Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m

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Definitions & Abbreviations

ALARP	As Low As Reasonably Practicable
CAPEX	Capital Expenditure
CFD	Computational Fluid Dynamics
CRI	Commercial Readiness Index
ERIC	Eliminate, Reduce, Inform, Control
FEM	Finite Element Method
FMEA	Failure Mode, Effect Analysis
FMECA	Failure Mode, Effect and Criticality Analysis
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
HSE	Health, Safety and Environment
KPI	Key Performance Indicator
LCoE	Levelised Cost of Energy
MMP	Manufacturing Maturation Plan
MRA	Manufacturing Readiness Assessment / Manufacturing Risk Assessment
MRL	Manufacturing Readiness Level
OPEX	Operational Expenditure
O&M	Operation and Maintenance
RD&D	Research, Development and Demonstration
SPR	Source-Pathway-Receptor
SPRC	Source-Pathway-Receptor-Consequence
TLP	Tension Leg Platform
TRA	Technology Readiness Assessment / Technology Risk Assessment
TRL	Technology Readiness Level
WP	Work Package

Executive Summary

This report provides an overview of risk management for deep water floating wind turbine substructures. It includes a description of a risk identification, analysis, evaluation and treatment process which can be applied to any floating wind substructure concept. The process utilises a number of standardised tools and references, including a risk register, risk impact and likelihood scales, and a risk matrix.

The methodology developed draws on good practice for risk assessment and risk management and is designed to be flexible enough to apply to different types of risk. This document deals with four categories of risk - technology risks, manufacturing risks, health, safety and environmental risks, and commercial risks. Each of these areas of risk is considered for all stages of the technology's lifecycle process - from design through to decommissioning. Although each of these types of risk have different dimensions or key indicators of risk to be measured, the principles of the risk assessment are the same for each. This is important as only the use of a consistent framework allows risks to be drawn together to form an understanding of overall risk.

- In the area of technology risk assessment (TRA), a functional composition analysis of floating wind technology has been used to develop a standard functional taxonomy. This taxonomy allows a structured review of specific concepts to identify the relative novelty of each functional element. Risk assessment is then focused on the novel elements of the technology.

- In health, safety and environmental (HSE) risk assessment, standard parts of the technology lifecycle have been set alongside standard types of HSE risk. These can be utilised to perform a structured assessment of HSE risks.

- In the area of manufacturing risk assessment (MRA), the concept of manufacturing readiness levels (MRLs) has been used to develop a structured framework for assessment of manufacturing risks (including socio-economic risks).

- To assess commercialisation risks, the concept of a commercial readiness index (CRI) has been employed to relate commercial and technology readiness levels (TRLs) and develop a structured approach to identifying and assessing commercialisation risks.

The process has been developed following a literature review of current relevant good practice documentation from across a range of industries. This includes international standards, national standards and guidance, certification standards and other industry guidance. It has been refined through engagement with a range of relevant stakeholders including independent engineers, certification bodies, public bodies, technology developers and testing centres.

It should be noted that this document outlines a process. It does not provide guidance on specific risks which may or may not be applicable to the technologies being developed in the LIFES50+ project. These risks will be assessed in future deliverables from the LIFES50+ project.

Contents

Table of Figures

List of Tables

1 Introduction to Risk Management

The activities of all types of organisations are exposed to potential hazards, due both to external influences and to the nature of their operations [1], [2]. This exposure, coupled with the potential consequences of the hazards, creates risk. This risk can be assessed via a series of activities designed to identify, analyse and evaluate the potential hazards. Risks can be managed by identifying actions to be taken to mitigate or treat the source or the consequence, or accepted once the risk is As Low As Reasonably Practicable (ALARP) or as an informed decision to pursue or retain risk as part of the risk treatment, as shown in Figure 1.

Risk treatment can introduce risks by ineffective or complete failure of implemented risk treatment measures, or secondary risks caused by treatment of the risk. As such, risk management needs to be a dynamic, iterative and responsive to change process [3], as shown by the loop back from risk treatment to the previous steps of risk management process.

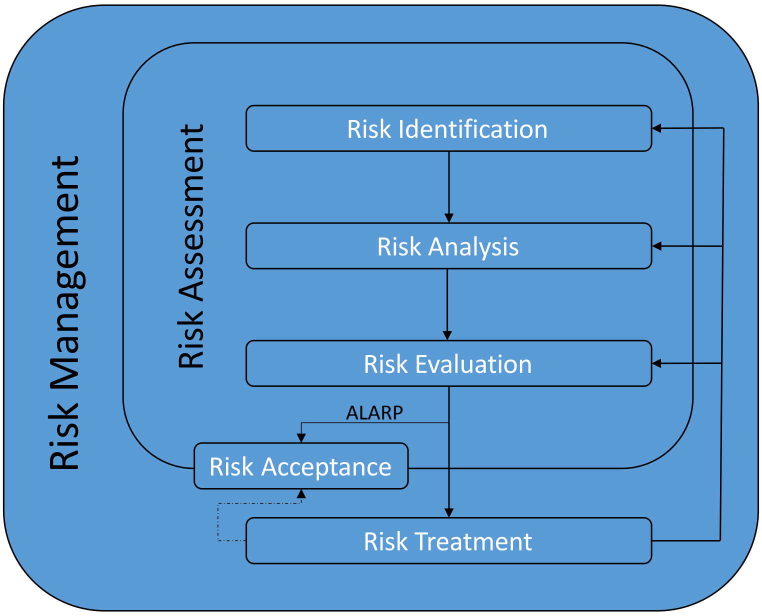

Figure 1: The Risk Management Process

Generic and specific procedures for risk assessment and risk management have been reviewed and adapted to the context of offshore deep water floating wind turbine substructures, to create guidance that can be applied to any floating wind turbine substructure concept.

The LIFES50+ Risk Management for Deep Water Substructures is based on a number of key standards and a recommended practice (ISO 31000 [3], ISO 31010 [1], ISO 12100 [4] standards and DNV GL Qualification of New Technology [5] recommended practice). It is suggested that anyone using the methodology described in this document should also refer to these.

1.1 Definitions

Risk is considered in terms of hazards, probability of occurrence and severity of consequence if the hazard occurs [1], [6], [7]. For purposes of this guidance on risk management, ISO standard terminology and definitions [8] have been adopted. This defines risk as the "*effect of uncertainty on objec-*

tives". Note that this is a general definition, meaning that although the nature of risks may vary depending on context, the principles of carrying out the assessment will be the same. Guidance for the assessment of risk relating to four different areas is considered in Sections 3 to 6 of this document:

- Technology
- Health, Safety and Environment
- Manufacturing
- Commercialisation

A consistent framework for risk assessment should be applied within each of these areas and in the context of the overall risk assessment to allow an overall understanding of risk to be formed.

Risk assessment, is defined as the "*overall process of risk identification, risk analysis and risk evaluation*" [8]. Such an assessment forms an integral part of the overall risk management procedures that any organisation should adopt and is a sequence of actions rather than a single event [3], [5], [6], [9]. This process is outlined in Figure 2.

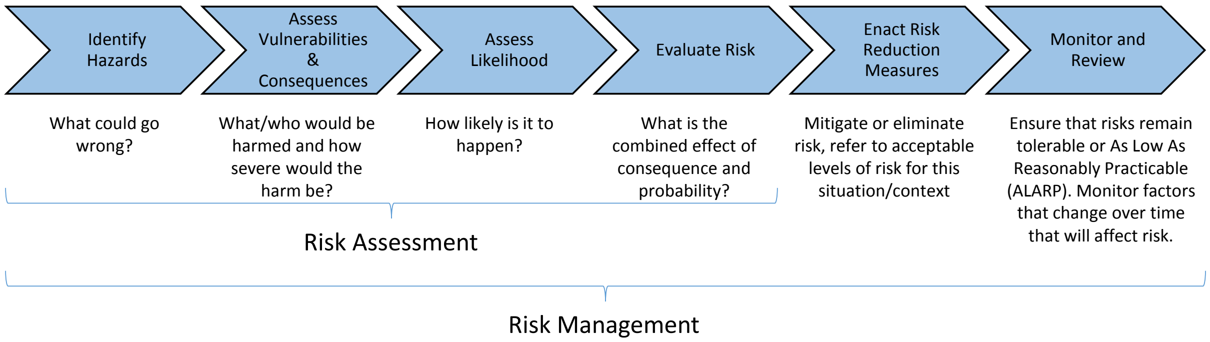

Figure 2: The Risk Assessment and Management Processes

The first four stages in Figure 2 constitute risk assessment. The final two stages are a part of the broader risk management process and focus on active management of risks.

A full list of terminology used within this guidance is given in Appendix A – Terminology.

1.2 Reasons to Assess Risk

Risk assessment is particularly important within safety-critical industries, where there are maximum risk tolerances associated with certain activities. Without an assessment of risk, it is not possible to make decisions about the treatment of risks to reduce these risks to tolerable levels. For example, the safety of offshore wind farm foundations and substructures falls within the remit of DNV GL's guidance for the design of offshore wind turbine structures [10] which assigns a safety class and target safety level to the design. These target levels set an industry benchmark for tolerable levels of risk.

Generally speaking risk assessment has multiple uses or outputs, including:

- Ensuring that technologies, processes or procedures are developed in line with acceptable levels of risk;
- Ensuring that risks are ALARP given the operational context;

- Ensuring that adequate health & safety guidance is formulated and given to those affected by risks;
- Ensuring that third parties are not unduly put at risk.

Whilst risks are most often associated with hazards to persons (health and safety), many other types of risk exist and are considered within this report. These include environment, reputation, cost, quality, technology, schedule, etc.

1.3 Approaches to Risk Assessment

The recommended approach to take to assess risk depends on the context and the ability to quantify the complexity of risk and its frequency and severity. The context of the risk assessment process is important and is considered in detail in Section 2 of this document.

The UK's Health and Safety Executive outlines three categories of approach [11] to risk assessment which are outlined in Figure 3[1]. The most appropriate of these categories to apply to a risk assessment will depend on the complexity of the problem, the magnitude of the risk (relative to the limit of tolerability) and the risk appetite of the organisation. Additionally, the stage at which the risk assessment is carried out can also influence the type of approach used (i.e. decommissioning risk assessment performed during the planning or design stage will most certainly use a less rigorous approach). The more rigorous the approach, the more detailed the resulting risk assessment. The key question in determining which approach to take should be '*Is the output of this assessment adequate for decision making*'. If not, then either the next level of rigour should be used or the model should be made more detailed at the existing level of rigour [11]. Regardless of where on the scale the risk assessment sits, the process of conducting the assessment will be as per Figure 2; it is the detail of the information gathered (i.e. information on decommissioning at the design stages could be limited) and the complexity of the methods used to estimate the probability of hazard occurring which will change.

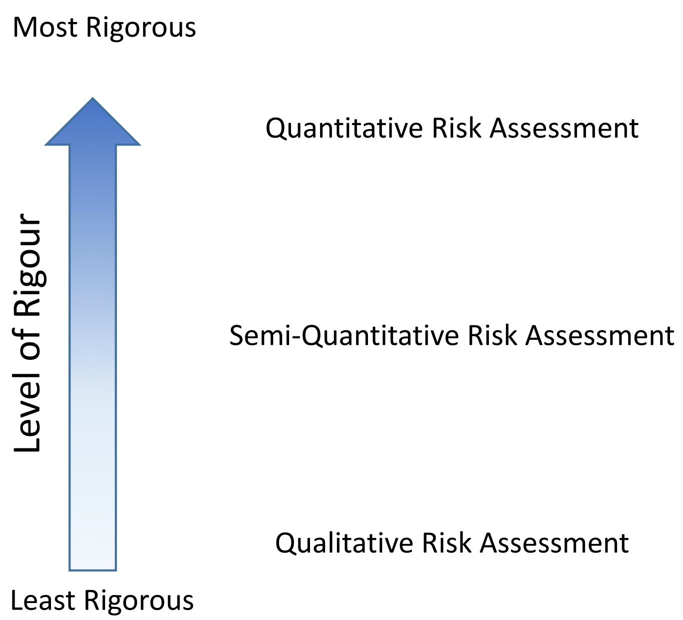

Figure 3: Levels of Rigour in Risk Assessment

[1] Whilst the approach is taken from the UK's Health and Safety Executive, it is appropriate to all types of risk.

1.3.1 Risk Identification

Sources of risk or hazards are elements which alone or in combination have the intrinsic potential to give rise to risk [1]. A systematic approach to identifying these is required to ensure all relevant sources of risk and hazards are identified.

1.3.1.1 Hazard Identification (HAZID)

Hazard Identification (HAZID) is the systematic identification of reasonably foreseeable hazards, hazardous situations and hazardous events [4]. A hazard is a *'source of potential harm'* [8] (harm being defined as a negative impact on a desired objective rather than just physical harm to a person). Methods for identifying hazards can be split into two broad categories, as per [1], [12]:

- Data Driven Methodologies – where recorded observations are available and can be used to identify hazards. This could include the outcome of investigations into past events where the risk has materialised, in addition to the results from investigation of 'near-miss' safety events;
- Qualitative Methodologies – where hazards are identified based on discussions, interviews and brainstorming. These processes should involve communication and consultation with internal stakeholders in the risk management process and also external consultation with subject matter experts if necessary. The HAZOP (Hazard and Operability Study) method falls into this category.

Hazard identification should not be data-driven only [7], as this would assume that all potential hazards have been realised and will have been recorded, which is highly relevant for floating offshore wind as the industry is immature and hence it is unlikely that there would be enough data to capture all relevant hazards . Instead, a team-based, qualitative methodology should ensure comprehensive coverage of all hazards (coupled with a data driven approach if sufficient data are available). Commonly the hazard identification part of the risk assessment process will be carried out as a workshop [5] and documented on a risk register alongside an assessment of consequence and probability of occurrence. Hazards should be identified in such a way that they encompass both the cause of the risk and the consequence of the risk should it arise [13].

1.3.2 Risk Analysis

Risk analysis is a process to comprehend the nature of risk (i.e. what is the risk, what are its causes and sources) and to determine the level of risk (expressed in terms of the consequence and likelihood of the risk, which are described next).

1.3.2.1 Assessment of Consequence/Severity

The risk associated with hazards identified should be assessed by combining an estimate of the likelihood of the hazardous event occurring with an estimate of the consequence/severity of the event should it occur.

