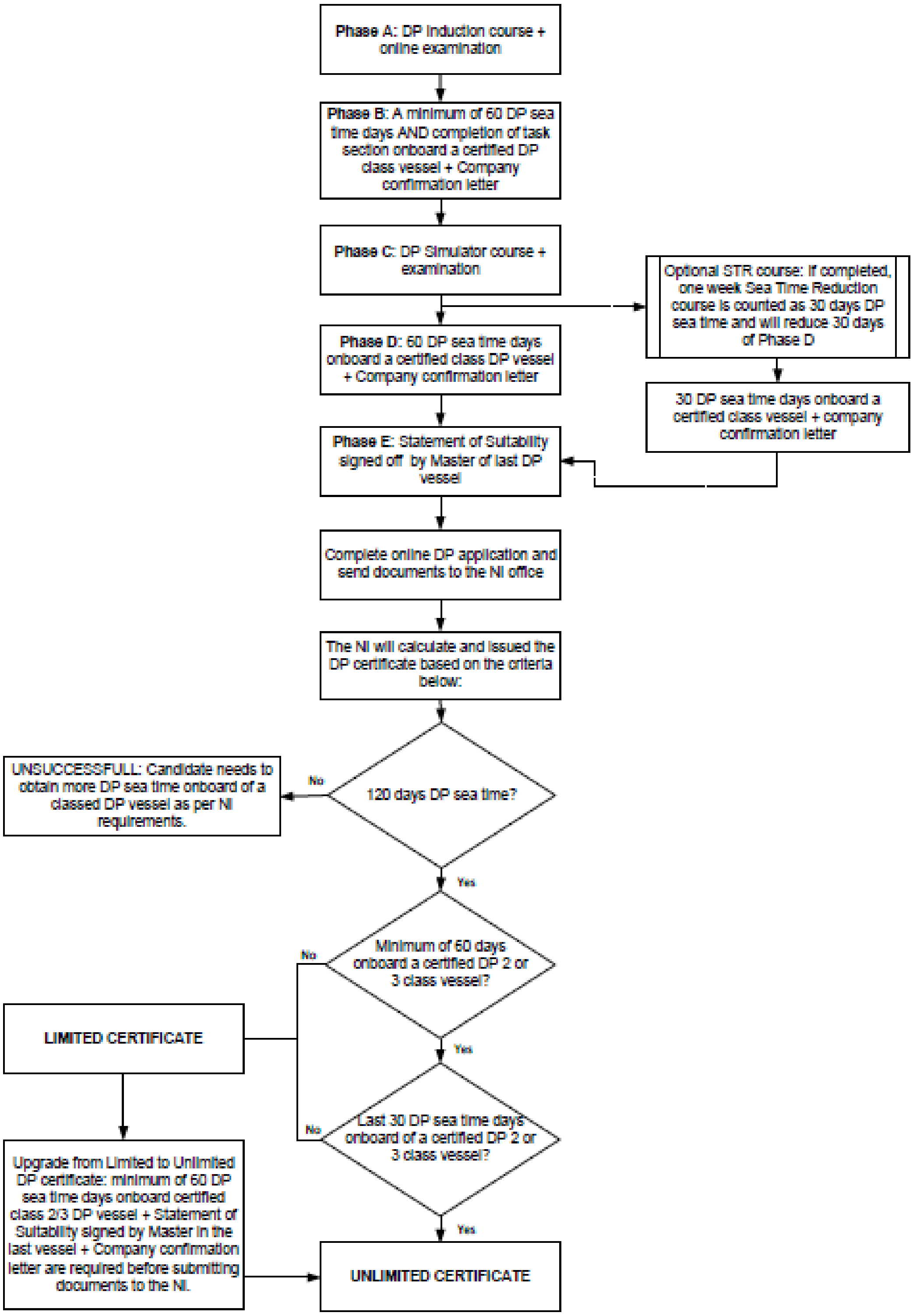


Figure 57: Overview of the Nautical Institute Dynamic Positioning Operator Training Scheme [77].

The following is a list of organizations currently involved in training and certification of offshore crane operation:

- OMHEC – Offshore Mechanical Handling Equipment Committee

- OPITO – Offshore Petroleum Industry Training Organisation
- LEEA – Lifting Equipment Engineers Association
- OGP – International Association of Oil & Gas Producers
- API – American Petroleum Institute
- LOLER – Lifting Operations and Lifting Equipment Regulations
- PUWER – Provision and Use of Work Equipment Regulations
- NORSOK – Norsk Sokkel

<u>Stage 1, 2 & 3 certification</u>:

Based on UK legislation LOLER, PUWER, with training according to petroleum industry guidelines. (OMHEC, OPITO, LEEA, OGP) and BS 7121.

- <u>Stage 1</u>: Introductory training 40 hrs.
- <u>Stage 2</u>: Theory & practice. Relevant practical training certified using Competency Assessment to allow the participant to operate the crane inboards without supervision.
- <u>Stage 3</u>: Assessment. Pre-requisite valid Stage 2 certification and 50 hrs practical crane operation of dynamic lifting. Allows the participant to operate the crane unsupervised.