Typically, both likelihood and consequence are placed on a 5-point scale[2] [5], [9], [11]. An example scale for consequence to persons, ranging from lowest to highest severity or impact, is given in Table 1. The specific type of harm associated with the points on this scale will be contextual, depending on the type of risk assessment being carried out – it could be, for example, harm to persons, harm to the

[2] In the context of LIFES50+, a 5-point scale was chosen to be the most optimal. However, 3, 4-point or even more than 5-point scales are not uncommon.

environment, harm to the business objectives or harm to the business financial prospects[3]. Given this, the specific definition of each category on the consequence scale will change with the context of the risk assessment however the scale - and interpretation of that scale - will be similar, i.e. the worst severity category should be assigned the highest 'value' of consequence on the 5-point scale. Table 1 outlines a scale of the severity of harm with reference to physical harm to humans.

Table 1: Consequence/Severity Scale [9]

Severity of Harm

Scale	Category	Example Description
5	Extensive	Multiple deaths
4	Major	Single death
3	Severe	Serious injury
2	Moderate	Moderate injury
1	Minor	Minor injury

1.3.2.2 Assessment of Likelihood/Probability

Similarly, likelihood (or probability) of occurrence should be placed on a 5-point scale[2] [5], [9], [11] ranging from lowest to highest probability. Table 2 provides a qualitative and quantitate example of likelihood.

Likelihood can be estimated in a number of ways, again ranging from qualitative methods such as expert judgement to quantitative methods such as mathematical modelling or based on historical data. The most appropriate approach to take will depend on how developed or well documented the data on historical incidents are, and on the nature of the risk being addressed. Technology risks such as component failures, for example, may lend themselves well to a quantitative approach whereas commercial risks, such as failure to attain environmental consents, are likely to lend themselves to a more qualitative approach, especially if estimating the probability of consent for a new type of technology.

Table 2: Probability of Occurrence Scale [9]

Probability of Occurrence of Harm

Scale	Category	Description	Example Probability (per year)
5	Very Likely	Almost certain to occur, happens frequently either in this context or in a similar context	$p > 10^{-1}$
4	Likely	Likely to occur, happens less than once per year either in this context or in a similar context	$10^{-2} < p < 10^{-1}$
3	Probable	Probable to occur, i.e. heard of in this context or in a similar context, less than once per year but still a credible scenario	$10^{-3} < p < 10^{-2}$
2	Possible	Possible but not probable to occur given what has been observed to happen in this context or in a similar context historically. Would require a number of simultaneous failures of risk controls.	$10^{-4} < p < 10^{-3}$
1	Unlikely	Unlikely to occur. Although in theory a possibility, this event has never been observed in this or in a similar context	$p < 10^{-4}$

[3] PriceWaterhouseCoopers (PwC) identify at least 14 different types of organisational risk assessment that can be undertaken [2].

If the assessment of probability is qualitative then the placement of hazards on this scale will be an estimate based on judgement. For hazards with high consequence the assessment should be as quantitative as possible to make the placement of hazards on the probability scale as objective as possible.

Note that in some industries and in particular safety-critical industries there are maximum levels of risk tolerance set against which designs (including new design concepts) should be evaluated (i.e. HSE guidance suggest probability of 10^{-3} of deaths per year within the offshore industry [11]). Therefore the probability of occurrence scale should be developed bearing such tolerability criteria in mind. The overall assessment of risk should be structured to ensure that if the probability of occurrence exceeds a set tolerance then action is taken to mitigate risk to an acceptable level. This is discussed in more detail in the risk evaluation section below.

1.3.3 Risk Evaluation

Probability of occurrence and consequence of the hazard, i.e. the *risk* of the hazardous event can then be combined into a matrix form like the one shown in Figure 4 [2], [5], [9]. This illustrates the ordering of events by risk score from lowest to highest, prioritising those which fall into the top right-hand corner (those which are high probability, high consequence events).

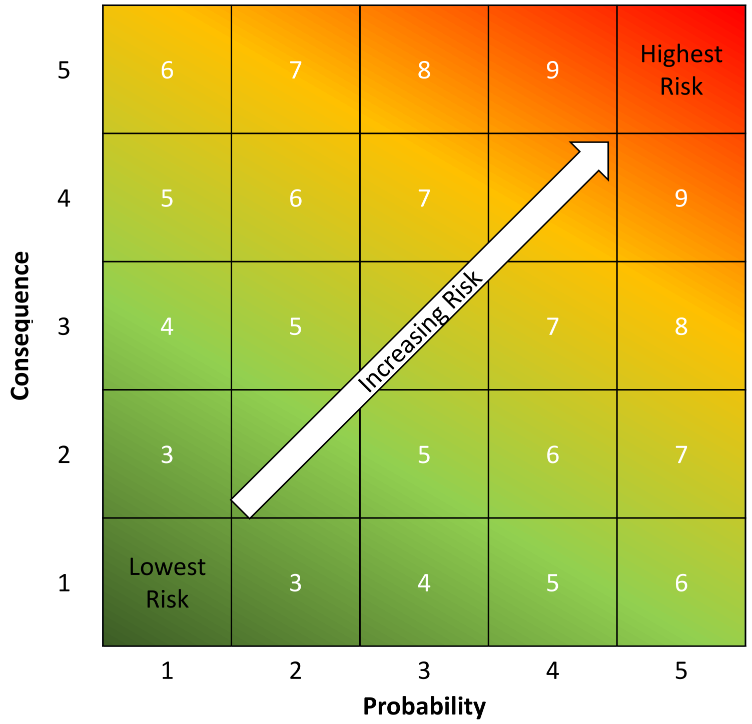

Figure 4: Risk Matrix

The risk matrix approach also enables a final risk score to be assigned to each of the hazards by combining the probability score and the consequence score through summation (an alternative and equally valid approach to multiplication). This combination allows the amount of risk to be categorised into a small number of risk levels as typically detailed information on risk probability and consequence is often not available or is hard to estimate accurately and precisely.

Placement of hazards on the risk scale means that the most critical hazards can be ranked according to risk and addressed accordingly. The scale of the action taken should be aligned with where in the risk matrix the hazard appears – if risk is already low, for example, then additional costly measures are unlikely to be necessary. If risk is anything other than ALARP then action should be taken to reduce risk until the cost of further reduction is disproportionate to the benefit gained [1]. The levels of over-all risk are outlined in Figure 5 alongside possible courses of action. As an aid to decision making the risk scale should be divided into three categories based on the sum of the probability and consequence scales. An example is shown in Table 3 [1], [9].

Table 3: Risk Scale and Actions

	Scale	Category	Description
Risk	8-10	High	Intolerable risk. Risk reduction is required. Eliminate hazard or introduce protective measures whatever the cost. Do not proceed until risk has been addressed.
	5-7	Medium	Risk reduction may be required. Cost/Benefit analysis recommended. Eliminate hazard or introduce protective measures. Only proceed with measures in place to mitigate risk.
	2-4	Low	Level of risk is regarded as acceptable. Check that risk is ALARP and advise as to whether risk can be reduced further with reasonably simple measures.

At the heart of risk evaluation is the comparison of risk levels against some form of benchmark level of acceptable risk (risk criteria) as the one shown in Table 3. This comparison means decisions can then be made as to whether actions need to be taken to reduce risk, depending on where in the risk matrix each risk appears.

This scale, and the boundaries set between risks being considered low, medium and high, will depend on the context of the risk assessment. Risk scales for technology risk, health, safety and environment risk, manufacturing risk and commercialisation risk are discussed in more detail in Sections 3 to 6.

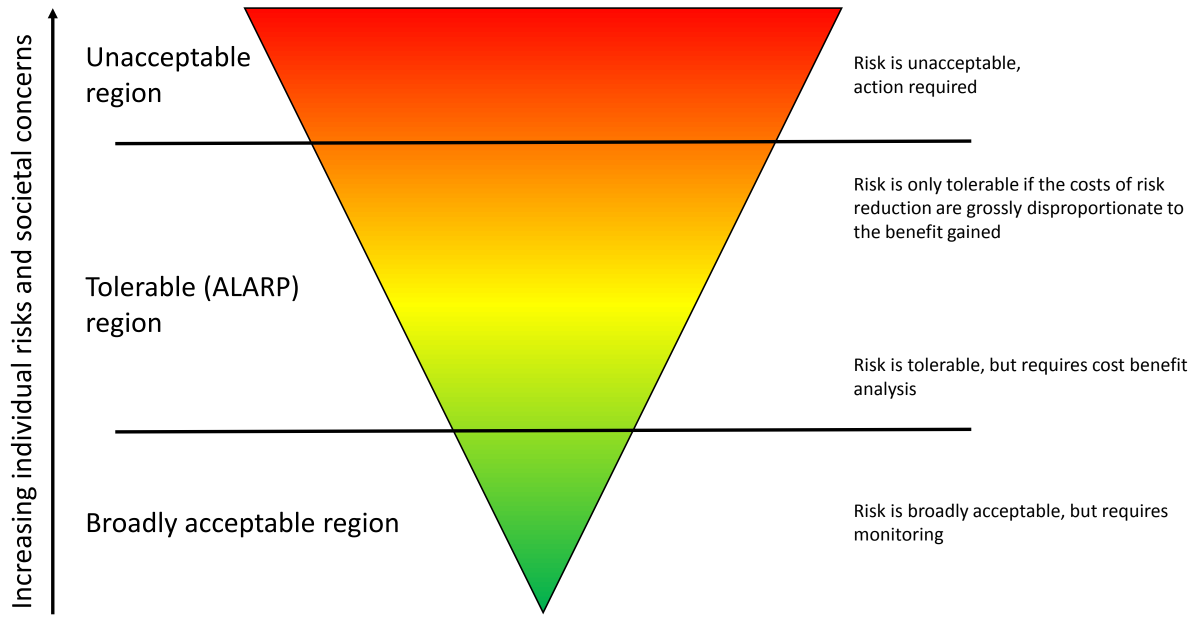

Figure 5: The ALARP Process Diagram [1]

1.3.4 Risk Treatment

Risk reduction can be achieved either by reducing the probability of occurrence or by mitigating the consequences of the hazard if it were to occur, or by both. In other words, measures should be introduced or actions taken which will move the hazard down either the severity of harm scale or the probability of occurrence scale relative to its initial position.

One approach to reduce or mitigate risk, from eliminating hazards during the design process to mitigating hazards during the operational phase of the substructure, is illustrated by the ERIC (Eliminate, Reduce, Inform, Control) hazard reduction hierarchy model [9] (Figure 6). Typically the eliminate, reduce and inform measures are those which would be implemented by the designers of the technology, with control measures implemented by users. Hazards should be eliminated if possible, otherwise reduced by inherently safe design and by protective equipment and information.

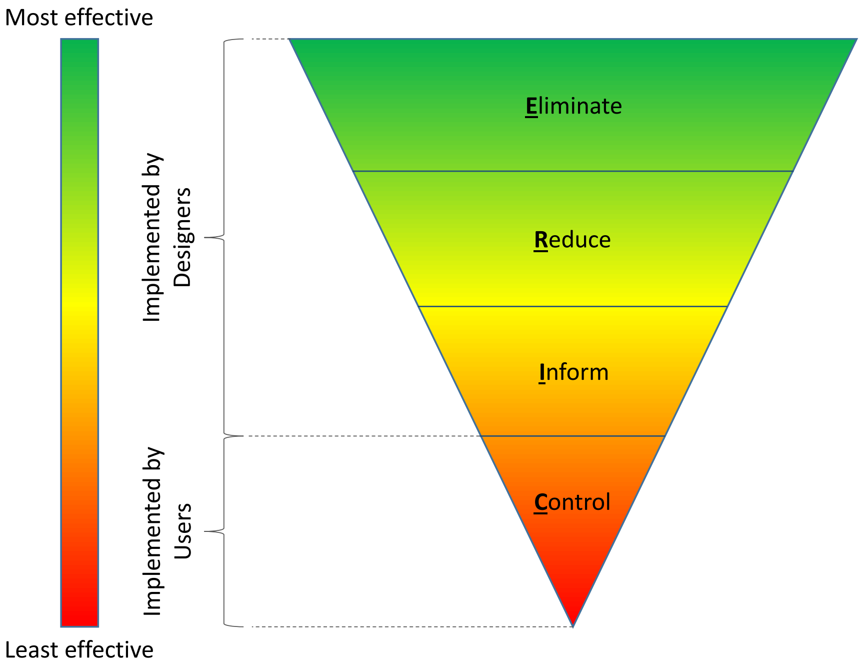

Figure 6: ERIC Model for Hazard Reduction [9]

It should be noted that this document focusses primarily on risk assessment. Risk reduction and ongoing monitoring are key elements of risk management; however, in the context of the LIFES50+ project, the risk treatment activities will be the responsibility of the technology concept developers. As such, this report has intentionally not provided any specific guidance in these areas as technology developers are better placed to determine how best these goals are achieved. This is discussed in more detail in Section 2.

1.3.5 Risk Monitoring and Review

Finally, it is important to understand that risk management is a live and continuous process. Risk assessments should be revisited periodically to ensure factors that vary over time are not having an undue effect on the risk of the system being evaluated. This is particularly relevant during times of sudden or significant change, such as during the technology development process.

Factors particularly likely to change over time should be identified as part of the risk assessment, and data gathered to demonstrate that ongoing monitoring is in place [1].

1.4 Uncertainty

Uncertainty is inherent part of risk (see definition of risk in Appendix A – Terminology). It can be associated with the data, methods[4] and models used to identify, analyse and estimate risks [14]. Therefore, an uncertainty analysis should be performed as part of the risk assessment process to understand better these uncertainties and their causes, and to make sure that risk scores (of probability and consequence) are estimated to the best of one's ability.

For a new technology in development, uncertainties tend to be very large. However, as the design progresses with time, and as knowledge, experience and evidence is generated, the level of uncertainty tends to generally decrease, see Figure 7 [5]. Uncertainty can increase when modifications to design are made, as shown by 'design change' in Figure 7. However, these design changes are quite often essential to obtaining final lower overall level of uncertainty of the technology, which would have not been possible if the original/unmodified design was used (shown by the grey dashed line in Figure 7).

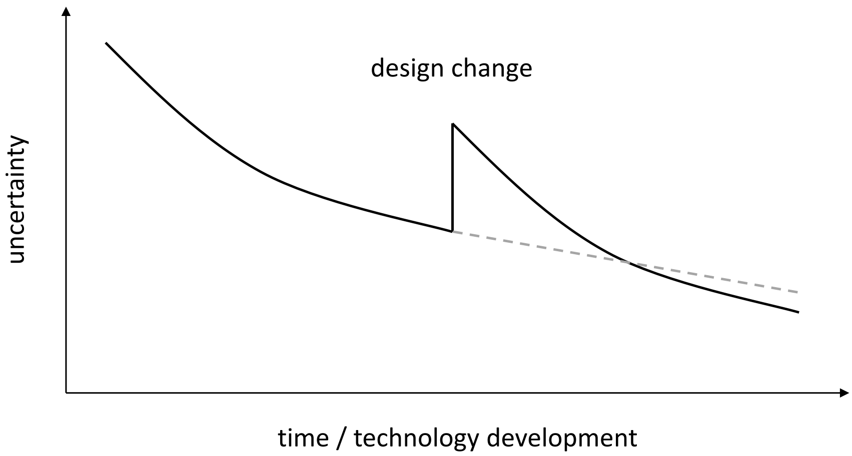

Figure 7: Illustration on uncertainty relation to time or technology development [5]

Uncertainties can be split into the categories of 'internal' and 'external'. Internal, or technology-related uncertainties, as the name suggests, include uncertainties directly influenced by the design, e.g. materials costs, labour costs, installation costs (only those which are a function of design), O&M requirements, installation procedure, etc. External, or technology-unrelated uncertainties, include exchange rates, environmental conditions, raw material price, and labour rates.

When expert judgment is used (e.g. in case of HAZID or dealing with novel technologies, such as floating wind turbine substructures), uncertainties should be reflected by conservative risk categorisations (consequence and probability). As expert judgment is highly subjective, a formal review of the results should be performed by a third party if possible.

Note that it is impossible to completely eliminate uncertainty, and as such it needs to be acknowledged that any decision made on the basis of a risk assessment will have some uncertainty associated with it.

[4] A review of risk assessment methods with varying degree of uncertainty is given by [1].

2 Risk Assessment for LIFES50+

A key consideration when developing any risk management process is the context within which that process will be used [1]. The context can be considered to comprise two separate areas – the internal context and the external context. The internal context refers to the internal environment in which the organisation is trying to achieve its objectives. This includes the organisation's culture, processes, structure and strategy [1]. The external context is the external environment in which the organisation is trying to achieve its objectives. Factors to consider include social and cultural, political, legal, regulatory, financial, technological, economic, natural and competitive environment, whether international, national, regional or local [1].

The risk assessment and management methodologies within this document have been developed for use within the LIFES50+ project. As such they consider the external context to be that of floating wind energy's place in a wider movement to develop low carbon energy generation capacity around the world. The internal context is the objectives of the LIFES50+ project itself and the objectives of each of the four technology developers participating in the project. These are discussed in more detail below.

2.1 External Context

The development of floating wind turbine technologies is part of a wider movement to develop cost effective low carbon electricity generating capacity around the world. A wide range of technologies are currently available and the cost effectiveness of each of these is generally a function of the maturity of the technology and the location of its deployment. Floating wind is early in its technological development but considered to have the potential to be cost effective in parts of the world with certain natural (climatological and geographical) characteristics. These are given below.

- Climatological – in the offshore environment wind resource is generally significant and the extremes of temperature limited;
- Geographical – the offshore environment is generally characterised by deep (>50m) sea located close to land (and centres of electricity usage).

These areas exist in various places across the globe, each with a range of different social and cultural, political, legal and regulatory environments. Each of which is generally outside the control of the floating wind technology developer but will be of considerable interest to potential floating wind farm project developers. However, the technology developers do have a greater level of influence over and interest in the financial, technological, economic and competitive environments they operate in. As such it is relevant that these areas have been selected as specific focus areas in the LIFES50+ project (in addition to the ubiquitous requirement for health, safety and environment risk management).

2.2 Internal Context

The objective of the LIFES50+ project is to develop and optimise floating substructure concepts for large (10 MW) turbines, advancing technology readiness and developing a streamlined, KPI-based methodology for the design and qualification of these technologies [15]. These KPIs are focussed on the technical, economic and industrial context of the designs. The relative risks for each substructure concept need to be identified and evaluated as part of this qualification process. The assessment of risk will form part of the evidence upon which a decision as to which of the substructure designs are considered to be the most promising technology concepts. The assessment required to achieve this must consider multiple types of risk.

The four designs of floating wind substructure, assessed as part of the LIFES50+ project, are:

- IDEOL – ring-shaped surface floater made from concrete;
- TLPWIND – TLP made from steel;
- NAUTILUS – semi-sub made from steel;
- OO-STAR – semi-sub made from concrete.

All four designs shall be up-scaled to accommodate the DTU 10MW reference turbine [16]. Additional information on the DTU 10MW wind turbine adapted for the floating wind substructure designs is provided in deliverable 1.2 “Wind turbine models for the design” [17] (public) and deliverable 1.4 “Wind turbine controller adapter to each concept” [18] (not publicly available).

To account for the potential floating wind markets and the fact that all four designs have different target deployment areas, three locations of varying water depths and met-ocean conditions were chosen and defined [19]. These include:

- Golfe de Fos, France (70 m water depth and mild environmental conditions);
- Gulf of Maine, the United States of America (130 m water depth and moderate environmental conditions);
- West of the Isle of Barra, Scotland (100 m water depth and harsh environmental conditions).

Furthermore, three different floating wind farm sizes of 10 MW (1 unit), 50 MW (5 units) and 500 MW (50 units) were chosen to represent the different stages of floating wind substructure design commercialisation – demonstrator, pre-commercial and commercial project [20].

The general definitions and concepts of risk measurement and risk assessment discussed in Section 1 have been adapted for four specific elements of floating substructure design, namely:

- Technology risk;
- Health, Safety and Environment (HSE) risk;
- Manufacturing risk;
- Commercialisation risk.

Note that an important consideration in the risk assessment for each of these types of risk in the context of developing new technologies is that it should highlight changes in risk due to the novel elements of the design or new risks which arise due to this. It is these risks rather than those which are common to all substructure design concepts which will be most useful when making relative comparisons between concepts.

Technology risk relates to the process of identifying the new or novel elements being used in each of the design concepts, and the risk assessment associated with these. The recommended approach to this assessment takes into account tolerable levels of risk and safety classes already assigned to support structures and foundations for offshore wind turbines [10], and recommended procedures for qualifying new technologies [5], [6].

Health, safety and environmental risk relates to harm to persons or environment due to the activities associated with the floating substructures at all stages of the process from manufacturing through to installation, operation and decommissioning. The recommended approach to assessment of HSE risk for this context takes into account the general guidelines reviewed in Section 1 and also guidelines, standards and legal requirements specific to health and safety in the offshore wind sector [21]. Environmental risk assessment (also known as ecological risk assessment) methodology has been developed from that of human health and safety. However, whilst the general principles of it are widely agreed upon, the application of the process still provokes considerable argument. The environmental risk assessment and management as part of the LIFES50+ project will be based on guidelines for environmental risk assessment and management [22].

Manufacturing risk relates to availability of materials, industrial base, supply chain, potential for mass-production when moving from concept to commercially available technology, quality management and availability of manufacturing facilities. Manufacturing risk should be assessed in conjunction with Manufacturing Readiness Level (MRL) [23] which depends on the development phase of the technology. As technologies develop in terms of technical (and also commercial) readiness, so too will the manufacturing risks evolve.

Commercialisation risk relates to those aspects of risk that are related to bringing a new product to market, including non-technological considerations such as regulatory environment/consents, financial performance and costs, and market opportunities. The recommended approach to assessment of commercialisation risk makes use of the concept of Commercial Readiness [24] in conjunction with the Technology Readiness Level (TRL) [25] of the design concepts.

The proposed methodology for risk assessment for deep water substructures has intentionally been split into four separate, yet interlinked, risk assessments (technology, HSE, manufacture and commercialisation). Each of the four risk assessments concentrates on hazards that, for the most part, are only relevant to the specific risk assessment being performed (i.e. technology risk assessment only looks at technology hazards and ignores HSE, cost (covered in commercialisation), etc., as these are covered in their respective risk assessments). However, inevitably, there will be hazards that could potential be attributed to more than one of the four risk areas considered. In such cases, expert judgment should be exercised to work out which of the four risk areas does the specific hazard fall under.[5]

In the context of the LIFES50+ project, the participating floating wind substructure concepts are all in their design phase. However, as part of the project each floating wind substructure concept designer is tasked with a hypothetical development of three different size wind farms, including a 500 MW. This represents a scenario where manufacturing has entered full scale production, which does not reflect the current state of floating wind technology (none of the participating designers have built a full-scale prototype). Hence it is important to acknowledge that risk assessment, particularly for manufacture, would differ between prototype development and full scale production.

2.3 LIFES50+ Deliverable Requirements

The LIFES50+ project has defined a number of specific requirements and deliverables from the risk management process. These are outlined below.

- Each of the four types of risk assessments need to be placed into the general framework of risk assessment developed in Section 1. This overall assessment of risk will form part of the evi-

[5] In the context of the LIFES50+ project, industry and research organisation technical advisors (see the next section for description) will make sure that a consistent approach is used when prescribing hazards to different risk areas.

dence upon which a decision as to which of the substructure designs are considered to be the most promising technology concepts [14]. This framework is described in this document. This includes describing methods for hazard identification, risk estimation, risk evaluation and risk treatment [14]. For risk estimation various categories of probability and severity are defined.

- Hazards specific to each area of risk need to be identified in LIFES50+ using the process outlined in this document. Whilst this document doesn't identify risks directly, it does make recommendations as to the type of information that should be reviewed and recorded by technology developers to enable these assessments to be made (making this framework generic and applicable to different floating wind turbine substructures).

To meet the requirements of the LIFES50+ project this document is accompanied by a number of templates which have been developed. These include:

- Functional taxonomy for floating wind substructures;
- A common risk register (format) for each of the four risk areas – technology, manufacture, HSE and commercialisation;
- HSE HAZID form.

2.4 Risk Management Responsibilities and Confidentiality

In the context of LIFES50+ it is important to clarify the roles of various partners in the risk management process, shown in Table 4.

Table 4: Risk Management Responsibilities

Stage / Partner	Risk Identification	Risk Analysis	Risk Evaluation	Risk Treatment	Risk Monitoring and Review
Technology Developers	Shall perform and record the risk identification process	Shall perform and record the risk analysis process	Shall perform and record the risk evaluation process	Shall perform risk treatment activities	Shall monitor and review risks
Industry Technical Advisors	Shall review and approve the risk registers	Shall review and approve the risk matrices and feed results into KPI based concept evaluation	None	None	Shall review and approve the modified risk matrices and feed results into KPI based concept evaluation at set project stages
Research Organisation Technical Advisors	Shall review and approve the risk registers	Shall review and approve the risk matrices and feed results into KPI based concept evaluation	Shall review and approve decisions about risk treatment necessity	None	Shall review and approve the modified risk matrices and feed results into KPI based concept evaluation at set project stages

Technology Developers: Ideol, Tecnalia, Iberdrola Engineering and Construction and Dr.techn.Olav Olsen.

Industry Technical Advisors: DNV GL and Ramboll.

Research Organisation Technical Advisors: ORE Catapult

The technology developers are best placed to assess, analyse, evaluate and treat risk. In addition, a key learning outcome from the project is the ability for the technology developers to manage risk effectively throughout the technology development process (i.e. well after the LIFES50+ project finishes). As such it is important they lead these activities.

However, it is important that risk is assessed objectively and that the outcome of the risk assessment processes from each technology developer can be compared directly (i.e. consistent use of the basis for assessment (risk areas, consequence and probability scales) across all LIFES50+ technology developers). As such the industry and research technical advisors will play an important and independent role in reviewing and approving the outcomes of the risk assessment process[6].

It is important that sensitive information relating to each technology concept is protected, even where this relates to risks. As such, each of the technology developers will only be exposed to the outcomes of their own floating wind substructure concept risk assessment in detail. However, aggregate outcomes from each technology concept developer will be shared as part of the concept evaluation process.

2.5 Uncertainty

In the context of LIFES50+, the four participating floating wind turbine substructure designs are highly innovative. Furthermore, there is very little or no field data available on floating wind turbine substructures, meaning that majority of risk assessment will rely heavily on expert judgment.

In the LIFES50+ project, when expert judgement is used, such as in HAZID, uncertainty shall be reflected by conservative risk values (consequence and probability). In areas where statistical evidence from testing or field experience can be used it shall be done so in accordance with ISO's "Guide to the Expression of Uncertainty in Measurements" [26]. When performing fatigue analysis uncertainty shall be accounted by using appropriate safety margins and factors which are defined in deliverable 7.2 "Design Basis" [27]. For discussion of uncertainty in the context of the levelised cost of energy for floating wind, please see Section 6.1.

[6] Outside the context of LIFES50+, any approval of the outcomes of a risk assessment process can only be performed by the organisation ultimately accountable for the results in the end.

3 Technology Risk Assessment

The objective of the technology risk assessment process is to identify risks associated with floating wind substructure technology which may lead to partial or complete loss of function. However, particular focus is given to new and novel technology being used in each floating substructure concept and risk assessment for these. The novelty of the technology may be either in its form or application (i.e. mature technology applied in a novel way is considered novel).

The definition of 'Technology' from DNV GL [5] and [6] shall be adopted where a technology is *"The scientific study and use of applied sciences, and the application of this to practical tasks in the industry."*

In accordance to ISO standards [1] and [3] and DNV GL definitions [5] and [6], the definition of technology risk within the context of the LIFES50+ Project can be considered as *"The effect of uncertainty on the application of scientific study and use of applied science to achieve its desired practical objective"*.

Technology risks may also include risks associated with the areas of health, safety and environment, manufacturing and commercialisation in relation to the specific technology being assessed. These risks should be captured in accordance to the respective sections in this report.

TRLs are commonly used within industry as a measure of maturity for technology development. The TRLs, as described by the Crown Estate [28], are shown in Table 5.

Table 5: TRL Definitions

TRL		Technology status	Description
1	Proof of concept in the lab	Basic principles observed and reported	Scientific research begins to be translated into applied research and development.
2		Technology concept and/or application formulated	Practical applications of basic key principles can be 'invented' or identified. The application is still speculative: there is no experimental proof or detailed analysis to support the proposal.
3		Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated: analytical studies to set the technology into an appropriate context, and laboratory-based work to physically validate that the analytical predictions are correct. These should constitute "proof-of-concept" validation.
4	Concept development and scale testing	Technology / part of technology validation in a laboratory environment	Following successful "proof-of-concept" work, basic technological elements are integrated to establish that the "pieces" will work together to achieve concept-enabling levels of performance. The validation is relatively small scale compared to the eventual technology: it could be composed of ad-hoc discrete components in a laboratory.
5		Technology / part of technology validation in working environment	At this level, the reliability / scale of the component being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications can be tested in a 'simulated' or somewhat realistic environ-

			ment (which is almost always the working environment for energy technologies).
6		Technology model or prototype demonstration in a working environment	A major step in the reliability / scale of the technology demonstration follows the completion of TRL 5. At TRL 6, a prototype going well beyond ad-hoc or discrete components is tested in a working environment.
7	Prototype demonstration	Full-scale technology demonstration in working environment	TRL 7 is a significant step beyond TRL6, requiring an actual system prototype demonstration in the working environment. The prototype should be near or at the scale of the planned operational system and the demonstration must take place in the working environment.
8		Technology completed and ready for deployment through test and demonstration	In almost all cases, this level is the end of true 'system development' for most technology elements. This might include integration of new technology into an existing system. Represents the stage at which an example of the technology is tried and tested.
9	Commercial demonstration and system development	Technology deployed	In almost all cases, the end of last 'bug fixing' aspects of true 'system development' and represents the point at which the technology is proven, but not necessarily yet commercially viable in either a free or supported market. This might include integration of new technology into an existing system. This TRL does not include planned production improvement of ongoing or reusable systems.