Stages 2 & 3 require re-assessment every 2 years.

<u>G5 certification</u>:

This certification is based on Norwegian Continental Shelf guidelines – NORSOK, Labour Department syllabus and Petroleum Department regulations.

- <u>Module O-1.1</u>: Lifting equipment - Labour dept. syllabus F-2702 (Certified training)
- <u>Module O- 2.1</u>: Offshore crane theory – Labour dept. syllabus F-2689 (Documented training)
- <u>Module O-3.1</u>: VHF radio (SRC) certificate
- <u>Module O-4.1</u>: Documented 150 hrs mixture of practical offshore crane operations including dynamic lifting
- <u>Module O-4.1</u>: competency assessment including verbal questioning and performance of dynamic lifting.

Norsok R-003 requires G5 certification to be refreshed every 3 yrs.

<u>Nogepa 1.2A certification</u>:

- Onshore theoretical course;
- Documented offshore practical training 40 hours including dynamic lifting;
- Offshore practical skills assessment.

<u>Wind industry certification</u>

At present there is no wind industry specific certification in place.

All types of offshore certification and onshore mobile crane certification are accepted. As Wind Installation vessels are governed by maritime regulations there is no specification for certification other than the requirement that employees have received necessary training. The competencies, the crane operators are assessed against, do not necessarily cover the actual competencies required in the industry.

5.2.2 Industrial Personnel

There is a clear difference between vessel crew and other persons on-board. Persons on-board who are not directly involved in the operation of the vessel are generally defined as passengers. IMO has recently held their 97th session on Maritime Safety Committee (MSC) and has here agreed to continue the work regarding carrying Industrial Personnel. IMO will continue to address the competencies required for industrial personnel to be on-board.

Initially, the safety trainings from Oil & Gas were applied, like Opito BOSIET (Basic Offshore Safety Induction and Emergency Training) and HUET (Helicopter Underwater Escape Training). Some companies are still using these trainings for offshore personnel.

The Global Wind Organisation (GWO) has developed more job specific standards, describing the competencies required by industrial personnel, including Basic Safety Standards, which are relevant to the persons operating in the offshore wind industry. These standards are:

- Basic Maintenance Training Standard
- Basic Safety Training Standard
    - First Aid
    - Manual Handling
    - Fire Awareness
    - Working at heights
    - Sea Survival
- Basic Safety Training Refresher Standard

5.3 Proposed Training Requirements

The LEANWIND Project has not developed any concepts which requires new operational considerations. Therefore, it is considered, that the technical competencies already developed in the industry are sufficient to cover the requirements in the project.

As mentioned under section *5.2.1.3 Dynamic positioning* and section *5.2.1.4 Crane,* no training schemes for DP or crane operators, are pointed directly towards the operations being carried out by Offshore Wind installation vessels. IMCA and The Nautical Institute are presently addressing this, as they are working on a new standard for the DP training for Wind Installation vessels.

With reference to the definition in Section *5.1*, technical knowledge and skill are not sufficient for competency. Also, correct behaviour is required in order to be competent. Most courses in the industry are focusing on technical skills and there is limited reference to behaviour as part of being competent in the present training standards. Without a combination of knowledge/skill training and behaviour training, the development of competencies in the industry will be slowed down. During most technical courses, the behaviour is also mentioned, but as the focus is normally on the technical part, it is not certain, that the correct behaviour is part of the outcome on a course.

It is proposed that the industry put more focus on combinations of Resource Management courses and technical courses. Resource management courses can be delivered in a variety of taxonomy levels, spanning from 2 days' theory, to more than a week and be carried out with or without the use of simulators (Figure 58).

Figure 58: Existing simulator model installed at Maersk Training Svendborg (Image source: MTS).

The technical knowledge training and behaviour training can be carried out differently by training institutes, manufacturers or by crew on-board, but common for all training is, that it must be delivered in a structured way. The structure should be described by the operating company and should be included in the company competence management system.

When required competencies are thoroughly defined, it will be possible to adjust the training according to requirements and thereby give the operating companies more value for the invested money.

6 Conclusions

The work presented in this deliverable report is a comprehensive analysis of the existing situation regarding health and safety issues in the offshore wind industry, in terms of regulatory framework and relevant guidelines from industry players, availability of health and safety specific accident databases, and the risk levels of critical accident scenarios. In addition to mapping the existing situation, this report also deals with assessing selected innovation categories that have been examined in the framework of the LEANWIND Project in terms of their effect on health and safety issues. Furthermore, the report presents an overview of existing regulations and requirements regarding training competencies of personnel involved in the O&M of Offshore Wind Farms. The report identifies gaps that need to be filled in order to cover the actual competencies required in the wind industry and proposes training requirement guidelines that will help in improving the overall level of safety for workers in Offshore Wind Farms.