TRL is the metric that is used within technology readiness assessment (TRA) to assess critical technology elements (technology representing a major risk). Whilst TRLs provide a common understanding of technology readiness and can assist in risk management, their primarily purpose is not to perform risk assessment but to broadly define what needs to be done to reach the next level of TRL.

DNV GL recommend that TRL methodology, if applied, be complemented by other ways of assessing qualification status [5]. The TRL methodology will not be used directly for the assessment of technology risk within the LIFES50+ project as the DNV GL guidance [5] provides a more robust and clear framework for the assessment of technology which requires less subjectivity in comparison.

DNV GL's Recommended Practice [5] provides guidance to the industry for the qualification of new technology. Qualification by definition is the process of providing evidence that a technology will function within the specified limits with an acceptable level of confidence. DNV GL's Recommended Practice [5] provides a suitable framework for the assessment of technology risks and is recommended for use within the LIFES50+ project. Figure 8 shows a summary of the technology qualification process and its compatibility with ISO Standard [3].

Figure 8 is very similar to Figure 1 by displaying an iterative process of risk management but calling it technology qualification [5]. Different parts of DNV's technology qualification process directly emulate the standard risk management process. Risk identification is substituted with qualification basis and technology assessment, risk analysis with threat assessment, risk evaluation with qualification plan, its execution and performance assessment, risk treatment with modification, and risk acceptance with technology qualification. However, whilst the process strongly resembles that of risk management, it is specifically tailored towards new technology development or qualification, which bonds nicely with the overall aim of LIFES50+. The following sections give a much more thorough overview of each step of technology qualification process as shown in Figure 8.

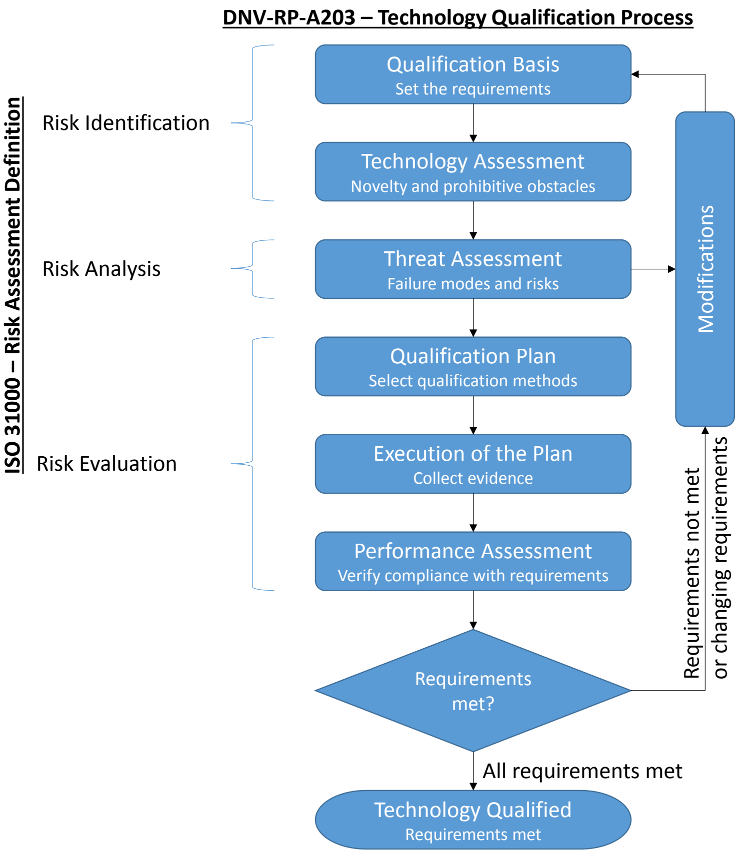

Figure 8: DNV GL Recommended Practice [5] Figure 5-1 mapped to ISO Standard [3] Definition 2.14

3.1 Technology Risk Identification

The aim of risk identification is to identify sources of risks, areas of impacts, events and their causes and their potential consequences [8]. The output of the technology risk identification phase is a comprehensive list of technology risks developed based on the events that they might influence. The overall process of technology risk identification, as supported in [5], is illustrated in Figure 9.

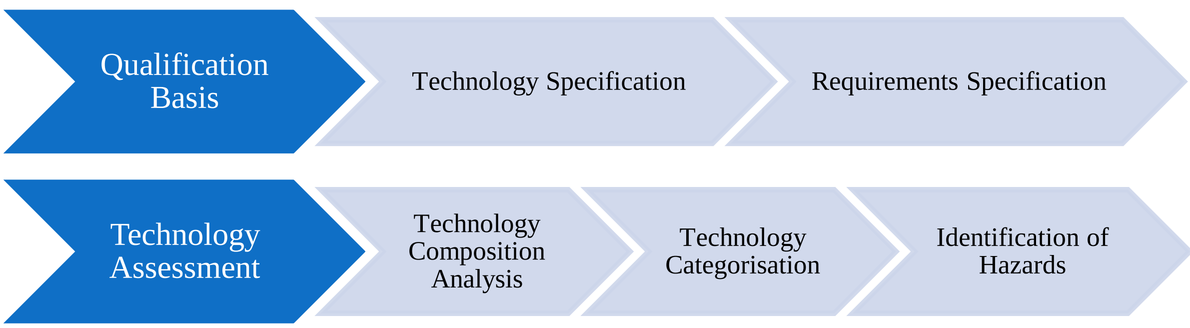

Figure 9: Technology Risk Identification Process

3.1.1 Qualification Basis

The qualification basis should provide a common set of criteria against which the technologies should be assessed; it shall specify the technology, define its use, the environment to be used in, it's required functions, acceptance criteria and performance expectation. DNV GL's Recommended Practice [5] provides a list of items to be addressed in the technical specification. These include, but are not limited by general system description; system functions and functional limitations; main principles for storage, transportation, installation, commissioning, operation and abandonment; maintenance and operation strategy; boundary conditions including interfacing system requirements; environment and environmental loads and functional loads; relevant areas of expertise considered necessary to understand technology; and already existing evidence claimed to support qualification.

Within the scope of LIFES50+ the technology requirement specifications should be common across all concepts.

The four designs of floating wind substructure assessed as part of the LIFES50+ project, which are all TRL $\geq$ 4, are described in Section 2. Additional information on the environment to be used in and wind turbine can be found in deliverable 1.1 "Oceanographic and meteorological conditions for the design" [19], deliverable 1.2 "Wind turbine models for the design" [17] and deliverable 7.2 "Design Basis" [27] (all publicly available). Deliverable 1.1 "Oceanographic and meteorological conditions for the design" provides an overall overview of the three wind farm locations and extreme met-ocean conditions, deliverable 1.2 "Wind turbine models for the design" provides description of the DTU 10 MW wind turbine model and deliverable 7.2 "Design Basis" provides a definition of the full set of environmental conditions and design load cases that shall be considered within the LIFES50+ project. In additional to providing information on the environment and wind turbine, the three aforementioned documents form the technology and requirements specifications within the context of the LIFES50+ project.

3.1.2 Technology Assessment

The technology assessment shall determine which elements of technology within the overall floating substructure concept involve new or novel technology, and identify their respective hazards.

The qualification basis (Section 3.1.1) shall form the main input into the technology assessment. The main output of the technology assessment will be a list of the novel technology elements, and hazards associated with them.

The technology assessment will consist of three parts (as shown in Figure 9):

- Technology composition analysis;
- Technology categorisation;
- Identification of hazards.

3.1.2.1 Technology Composition Analysis

A technology can be the integration of multiple element technologies within a system (e.g. the overall substructure) or a single element of technology (e.g. a bolt). In order to understand the novel elements within the concept, and subsequent individual and cumulative risk associated with them, the system must be decomposed into elements. A top-down technology composition analysis should be carried out for each floating substructure concept, starting at a system-level (the overall floating wind sub-structure concept) and as far as practicable, breaking this down into element form, including interfaces.

Within the scope of LIFES50+ substructure concepts, function based sub-division of the system is recommended as it enables failure modes at a functional level to be identified at an early stage, as highlighted in DNV GL's Recommended Practice [5].

A system (a floating wind substructure concept) can be subdivided into functions (e.g. stability, structural integrity, etc.), sub-systems (e.g. mooring system) and down to elements (e.g. anchors). A standard list of functional systems and sub-systems for a generic floating wind substructure has been developed and is provided in Figure 10.

Figure 10 is given as a basis upon which each floating wind substructure concept should be further decomposed, top-down, from the sub-system level provided to as far as practicable in order to achieve a full technology decomposition which would then represent the entire system. This task should be performed by floating wind turbine concept designers as they have the best understanding of the design.

The provided example of a functional system breakdown in Figure 10 has intentionally been left very high-level to foster some input from floating wind turbine substructure concept designers. In the context of the LIFES50+ project, it is expected that the majority of functions, systems, sub-systems and elements will be applicable to the majority of participating concepts[7]. Some examples of further decomposition include adding heave plates and damping pools as passive stability elements; active ballasting as active stability sub-system; J-tubes in power transmission, etc.

Table 8 contains functional description of each element in Figure 10.

An analysis of each of the identified functional elements across the entire life cycle of a floating wind substructure concept shall be performed. This will generate a complete breakdown of each system, sub-system and element within the concept and help identify hazards that might otherwise would have been missed.

Life cycle phases, as given by DNV GL's Recommended Practice include [5]:

- Design;
- Fabrications and testing;
- Transportation and storage;
- Installation;
- Commissioning;
- O&M;
- Decommissioning, including retrieval and abandonment.

These are grouped and explained in Table 9.

Similarly to functional analysis, life cycle phases can be further broken down into sub-phases. For example, design split into concept design, basic design and detailed design. Additionally, as per DNV

[7] For TLPs the majority of stability is provided by their mooring system and hence should be included as a system under stability.

GL's Offshore Service Specification [29], site conditions (what are they, how are they determined) should also be considered as part of the design, as these (wind, wave, soil, etc.) can have a profound effect on the overall design of the substructure.

3.1.2.2 Technology Categorisation

Advances in technology are generally evolutionary from proven technology. Only particular elements of the technology are typically novel. Uncertainty and risk are generally associated with novel elements. The uncertainty surrounding a technology is driven by not only its novelty but also the application of the technology.

In order to prioritise and focus on the areas of uncertainty and therefore, higher risk, the identified technologies from the technology composition analysis can be categorised with respect to the degree of novelty and the area of application.

For each element identified in the technology decomposition, a technology categorisation can be defined by using the matrix shown in Table 6. The corresponding indicators for each of the categories are shown in

Table 7. All elements categorised as 'New Technology' (Category 2, 3 or 4) shall be taken forward in the technology risk assessment process for further analysis. Category 1 technologies can be considered as 'Proven Technology' and requires no further technology risk assessment. However, Category 1 technologies should still be continuously monitored and reviewed to ensure that factors that vary with time or any implemented risk treatments do not raise the degree of novelty. Only documented and accessible evidence should be used through the technology novelty assessment process.

Table 6: Technology Categorisation to DNV-RP-A203 [5]

Application Area	**Degree of Novelty of Technology**		
	Proven	Limited Field History	New or Unproven
Known	1	2	3
Limited Knowledge	2	3	4
New	3	4	4

Table 7: Technology Categories to DNV-RP-A203 [5]

Technology Category	**Indicator**
1	No new technical uncertainties (proven technology)
2	New technical uncertainties
3	New technical challenges
4	Demanding new technical challenges

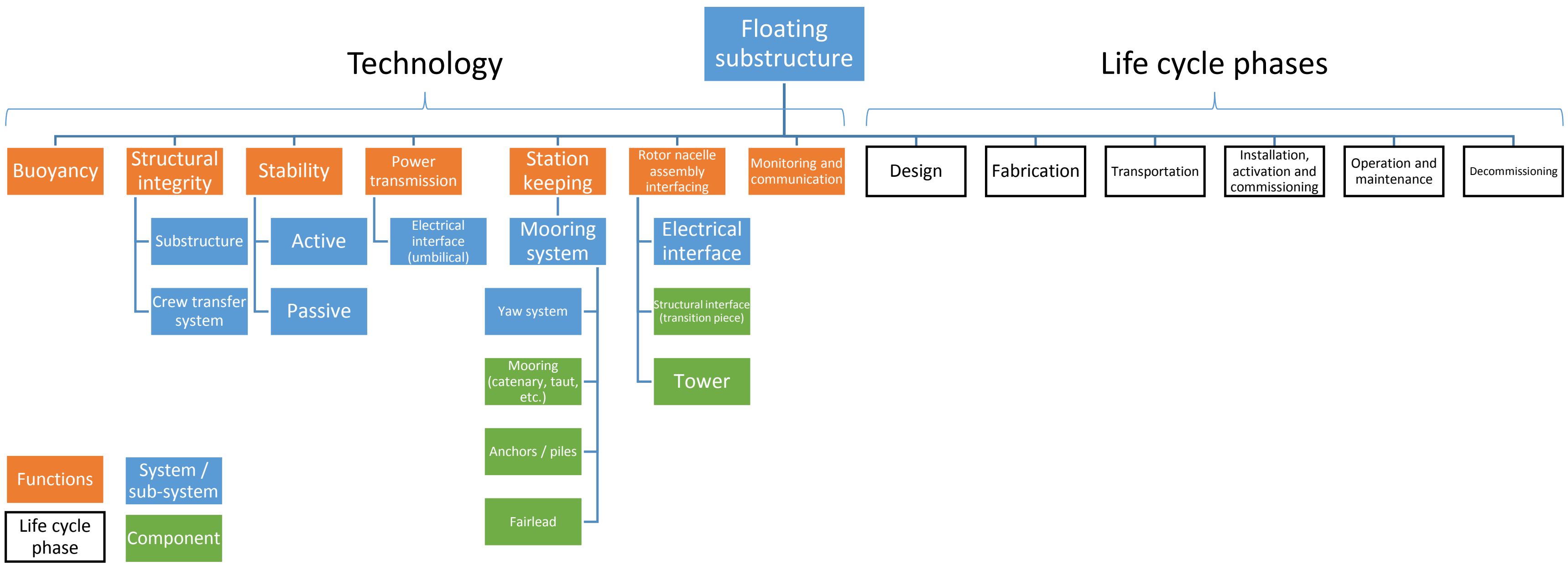

Figure 10: Example Function Hierarchy of Floating Substructure for Technology Decomposition

Table 8: Example Functional Hierarchy of Floating Substructure for Technology Decomposition with Explanation

		Function	System/ sub-system / element	System / sub-system / element	Functional detail
Floating substructure	**Technology**	Buoyancy	–	–	Buoyancy – the ability to provide sufficient buoyancy force
		Structural integrity	Substructure	–	Structural integrity – the ability to support design loads Substructure – the ability to maintain structural integrity of platform
			Crew transfer system		Crew transfer system – the ability to routinely and safely transfer crew and equipment from vessels to the substructure and wind turbine serviceable areas
		Stability	Active	–	Stability – the ability for the operational substructure to remain within defined acceleration and displacement limits Active – the ability to actively and controllably provide stability to the system
			Passive		Passive – the ability of the system to return to its equilibrium after some disturbance

		Function	System/ sub-system / element	System / sub-system / element	Functional detail
		Power trans-mission	Electrical interface (umbilical)	–	Power transmission – the ability to transmit power from the floating wind turbine Electrical interface – the ability to electrically and mechanically connect from the inter-array network to the wind turbine and substructure electrical systems
		Station keeping	Mooring system	Mooring (catenary, taut, etc.)	Mooring system – the ability to interface with the seabed to maintain a defined station Mooring – the ability to maintain a maximum distance displacement between platform and anchor
				Anchors / piles	Anchors / piles – the ability to rigidly fix to the seabed
				Fairlead	Fairlead – the ability to connect mooring and floating substructure
				Yaw system	Yaw system – the ability of substructure to actively or passively align itself with the wind
		Rotor nacelle assembly inter-facing	Electrical interface	–	Electrical interface – the ability to connect wind turbine and substructure electrical systems
			Structural interface (transition piece)	–	Structural interface – the ability to connect the tower and substructure
			Tower	–	Tower – the ability to support the wind turbine nacelle, hub and blades above the substructure
		Monitoring and communication	–	–	Monitoring and communication – the ability to measure and transmit parameters of condition

Table 9: Example Life Cycle Phases with Explanation

		Phase	Functional detail
Floating substructure	**Life cycle phases**	Design	The design of a substructure
		Fabrication	The manufacture, assembly, finishing and factory testing of a substructure
		Transportation	The transportation and storage of a substructure (with or without a wind turbine) to operational location
		Installation, activation and commis-sioning	The installation, activation and commissioning of a floating wind turbine at its operational location
		Operations and maintenance	The enduring operation and maintenance activities of a floating wind turbine (including the wind turbine, substructure, mooring, etc.)
		Decommissioning	The decommissioning of a floating wind turbine at the end of operational life (including retrieval, abandonment, reuse, refitting and recycling of the wind turbine, substructure, mooring, etc.)

An example of the technology categorisation is provided in Table 10, where two elements identified following the technology composition analysis are a mooring chain and a 'novel' anchor. For this example the mooring chain is a standard element, but will be used in a similar, however not identical application. It is therefore 'Proven' in terms of technology novelty and 'Limited Knowledge' in terms of application area. It is assumed the novel anchor proposed is 'Unproven' and the application area is 'New'. In the instance of this example both the mooring chain and 'novel' anchor will require further technology risk assessment as the technology category is greater than 1.

Table 10: Example Technology Categorisation

Function	Sub-function	Element	Technology Category	Evidence
Station keeping	Mooring	Mooring chain	2	'Supplier name' BS ISO 1704:2008
		'Novel' anchor	4	N/A

3.1.2.3 Identification of Hazards

The identification of hazards at an early phase in the design will aid the understanding of each of the technology elements within the concept and identify parts of the system which need further development and/or documentation prior to starting the technology risk analysis.

A high level HAZID assessment should be performed as part of the technology assessment phase to identify the key hazards associated with each of the technology elements. An example of the outcome of a HAZID process applied to the station keeping function of a floating foundation with a gravity anchor is presented in Table 11.

The following sources of information can be used to identify hazards and drive technology assessment for different floating wind substructure concepts as part of the LFIES50+ project:

- Historical data on the use of technology and its elements;
- Technical drawings and schematics;
- Standards and guidelines;
- Substructures' life cycle phases and the functional breakdown.

Table 11: Example of Functional Sub-sectioning Down to Hazard

Function	Sub-function	Element	Hazard
Station keeping	Mooring	Mooring chain	No tension
		Gravity anchor	Moving when loaded

For more comprehensive information on HAZID techniques for offshore installations and safety cases see [30], [31]. Alternative techniques that could be employed in the initial risk identification process include, but are not limited to: Brainstorming, Structured and semi-structured interviews, Delphi and Primary hazard analysis [1].

3.2 Technology Risk Analysis

The aim of risk analysis is to identify relevant failure modes of the identified elements of technology and assess their associated risk. The output of the technology risk analysis phase is a list of failure modes with consequence and probability ratings for the novel technology elements identified in the risk identification process. The overall process of technology risk analysis is illustrated in Figure 11 [5].

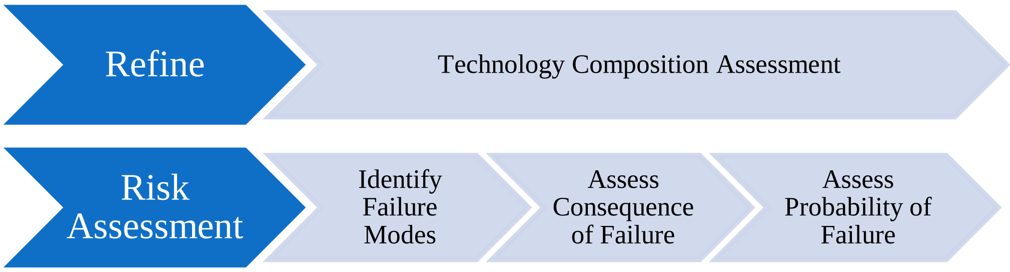

Figure 11: Technology Risk Assessment Process

3.2.1 Refine Technology Composition Analysis

A review of the technology composition for the floating substructure concept shall be performed, if necessary as per Section 3.1.2.1, to help to identify and better understand the novel elements of technology. Figure 10 shall be further decomposed into elements and interfaces until the necessary level of detail, deemed sufficient to perform failure mode identification, has been achieved. It is particularly important to identify all interfaces to facilitate communications between parties responsible for the different parts of the system or stages of development.

Refined technology composition analysis supports identification and isolation of novel elements and hence aids in early identification of potential failure modes.

3.2.2 Identify Failure Modes

A systematic approach for the identification of possible failure modes and related failure mechanisms should be performed as part of the LIFES50+ project. Each floating wind substructure concept designer should carry out failure mode identification for each of the elements with technology category 2, 3 or 4, as categorised during Section 3.1.2.2 (Table 6 and

Table 7).

The identified hazards from Section 3.1.2.3 may be used to aid or as a starting point for the identification of failure modes, however shall not replace the need for failure mode identification by appropriate expert/s.

Failure mode identification is at the heart of technology risk analysis. Without it, consequence and probability of failure cannot be assigned and technology risk evaluation cannot be performed. Identifying potential failure modes of the LIFES50+ floating wind turbine substructure concepts should ideally be expanded to include failure mechanism ("the physical, chemical, temporal or other process that leads or has led to a failure" [5]) and root cause identification (identification of the factors that have led to the occurrence of the harmful outcomes), as these might foster further failure mode identification. However, due to constraints in time and available resources, these (failure mechanism and root cause identification) shall not form the core requirement of the LIFES50+ floating wind turbine substructure risk assessment and should rather be seen as additional information that can be provided if the participating floating wind turbine substructure designers think it might help in performing risk assessment. As the technologies mature we would expect the failure mode identification to be expanded as such.

To date, multiple risk assessment techniques have been developed. Some are more applicable to specific industries whilst others are very generic[8]. As part of this project a Failure Mode, Effect and Criticality Analysis (FMECA) worksheet has been developed. FMECA is an extension of Failure Mode and Effect Analysis (FMEA) which, on top of identifying failure modes, mechanisms and their effects on the system, also includes criticality analysis which defines the significance of each failure mode. This can be achieved qualitatively, semi-qualitatively or quantitatively.

Compared to some other risk assessment techniques (e.g. Fault Tree Analysis or Root Cause Analysis) FMECA allows all parts of risk assessment, as defined by ISO 31000 [3] and shown in Figure 8, to be considered. Additionally, it is systematic and simple to use. However, the main disadvantage of FMECA is its limitation to investigate only one failure mode at a time (as oppose to combination of failure modes).

For the ease of using this report a brief introduction and overview is given to FMECA. For more detailed description and explanation IEA standard should be consulted [32].

FMECA can be used to identify potential failure modes, the effect these have on the system, including their importance or criticality, the mechanisms of failure and how to avoid the failures. The technique can be applied during the design, manufacture or operation stage. The FMECA process, as given by ISO 31010 [1] and split into two sections, contains the following steps:

- Define the scope and objectives of the study;
- Assemble the team;
- Understand the system to be subjected to the FMECA process;
- Breakdown of the system into its elements (piece part level or functional);
- Define the function of each element;

These are the steps that are performed before technology risk analysis in Section 3.1.

The following steps form the core of technology risk analysis, evaluation and treatment and are directly related to the hazards identified in HAZID by analysing what effect these would have on the overall system and how they can be treated, if they were to materialise. In the context of the LIFES50+ project, floating wind substructure concept developers are best place to answer these questions.

- For each element identified consider;
    - How can each part possibly fail?
    - What mechanisms might lead to these failures?
    - What effects these failures might have?
    - Are these failures harmless or damaging?
    - How critical are these failures?

[8] A detailed list of different risk assessment tools and techniques is given by the ISO standard on risk management [1].

  - How can these failures be detected?
- Identify provisions to compensate for the failure[9].

The classification of failure criticality is achieved using the level of risk method, which is obtained by addition of the probability and consequence of a failure mode occurring, as described in more detail in Sections 3.2.3 to 3.2.5.

There is no standard FMEA or FMECA worksheet as different industries and organisations have their own preferred style that suits their needs. An example of FMECA worksheet developed during the LIFES50+ project is shown in Table 38 (Appendix B – FMECA).

In the context of technology risk for LIFES50+, the consequence of failure can be categorised in to three scales. These are the consequence of failure for the local system, the global system, and economic consequences. Within the LIFES50+ project, the local system shall be considered as the element of technology being assessed (e.g. the anchor chain), the global system shall be considered as the floating wind turbine substructure, and economic consequence as the monetary impact of any (local and/or global) failure. The local, the global and economic impact assessments only need to be assessed for the consequence (severity) of a hazard materialising and risk rating (Sections 3.2.3 and 3.2.5), and not probability (likelihood)[10], which is the same for all three consequence scales.

Whilst in this report classification of each failure mode criticality is achieved by means of using the risk matrix, alternative methods, as suggested by [1], include mode criticality index and risk priority number, which are more applicable for quantitative data and quality assurance applications, respectively.

The information provided in Table 38 is by no means exhaustive. Additional information that could be added to match particular needs could include, but is not limited to, recommended corrective action, action by (responsibility), action date, revised control system, revision and comment.

In the context of technology risk assessment as part of the LIFES50+ project, it is suggested that the participating floating wind turbine substructure developers use the simplified technology risk register (shown in Table 15) instead of the full FMECA worksheet developed (Table 38), due to lack of experience, data and available resources.

3.2.3 Consequence of Failure

Expert judgement and knowledge is essential when assessing the consequence of failure. It shall be ensured that relevant expert personnel will be carrying out the assessment of the consequence of failure. The consequence scale of failure for local system and global system to be used for technology risk assessment has been defined in Table 12.

[9] Changes are more easily implemented during the design stage (Design-FMECA), as opposed to the manufacture (Process-FMECA) or the operation (Service-FMECA) stage [1].
[10] For examples, see Table 15 and Table 38.

Table 12: Example Technology Consequence of Failure, as recommended by DNV-RP-A203 [5]

Scale	Consequence		
	Category	**Local System**	**Global System**
5	Extensive	Loss of main function and damage to interfacing and surrounding system	Severe damage to interfacing and surrounding system
4	Major	Loss of main function	Noticeable damage to interfacing and surrounding system
3	Severe	Loss of parts of main function	Shutdown of interfacing and surrounding system
2	Moderate	Reduced part of main function	Insignificant effect on interfacing and surrounding system
1	Minor	Insignificant	No effect on interfacing and surrounding system

Additionally, technology risks shall be assessed in terms of economic consequences using Table 13. These range from minor lost energy generation production (e.g. modification of wind turbine controller due to sea growth accumulation on the floating wind turbine substructure) to severe damage to reputation or brand, the latter being particularly damaging to floating wind turbine substructure designers as it could diminish or completely eliminate investment in the technology by reducing investor confidence in new and unproven technologies.

Table 13: Example Economic Consequence of Failure

Scale	Economic Consequence	
	Category	**Description**
5	Extensive	Severe damage to reputation or brand
4	Major	Dockside repair
3	Severe	High-priority onsite repair
2	Moderate	Low-priority onsite repair
1	Minor	Minor lost energy generation production

3.2.4 Probability (Likelihood) of Failure

The probability of failure shall be estimated for each failure mode identified. Where quantitative measures are unavailable qualitative measure may be used until quantitative measures become available (the probability of failure shall be revised).

Expert judgement and knowledge is essential when assessing the probability of failure. It shall be ensured that expert personnel with relevant training and work experience will be carrying out the assessment of the probability of failure. The probability (likelihood) of failure for the Technology Risk Assessment shall be assessed in accordance to Section 1.3.2.2 and Table 14.

The Design of Offshore Wind Turbine Structures standard [10] suggests design of support structures to the normal safety class; some risk to personal injuries, pollution or minor societal losses, or possibility of significant economic consequences. Additionally, support structures are assigned a target safety level of 10^{-4} of annual probability of failure. However, HSE guidance, which is based on typical offshore values (most likely oil and gas), suggest probability of 10^{-3} of deaths per year [11].

This report suggest using value of 10^{-4} (taken from [10]) to reflect on the limited previous experience and existing evidence/data available on floating offshore wind turbines.