The analysis of the existing regulatory framework revealed a number of gaps and concluded that **explicit references to Offshore Wind Farms** should be incorporated in order to cover the particular health and safety challenges of the industry. **Existing health and safety requirements should also be updated** to take into account the novel challenges that arise from the installation of wind farms further out to sea, which means deeper waters and more exposed to adverse weather conditions. An important conclusion from the fragmented state of the existing regulatory framework is that **requirements should be unified across the European Union** to provide a comprehensive and consistent treatment of Offshore Wind Farm health and safety issues. Simplification and unification of the existing regulatory framework might also aid in making compliance easier.

The review of existing accident databases, which specifically record health and safety related incidents, revealed that **important efforts have been made to improve accident reporting during the recent past**, from key players in the industry. However, the **information that is made available to the public is of such a summary nature** that reduces their effectiveness in analyses and modelling efforts aiming to provide specific recommendations for improving health and safety. Therefore, **increased access to health and safety accident information** would help independent studies that aim to improve the health and safety landscape for Offshore Wind Farms. Furthermore, it is important to note that it was not deemed necessary to develop a **novel health and safety accident database structure** in the context of Task 6.3.

The health and safety risk assessment that was implemented in the context of this report comprised of the following steps: a) hazard identification (through extensive survey of the relevant literature), b) identification of critical accident scenarios, c) fault tree and event tree modelling, d) qualitative analysis, e) semi-quantitative assessment of selected innovation categories. The selection of the accident scenarios that were further examined was based on relevant published statistics. The identified critical accident scenarios Offshore Wind Farms are the following: 1) **Falling object during offshore lifting operation**, 2) **Collision of offshore windfarm CTV with Wind Turbine Generator tower during approach**, and 3) **Worker loses his balance while moving from a Crew Transfer Vessel to the Wind Turbine Generator tower**.

The qualitative analysis of the constructed fault tree shoed that, in terms of the level of the resulting health and safety consequences, accident scenario #1 (falling object) and #3 (worker access) appear to be almost **equally dangerous**, while accident scenario #2 (collision of vessel) appears to be slightly **less dangerous**. When examining how many events (out of the total basic events) must occur for each accident scenario to be realized, **the most vulnerable is scenario #1 (falling object)**, followed by scenario #3 (worker access), while the least vulnerable is scenario #2 (collision of vessel). The qualitative analysis of the constructed event trees showed that the following events after the occurrence of the examined accident scenarios are the most crucial for minimizing the health and safety consequences: **worker located in the impact area of a falling object**, **immediate worker salvage**, **SAR vessel operating nearby**, and **state of weather conditions**.

The following existing preventative RCOs have been identified as the most effective, in terms of minimal cut set reduction for each examined accident scenario: **work progress monitoring** (scenario #1), **entry permit for the 500m zone** (scenario #2), and **checking of state of equipment** (scenario #3).

The applied risk assessment methodology is a **high-level approach** that is utilized towards assessing the health and safety risk level for current practices and also for assessing the effect of innovations, which have been examined in the context of the LEANWIND Project, on current risk levels. The ultimate goal of this approach was to **detect the need for the potential implementation of novel RCOs** in order to maintain the current health and safety risk level. The innovation categories that were examined are the following: a) **access systems**, b) **lifting arrangements** and c) **innovative lifting concepts**. The main risk metric that was used in the applied innovation assessment methodology is the **likelihood of equivalent fatalities**, the calculation of which was based on a semi-quantitative approach that combined a defined likelihood (frequency) index with a defined consequence severity index through a risk matrix.

The order of magnitude for the calculated likelihood of equivalent fatalities for all innovation categories is **in the range of 10^{-2} and 10^{-4}**. Additionally, the calculated likelihood of equivalent fatalities for every accident scenario that was examined was in the same order of magnitude as annual frequencies calculated from data provided by the G+ Offshore Wind Health and Safety Association. This comparison strengthens the validity of the constructed risk models. The overall conclusion from the assessment is that **all innovations seem to improve the current risk levels**, in terms of a reduction in the likelihood of equivalent fatalities ranging from **50% to over 80%**. In addition, the overall **calculated risk level is low**. Therefore, **no additional RCOs** need to be examined and the recommended course of action would be to **monitor existing controls** regarding the effect of the various innovations to health and safety issues.

The examination of the current framework for training competencies required by the offshore wind industry has revealed that while competencies for marine crews are regulated by the requirements of the ISM Code and the STCW Convention, there is a lack of wind industry specific training schemes for **DP** and **Crane Operators**. This is matter that should be addressed in the future in order to cover the actual competencies required in the wind industry.

The road ahead for training requirements for the offshore wind industry is to put **additional focus on safe behaviour**, as it is an integral part of being competent, in addition to developing the necessary technical skills and knowledge. Therefore, it is recommended that **technical competence courses are complemented by appropriate Resource Management courses**, in a structured manner determined by the operating companies. These additional courses should be **included in the competence management system** of the operating companies.

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8 Appendices

8.1 List of Figures

8.2 List of Tables