Table 14: Example Technology Probability of Failure

Scale	Probability (Likelihood)		
	Category	**Qualitative Measure**	**Quantitative Measure (per year)**
5	Very Likely	Almost certain to occur, happens frequently either in this context or a similar context.	$p > 10^{-1}$
4	Likely	Likely to occur, happens less than once per year either in this context or in a similar context	$10^{-2} < p < 10^{-1}$
3	Probable	Probable to occur, i.e. heard of in this context or in a similar context, less than once per year but still a credible scenario	$10^{-3} < p < 10^{-2}$
2	Possible	Possible but not probable to occur given what has been observed to happen in this context or in a similar context historically. Would require a number of simultaneous failures of risk controls.	$10^{-4} < p < 10^{-3}$
1	Unlikely	Unlikely to occur. Although in theory a possibility, this event has never been observed in this or in a similar context	$p < 10^{-4}$

3.2.5 Technology Risk

Following the identification of failure modes, consequence of failure and the probability of failure the technology risk rating can be assessed. This shall be performed according to Section 1.3.3 of this report.

Figure 12 shows the technology risk matrix which shall be used to assess the overall risk of the failure mode based on the probability and consequence of failure. A local risk (risk localised to the element of technology), a global risk (risk to the overall substructure concept) and an economic risk can be evaluated using those consequences of failure identified previously (Table 12 and Table 13).

The technology risk matrix (Figure 12) shall assign medium (“M”) or high (“H”) risk to any high consequence and/or high probability risks, hence assuring that high consequence and low probability, and low consequence and high probability risks are addressed and not dismissed based on their low probability of consequence or occurrence. This was deemed necessary as there is very little historical data and experience in design of floating wind turbine substructures.

Table 15 shows an example of the overall risk analysis process where the relevant data has been supplied from the previously performed analysis, and the Risk levels are identified using the Technology Risk Matrix.

Consequence	5	M	M	H	H	H
	4	M	M	M	H	H

	3	L	M	M	M	H
	2	L	L	M	M	M
	1	L	L	L	M	M
L=Low, M=Medium, H=High		1	2	3	4	5
		Probability				

Figure 12: Technology Risk Matrix

Table 15: Example Technology Risk Register with Risk Ranking

Function	Sub-system	Element	Hazard	Failure mode	Life cycle phase	TRL	Novelty	Probability	Consequence			Risk		
									Local system	Global system	Economic	Local system	Global system	Economic
Station keeping	Moor-ing	Mooring chain	No tension	Chain link fracture	O&M	8	2	3	4	3	3	M	M	M
				Interface pin fracture	O&M	8	2	4	4	3	3	H	M	M
				Increased length	O&M	8	2	1	2	1	2	L	L	L
		Gravity anchor	Moving when loaded	Friction too low	O&M	8	2	3	3	2	3	M	M	M

3.3 Technology Risk Evaluation

Technology risks identified during the technology risk analysis phase must be evaluated. The aim of the technology risk evaluation process is to compare results of the technology risk analysis with the technology risk criteria defined in Section 3.1.1 to determine whether the risk/s are acceptable, tolerable or unacceptable. This also includes deciding whether any further risk reduction is necessary, and making sure that the risk reduction procedures have not introduced any new or increased severity of already evaluated risks. The output of the technology risk evaluation phase is a list of risks that require treatment and the precedency for treatment implementation.

The technology risk evaluation shall be performed according to Section 1.3.3 of this report.

For the technology risk assessment, risks falling within scale ranges of 5-7 (medium risks) and 8-10 (high risk) are considered critical and require risk treatment. Within this report no specific risk treatments are suggested as technology developers are best placed to decide what kind of treatments to be used and how to implement these. Failure modes with low risk do not require any further investigation, but need to be kept on the risk register for future reference and update.

3.3.1 Technology Qualification Process

Risk evaluation can be further extended to assist with qualification of new technologies. The overall process of technology risk evaluation as part of qualification of new technology [5], is illustrated in Figure 13.

Although technology qualification is not the main objective of the technology risk assessment, floating wind turbine substructure concept developers, including those of the LIFES50+ project, might want to consider incorporating technology qualification process into their overall risk assessment process, as this might help to advance their concept in the context of the TRL scale. In addition, technology qualification does tie in with the overall aim of the LIFES50+ project *Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50 m* [15], as the name suggests.

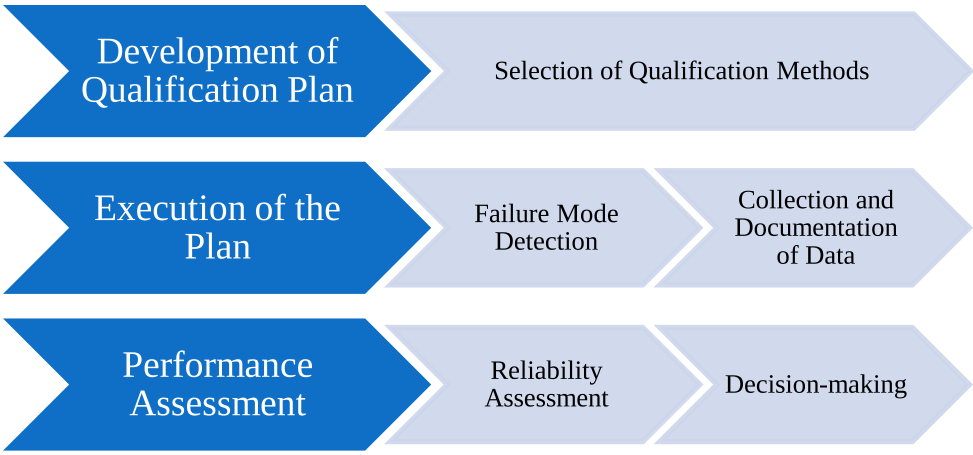

Figure 13: Risk Evaluation of Technology Qualification Process

3.3.1.1 Technology Qualification Plan

A technology qualification plan should be developed by floating wind substructure concept developers setting out how the technology will be qualified or the milestones expressed in the technology qualification basis (Section 3.1.1) reached. This includes selecting qualification method/s to be used. These need to be described in sufficient detail for the technology qualification activities to be performed and evidence to be collected. It is important that success criteria for each of the qualifications methods are defined in the qualification plan (i.e. defining what has to be achieved through the qualifications to fulfil the goals of the activity). Qualification methods to be used can cover anything from expert judgement to highly detailed numerical models such as CFD or FEM, to experimental methods. The choice of selecting the most applicable qualification method rests with floating wind substructure developers, as they are best place to choose a method that reflects their needs and capabilities.

The technology qualification plan developed should be in line with the LIFES50+ project and should aim to mirror the objective of the LIFES50+ project of qualifying floating wind substructure concept to TRL 5 [15].

3.3.1.2 Execution of Technology Qualification Plan

The execution of technology qualification plan consists of failure mode detection, collection and documentation of the data generated as part of the qualification activity. The data collected is then used as an input to performance assessment.

3.3.1.3 Performance Assessment

The data collected in the execution phase of the technology qualification process is assessed against the technology qualification basis (Section 3.1.1). As the whole process of technology qualification is iterative, multiple iteration might be required before the technology can be qualified on the basis of meeting all of its requirements and showing acceptable levels of risk and uncertainty.

An example of technology qualification could be promotion of the technology to the next level of TRL (Table 5).

3.4 Technology Risk Treatment

Risk evaluation is normally followed by risk reduction/control, also known as risk treatment. This involves:

- Decision making on what type of risk reduction and control arrangements are necessary, if any;
- Implementing risk reduction and control;
- Continuous monitoring of risks.

Risk reduction can be achieved by the complete elimination of hazards, or by reducing their severity or probability of occurrence, or both [4]. A common approach to risk treatment is by implementation of the ERIC model which is described in Section 1.3.4.

No specific technology risk treatments are suggested in this guidance as technology developers are best placed to decide what kind of treatments to be used and how to implement these. However, for an overview and guide on risk reduction/control, the following sources of information should be consulted [3], [4].

3.5 Technology Risk Summary

A technology risk assessment procedure for the floating wind substructure concepts participating in the LIFES50+ project, but also applicable to other floating substructures, has been developed. The developed technology risk assessment process is in line with the generic process of risk assessment as suggested by the ISO 31000 standard [3]. This is further supplemented with the process from DNV GL [5] which offers a much more detailed approach to qualification of new technologies and ties in with the overall aim of the LIFES50+ project. Instead of concentrating on TRLs, which are very similar for the participating concepts, emphasis is placed on a functional breakdown of floating wind substructures. A further breakdown into sub-systems and elements is used to identify novel elements of technology and new areas of application (proven technology but used in new environment). Additionally, all life cycle phases of technology are considered. A full FMECA-based risk register and a simplified, stripped down version of it, were developed. The latter is the preferred choice to be used as a generic risk register for technology hazards as part of the LIFES50+ project due to time, resource and data constraints. A suggested probability and severity of risk scale is also provided and the ranking of local, global and economic risks and their placement on a technology risk matrix has been demonstrated.

A simplified flowchart for the technology risk assessment and management process, as set out in this section, is provided in Appendix D – Flowcharts.

Suggested further reading includes:

- *Recommended Practice DNV-RP-A203: Qualification Procedures for New Technology* by DNV GL [5]. Provides a systematic approach to qualification of new technologies.
- *Technology Readiness Assessment (TRA) Deskbook* and *Technology Readiness Assessment (TRA) Guidance* by the U.S. Department of Defense [25], [33]. These provide detailed guidance on performing technology readiness assessment, including best practices.

4 Health, Safety and Environment Risk Assessment

Health, safety and environment risks relating to floating wind substructure designs should be assessed for various stages of the project life cycle (i.e. manufacture, construction, commissioning, operation and maintenance, and decommissioning) according to the processes laid out in Section 1. The scope of this risk assessment, as given by [9], [21], is illustrated in Figure 14. Additional areas of manufacturing risk are discussed in Section 5. Although the LIFES50+ technology concepts are currently in the design phase, the health and safety implications for construction, commissioning, operations, maintenance and decommissioning should be understood. Many of the decisions made during the project definition and design stage will influence the health, safety and environmental risk at later stages of the project lifecycle.

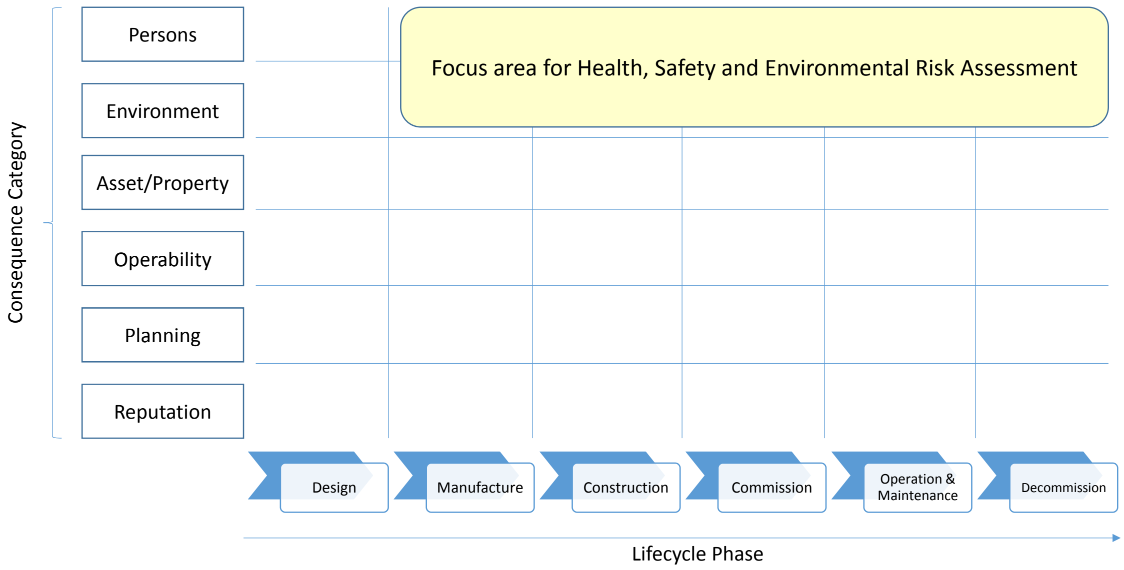

Figure 14: Health and Safety Risk Assessment Focus Areas [9]

In the context of the LIFES50+ project, the HSE assessment is only applicable to the substructure, as wind turbine risks are the same for all participating floating wind substructure concept designs (all use DTU 10MW wind turbine [16]).

4.1 Health and Safety

In the absence of dedicated protective measure standards for floating wind turbines, the governing health and safety standard applicable to the design of offshore wind turbines, including their substructures, is EN 50308 [34]. This standard is supported by a wide range of much more detailed standards applicable to specific areas of health and safety as shown in Figure 15 [9]. These standards should be considered in the design phase to minimise risks that could appear in the later phases.

The EN 50308 standard [34] applies only to health and safety of personnel. Additionally, only commissioning, operations and maintenance of wind turbines is covered. For information on manufacture, construction, and decommissioning of wind turbines, environment and issues specific to offshore wind turbines alternative sources of information are required. However, due to immaturity of floating wind turbines, no specific guidelines in these areas appear to exist.

RenewableUK have identified 24 different categories of risk relating to health and safety for offshore wind and marine energy [21], all of which can be evaluated within a HSE risk assessment. These are outlined in Table 16 and should be used as guidance for HAZID (help identify HSE hazards). Note that not all of these will apply to all aspects of the project life cycle – for example, HSE risks due to piling and grouting will be relevant to the construction phase of a wind farm but less so to the operation and maintenance phase. Additionally, as the provided list of risk categories is rather generic (applicable to all offshore wind and marine energy types), some floating wind specific health and safety risk categories are not accounted for (i.e. ballasting, anchor installation, hook-up, etc.). Therefore, it is important to consider floating wind specific risks in addition to the risk categories in Table 16.

Table 16: Health and Safety Risk Categories [21]

Category	Type of Risk
1.	Access and egress
2.	Aviation
3.	Cable laying and entry
4.	Confined Spaces
5.	Electrical safety
6.	Ergonomics
7.	Fire
8.	Geological unknowns
9.	Hazardous substances
10.	Lifting
11.	Marine co-ordination
12.	Metocean conditions
13.	Navigation
14.	Noise
15.	Piling and grouting
16.	Ports and mobilisation
17.	Remote working
18.	Subsea operations
19.	Unexploded ordnance
20.	Vessel selection
21.	Vibration
22.	Waste and spillage management
23.	Welfare
24.	Working at height

It is likely that some health, safety and environmental risks will be common across different types of floating substructures, whilst others are likely to be design-specific. The health, safety & environmental risk assessment for LIFES50+ should distinguish between these categorisations. For example, general health and safety considerations applicable to all technologies during the construction phase may be:

- People will be required to work offshore during installation;
- Installation will require operation of vessels in deep water and differing sea states (depending on site);
- Installation will require execution of weather-sensitive tasks;
- Installation activities may lead to interactions with other sea users.

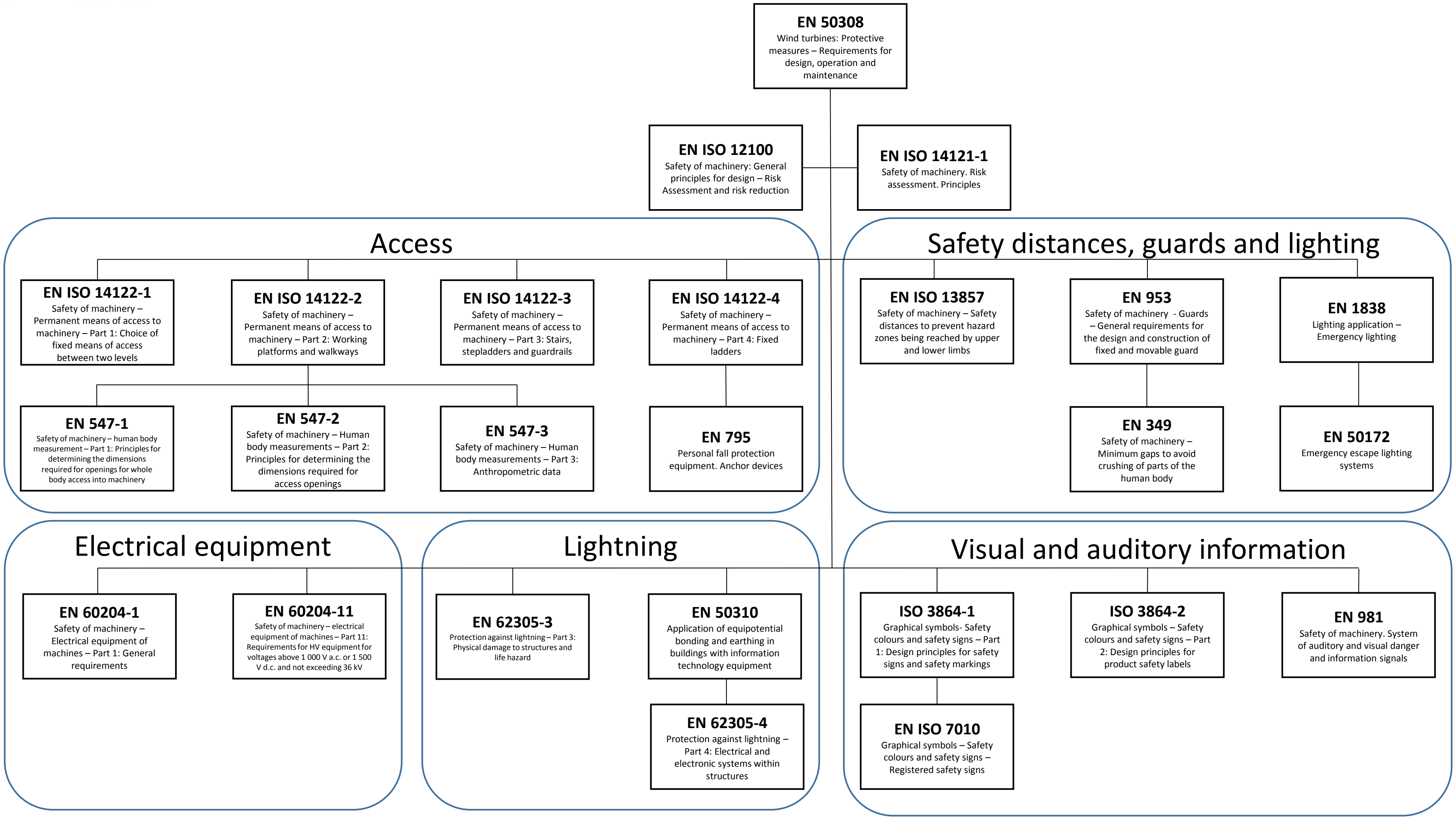

Figure 15: Hierarchy of Health and Safety Standards relating to Offshore Wind Turbine Substructures [9]

However, the details of how these operations are to be completed may differ for each substructure type, in terms of (for example):

- Activities required to complete the task;
- Number of people required to complete the task;
- Vessel requirements and weather restrictions;
- Materials used and installation methods required;
- Estimated time taken to complete task.

Details such as these, which differentiate between technology concepts, and absolute risks should be captured by the health, safety and environmental risk assessment.

4.2 Environment

The methodology for environmental risk assessment will be based on Guidelines for Environmental Risk Assessment and Management – Green Leaves III [22].

The source-pathway-receptor (SPR) and/or source-pathway-receptor-consequence (SPRC) concept can be used in environmental assessment to identify the link between a hazard and risk. SPRC, as opposed to SPR, can also be used to quantify damage or benefits expressed in financial terms. In these concepts, the source or contaminant is something that has potential to harm environment (also human life), the pathway is the means by which exposure might occur, the receptor is something that could be harmed and consequence is harm expressed in financial terms. It should be noted that a potential risk is only created when a link between the different elements of SPR exists. Without the linkage these elements can exist completely independently and not pose any risk.

A flow diagram for SPR and SPRC, and an example SPR linkage are shown in Figure 16 and Table 17.

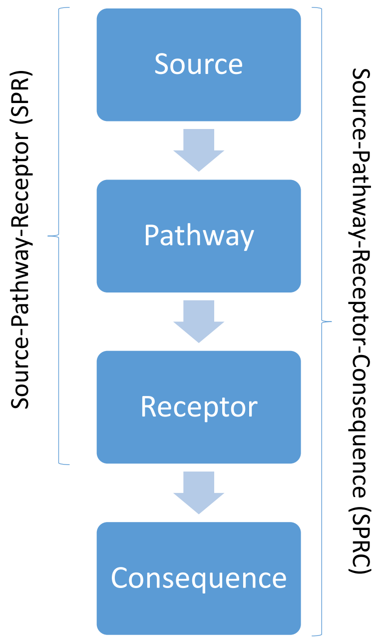

Figure 16: SPR and SPRC Flow Diagram

Table 17: Example of SPR Concept

No.	Hazard	Source	Pathway	Receptor	SPR linkage
1	ballast	ballasting system	leaking	surrounding environment, sea life	yes
2	anchors	anchor piling	water	fish	yes

Additionally, it is important that all relevant wildlife, protected species, etc. legislation and guidance are considered. In terms of the LIFES50+ project, these are expected to be very different for each of the three chosen installation sites.

As per the general process of risk assessment identified in Section 1, the HSE risk assessment should begin with hazard identification, followed by estimation of probabilities and consequence of hazard (risk analysis), followed by risk evaluation and concluded by risk treatment where possible.

4.3 HSE Risk Identification

In the case of HSE, hazards are typically qualitative (see Section 1.3.1) and identified by a risk workshop (HAZID) rather than by quantitative data. It is good practice, however, to look beyond the hazard identification workshop to the wider industry context to supplement company-specific HSE risks with industry-standard components of HSE risk and to record these in a generic risk register which will apply at the outset of most projects relating to substructures for floating wind turbines. The HAZID process should cover a range of different deployment scenarios for the proposed floating wind substructures, in terms of site conditions and characteristics.

The consequence and likelihood of each hazard identified using the HAZID technique should be estimated as part of the hazard identification workshop (see Sections 1.3.2 and 1.3.2.2), either as part of the initial workshop or in a separate design risk assessment workshop scheduled as a follow-up to the HAZID. HSE risk assessment should be considered an iterative process rather than a single event, allowing both the designers of the system and the users of the system to suggest and implement protective safety measures [35].

Similarly to FMECA in Section 3.2.2, no standard HAZID worksheet exists. HAZIDs are often used in different industries and risk areas, and hence require specific information to be provided. For the purpose of the LIFES50+ project an example HSE HAZID worksheet has been developed that could be used to identify all relevant HSE hazards. In addition to identifying hazards for specific life cycle phases (from design to decommissioning) and their supporting evidence, each hazard should be identified to be generic or site specific (i.e. in the context of the three locations considered in LIFES50+), and assigned a dimension of HSE risk, which is described next.

The target safety level applicable to structures in offshore wind farms is highlighted in Table 18. Implications for personal injury and pollution, economic consequence and human life are considered to be in the 'Normal' safety class [10]. As the installations are normally unmanned risk to human life is not considered large. However the installation and maintenance procedures associated with substructures means that it is greater than negligible.

Table 18: Safety Classes for Offshore Wind Turbine Structures (including Substructures) [10]

	Dimensions of Risk			
Safety Class	***Risk of Personal Injury***	***Potential Pollution/ Societal Losses***	***Potential Economic Consequence***	***Risk to Human Life***
Low	Low	Low	Low	Negligible
Normal	Some	Some	Significant	Some
High	Large possibilities	Significant/Major	Very Large	Large possibilities for fatality

It should be noted that multiple dimensions of risk could be applicable to one HSE hazard. For example, use of hazardous substances in manufacturing can pose a potential risk to both human health (risk of personal injury and to human life) and environment (potential pollution). Specification of risk dimension in risk register, as shown in Table 19, allows this ambiguity to be eliminated.

Some of the information that may aid in hazard identification, when performing HSE risk identification, includes:

- Offshore standards and guidance applicable to both persons (working offshore) and environment (pollution and sea life);
- Historical data (including best practices, incidents, accidents and near misses for the oil and gas, shipping and fishing industries);
- Existing and historical use of sea (cables, gas lines, fishing zones, etc.).

4.4 HSE Risk Analysis

4.4.1 Consequence Scale

Consequence of HSE hazards can be split into two sub-categories: harm to person and harm to the environment. This means that although the generic 5-point consequence scale can be used, the interpretation of each risk category should be adjusted to ensure that it is relevant to the context of the risk being estimated. Interpretation of the consequence scale for harm to persons is given in Table 20 whilst that for harm to environment is given in Table 21.

Table 19: Example HSE HAZID

Phase of Life Cycle	Dimension of HSE Risk	Generic or Site Specific	Hazard	Example Data Sources / Evidence
Manufacture			Use of hazardous materials	
			Use of new manufacturing techniques/processes	
			Inadequate protective measures	
Construction and Commission			Environmental impact e.g. to marine life of piling, drilling, cable installation (given soil conditions and water depth)	
			Unexpected implications to installation	
			Incompliance with health and safety guidelines for offshore working (protective measures/clothing required)	
			Unproven systems for safe transfer of personnel to and from vessels	
Operation and Maintenance			Inability to demonstrate environmental compliance	
			Marine growth altering system’s response	
			Potential harm to personnel while transferring from a boat to a landing platform	
			Lack of qualified personnel	
			Inaccurate weather prediction	
			Lack of available vessels to perform O&M functions	
Decommission			Potential harm to environment due to disposal of assets	
			Inability to returned seabed to its ‘original state’ (related to anchoring)	
			Need for the disposal of hazardous substances	

For harm to persons:

Table 20: Example Consequence Scale for Health, Safety and Environmental Risks (Harm to Persons) [9]

Severity of Harm

Scale	Category	Description (Harm to Persons)
5	Extensive	Multiple deaths, life-threatening or permanent disabling injuries or illnesses, unable to return to work
4	Major	Single death, life-threatening or permanent disabling injury or illness, unable to return to work
3	Severe	Serious or debilitating injury or illness requiring hospitalisation, able to return to work at some point
2	Moderate	Moderate injury or illness requiring medical treatment, able to return to same job
1	Minor	Minor injury or illness requiring no more than first aid, no or little lost work time

For harm to environment:

Table 21: Example Consequence Scale for Health, Safety and Environmental Risks (Harm to Environment) [9]

Severity of Harm

Scale	Category	Description (Harm to Environment)
5	Extensive	Major damage to environment with widespread long-term effects and international impact, requiring restoration
4	Major	Major damage to environment with widespread long-term effects and national impact, requiring restoration
3	Severe	Severe damage to environment, with long term effects or not locally contained impact, requiring restoration
2	Moderate	Significant damage to environment with short-term effects and local impact, requiring restoration
1	Minor	Slight damage to environment with minor effect and local impact, may be reportable, complaints from public

4.4.2 Probability Scale

The likelihood of HSE hazards recorded in the risk register being realised should be estimated on a 5-point scale. The interpretation of these probability categories for this context is given in Table 22.

Table 22: Example Probability Scale for Health, Safety and Environmental Risks [9]

Probability of Occurrence of Harm

Scale	Category	Description	Probability
5	Very Likely	Almost certain to occur, happens frequently in wind energy, offshore or other related industry when developing new or innovative technologies	$p > 10^{-1}$
4	Likely	Likely to occur, happens often in wind energy, offshore or other related industry when developing new or innovative technologies	$10^{-2} < p < 10^{-1}$
3	Probable	Probable to occur, heard of in wind energy, offshore or other related industry when developing new or innovative technologies, but does not happen often, credible scenario	$10^{-3} < p < 10^{-2}$
2	Possible	Possible to occur, but not known in wind energy, offshore or other related industry when developing new or innovative technologies, foreseeable though would require multiple market failures	$10^{-4} < p < 10^{-3}$
1	Unlikely	Unlikely to occur, never heard of in wind energy, offshore or other related industry when developing new or innovative technologies, very little credibility as scenario	$p < 10^{-4}$

The scale assigned should be agreed amongst interested parties recorded in the risk register either during or after the HAZID.

For offshore substructures the relevant safety class is the ‘Normal’ class, which implies that failures or hazards would result in some personal injury, pollution or minor societal losses, or possibility of significant economic consequences. The target safety level for this class is an annual probability of failure of 10^{-4} [10]. In the context of the LIFES50+ project, this is not a target. However, floating wind substructure concept designers should work towards achieving this, especially with regard to succeeding in full scale commercialisation of their floating wind substructure concepts.

4.4.3 Risk Rating

Following the identification of HSE risks, their consequence and likelihood, the HSE risk rating can be assessed. This should be performed as per Section 1.3.3.

Figure 17 shows the HSE risk matrix which shall be used to assess the overall HSE risk based on the consequence and likelihood scaled given before.

Consequence						
	5	M	M	H	H	H
	4	M	M	M	H	H
	3	L	M	M	M	H
	2	L	L	M	M	M
	1	L	L	L	M	M
L=Low, M=Medium, H=High		1	2	3	4	5
		Probability				

Figure 17: HSE Risk Matrix

To date there has been very limited deployment of full scale floating wind turbines. In terms of the LIFES50+ project, none of the participating floating wind substructure concept designers have had a full scale prototype installed offshore. The lack of experience and available data on floating wind turbines is built into the HSE risk matrix in Figure 17 by using a conservative risk level breakdown.

Table 23 shows an example risk register populated using the HSE risk analysis techniques described above and hazards identified as part of the HSE risk identification using HAZID approach.

Table 23: Example HSE Risk Register with Risk Ranking

Life Cycle Phase	Dimension of HSE Risk	Generic or Site Specific	Hazard	Probability	Consequence	Risk
Manufacture	Pollution / Societal Losses	Generic	Use of hazardous materials	2	2	L
Construction and Commission	Pollution / Societal Losses	Site Specific	Harm to fish by anchor piling	3	2	M
Operation and Maintenance	Personal injury / Human life	Generic	Potential harm to personnel while transferring from a boat to a landing platform	3	4	M
Operation and Maintenance	Economic	Generic	Inaccurate weather prediction	1	3	L
Decommission	Pollution / Societal Losses	Generic	Need for the disposal of hazardous substances	1	3	L

4.5 HSE Risk Evaluation

The HSE risk identified and analysed as part of the HSE risk identification and analysis phases must be evaluated. The aim of the HSE risk evaluation is to compare the results of the HSE risk analysis with the risk criteria scale as described in Section 1.3.3. This allows acceptable, tolerable and unacceptable HSE risks to be determined. Additionally, HSE risk evaluation allows risks that require further risk reduction to be determined and helps to make sure that the risk reduction procedures have not introduced new or increased severity and/or probability of already evaluated risks.

As given by DNV GL's offshore standard [10], the target safety class for floating wind substructure concepts is 'Normal' (Table 18). Designers and operators of floating wind substructures should make sure that the associated probabilities of HSE hazards realising are not exceeded and, when possible, strive for 'Low' safety class. However, if the target safety class is not met, risk treatment should be identified and implemented.

The HSE risk evaluation should be performed according to Section 1.3.3.

For the purpose of the LIFES50+ project it has been assumed that risks falling within the risk scale range of 8-10 are unacceptable and require treatment, whatever the cost. For the risk scale range of 5-7 risks are only tolerable if the cost of risk reduction is grossly disproportionate to the benefit gained. The risks falling within the scale range of 2-4 are assumed to be broadly acceptable, and, while no risk treatment is required, these should be monitored as the risk rating might change in the future.

4.6 HSE Risk Treatment

Measures to reduce or mitigate HSE risk range from eliminating hazards during the design process to mitigating hazards during the operational phase of the substructure, as illustrated by the ERIC (Eliminate, Reduce, Inform, Control) hazard reduction hierarchy model [9] (Figure 6).

Typically the eliminate, reduce and inform measures are those which would be implemented by the designers of the technology, with control measures implemented by users. Hazards should be eliminated if possible, otherwise reduced by inherently safe design and by protective equipment and information.

Risk reduction relating to health, safety and environmental hazards should correspond to the ALARP principle which is that the *residual risk* after risk reduction measures have been implemented shall be as low as reasonably practicable, i.e. the cost to reduce further the risk remaining would be disproportionately large relative to the benefits (Figure 5).

A person responsible for the management of each HSE risk and the actions that should be taken to manage or mitigate risk should be assigned, and the hazards should be recorded in an HSE risk register. This risk register will be one component of the overall project risk register, complementing the technology risk register (see Section 3) and the manufacturing risk register (see Section 5). The HSE risk register and its outcomes will also inform the commercial risk register (see Section 6).

4.7 HSE Risk Summary

A HSE risk assessment procedure for evaluation of floating wind substructure concepts participating in the LIFES50+ project, but also applicable to those not considered within the project, has been developed based on the generic process of risk assessment as recommended by various standards and includes design risk assessment. The procedure developed covers areas of consequence to persons and environment. Multiple relevant standards have been reviewed and incorporated into the HSE risk assessment procedure to fill the gap that has formed due to lack of standards exclusive to floating wind. A list of health and safety categories is provided to help identify HSE risks. Furthermore, a SPR approach has been adopted to help identify environmental risks. A generic HAZID form is proposed to be used by the LIFES50+ participants. The four risk dimensions of risk of personal injury, risk to human life, potential pollution / societal losses and potential economic consequence have been selected and incorporated into the HSE risk assessment. In addition to a probability scale, two consequence scale interpretations for risk in the context of HSE are also provided to cover both harm to persons and environment. Based on the aforementioned scales a risk matrix was developed.

In the broader context of risk management, no specific risk treatments have been suggested. However, ERIC and ALARP methods have been suggested as a valid approach for HSE risk treatment.

A simplified flowchart for the HSE risk assessment and management process, as set out in this section, is provided in Appendix D – Flowcharts.

Suggested further reading includes:

- *Offshore Wind and Marine Energy Health and Safety Guidelines* by RenewablesUK [21]. Comprehensive guidelines on health, safety and environment for offshore renewable energy.
- *Guidelines for Environmental Risk Assessment and Management. Green Leaves III* by Cranfield University and Department for Environment, Food and Rural Affairs [22]. Generic guidelines of risk assessment and management in the context of environmental risks.

5 Manufacturing Risk Assessment

The objective of the manufacturing risk assessment is to identify any manufacturing related hazards, such as cost, schedule and quality, for each of the floating substructure designs in LIFES50+ and to perform risk assessments for these.

Manufacturing risks shall be assessed in conjunction with the Manufacturing Readiness Level (MRL) process as defined by [23]. The U.S. Government Department of Defense has defined MRL across a scale of MRL 1 to MRL 10, progressing in maturity to full rate production as the number increases. These MRLs as defined in [23] are shown in Table 24.

Table 24: Concise MRL Definitions [23]

MRL 1	Basic manufacturing implications identified
MRL 2	Manufacturing concepts identified
MRL 3	Manufacturing proof of concept developed
MRL 4	Capability to produce the technology in a laboratory environment
MRL 5	Capability to produce prototype components in a production relevant environment
MRL 6	Capability to produce a prototype system or subsystem in a production relevant environment
MRL 7	Capability to produce systems, subsystems, or components in a production representative environment
MRL 8	Pilot line capability demonstrated; Read to begin low rate initial production
MRL 9	Low rate production demonstrated; Capability in place to begin full rate production
MRL 10	Full rate production demonstrated and lean production practices in place

Table 24 only gives the title of each MRL. For full description of each MRL please see Appendix C – MRLs.

In early stages of technology development, MRL focuses on manufacturing feasibility by identifying and reducing the production risk of the proposed concept [5]. Additionally, performing an MRL-based assessment is an effective way to identify and manage risks as early as possible. It can also provide the basis for manufacturing maturation.

The manufacturing risk analysis process shall be completed in accordance to the ISO 31010 standard [1] where Risk Identification, Analysis and Evaluation will be carried out. The U.S. DoD MRL Deskbook [23] has defined nine manufacturing risk areas, called threads, which are generally considered as critical for successful manufacturing, these are:

- **Technology and the Industrial Base**: Requires an analysis of the capability of the national technology and industrial base to support the design, development, production, operation, uninterrupted maintenance support of the system and eventual disposal (environmental impacts).
- **Design**: Requires an understanding of the maturity and stability of the evolving system design and any related impact on manufacturing readiness.
- **Cost and Funding:** Requires an analysis of the adequacy of funding to achieve target manufacturing maturity levels. Examines the risk associated with reaching manufacturing cost targets.
- **Materials**: Requires an analysis of the risks associated with materials (including basic/raw materials, components, semi-finished parts, and sub-assemblies).

- **Process Capability and Control**: Requires an analysis of the risks that the manufacturing processes are able to reflect the design intent (repeatability and affordability) of key characteristics.
- **Manufacturing Workforce (Engineering and Production)**: Requires an assessment of the required skills, availability, and required number of personnel to support the manufacturing effort.
- **Facilities**: Requires an analysis of the capabilities and capacity of key manufacturing facilities (prime, sub-contractor, supplier, vendor, and maintenance/repair).
- **Quality Management**: Requires an analysis of the risks and management efforts to control quality, and foster continuous improvement.
- **Manufacturing Management**: Requires an analysis of the orchestration of all elements needed to translate the design into an integrated and fielded system (meeting Program goals for affordability and availability).

The manufacturing risk areas listed above can be further broken down into thread sub-categories. A detailed list of the MRL criteria for different types of threads and sub-threads is given in [23].

Table 25 has been compiled to provide a summary of these; additionally indicating their initiation stage, when linked to specific MRL criteria.

Table 25: Summary of sub-threads

No.	Thread	Sub-thread	MRL at initiation
1	Technology and the industrial base	Manufacturing technology development	2
		Industrial base	3
2	Design	Maturity	1
		Producibility	3
3	Cost and funding	Cost analysis	1
		Manufacturing investment analysis	1
		Cost modelling	2
4	Materials	Maturity	1
		Availability	2
		Special handling	2
		Supply chain management	3
5	Process capability and control	Modelling and simulation	2
		Manufacturing process maturity	2
		Process yields and rates	3
7	Manufacturing workforce	Manufacturing workforce	3
8	Facilities	Facilities	3
		Tooling and special equipment	4
6	Quality management	Quality management	4
		Product quality	4
		Supplier quality	4
9	Manufacturing management	Manufacturing planning and scheduling	4
		Materials planning	4

The list in Table 25 is not exhaustive and can be populated throughout the process of manufacturing risk assessment or management. Additionally, it should be adjusted to meet a particular technology's or application's needs.

MRLs (Table 24) and TRLs (Table 5) are highly interlinked and can be mapped against each other, as shown in Figure 18 (based on [36]). It is not uncommon for TRLs to lead MRLs as product design and technology have to be established before the manufacturing processes can truly mature.

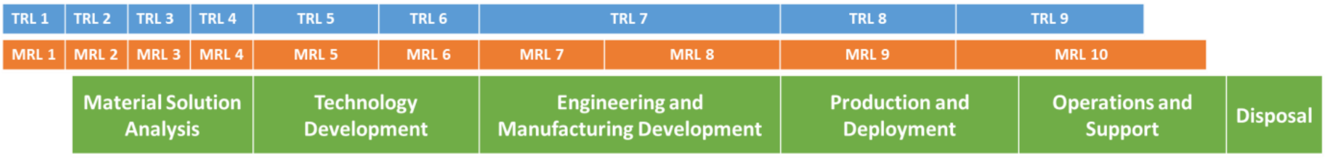

Figure 18: Mapping of TRLs to MRLs

With all four designs considered as part of the LIFES50+ project being TRL 4-5, the manufacturing risk assessment will concentrate on the lower levels of the MRL scale (MRL $\leq$ 5). Furthermore, using

Table 25, the main threads and sub-treads can be identified that are particularly relevant to low MRLs.

From Figure 18, the LIFES50+ floating substructure designs are in either the Material Solution Analysis or Technology Development phase. In terms of manufacturing risk assessment, the material solution analysis involves performing a manufacturing feasibility assessment. Consideration should be placed on identification of manufacturing technologies and processes that will have to be developed and risks associated with developing them; performing a production feasibility and considering investment needed for manufacturing. The output of the material solution analysis phase is an evaluated manufacturing process that suggests the most feasible materials, manufacturing processes and facilities that should be used to build a prototype in the technology development phase. In term of manufacturing risk assessment, the technology development phase involves performing a manufacturing capability assessment. This entails obtaining some key information regarding the critical manufacturing processes, efforts required for production scale-up (prototype to low rate initial production) and potential supply chain issues. Consideration should be placed on [23]:

- Identifying manufacturing process and techniques that are not currently available,
- Calculating probability of meeting delivery times,
- Identifying design producibility risks,
- Identifying potential impact on critical and long-lead time material,
- Identifying production equipment availability,
- Identifying production unit cost goal achievement,
- Performing a manufacturing capability and cost and schedule impact analysis,
- Providing recommendations for anticipated production testing and demonstration efforts,
- Identifying methods for conserving critical and strategic materials.

The output of manufacturing readiness assessment performed in the technology development phase is the basis for knowledge of manufacturing maturity and risk for all technology under development.

As shown in Figure 18, later phases of project life cycle entail reaching TRL and MRL 7 and hence are not discussed in this report. Information on these phases can be obtained in the U.S. Department of Defense deskbook and instruction [23], [36].

5.1 Manufacturing Risk Identification

Manufacturing risk can apply at a system level (i.e. the substructure) and down to an element level (i.e. the mooring chain). Risks shall be identified from system level down to element level. This can be achieved using the process illustrated in Figure 19.

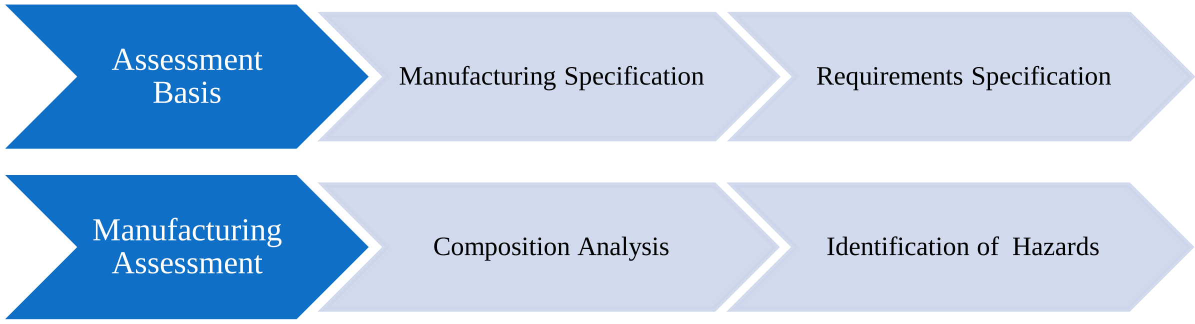

Figure 19: Manufacturing Risk Identification Process

5.1.1 Assessment Basis

The qualification basis should provide a common set of criteria against which the manufacturing should be assessed. It should include, but is not limited to, specifying the manufacturing process, defining its use, its requirements and facilities, rate times and quality.

Within the scope of LIFES50+ the manufacturing specification and hence also the requirement specifications will be different across all concepts (partially due to the different locations the concepts are being developed at and for, but mainly due to significant design differences between each of them). Whilst there will be some similarity in the manufacture of comparable substructures types (i.e. semi-submersible) using the same material (i.e. concrete or steel), the overall process is expected to vary significantly from concept to concept. This means that it is not possible to define requirement specifications that will be detailed enough and at the same time applicable to all LIFES50+ floating wind substructure concepts.

The four designs of floating wind substructures assessed as part of the LIFES50+ project are described in Section 2 (including type of floater and material used). For detailed information on each floating wind substructure alternative sources of information should be consulted. Additionally, deliverable 2.1 “General consideration for evaluation procedures” provides details on what information should be considered and how manufacturing evaluation will be performed (this report is not publicly available).

5.1.2 Manufacturing Assessment

5.1.2.1 Composition Analysis

The composition analysis as carried out for the technology risk assessment may be used for the analysis of manufacturing risks. Please refer to Section 3.1.2.1.

A team or individual with suitable level of manufacturing expertise (in-depth knowledge of the manufacturing processes and procedures, and good understanding of the technology) should review the composition analysis. Further decomposition of the elements may be necessary to fully capture the respective manufacturing phases and processes.

5.1.2.2 Risk Identification

Each of the systems, sub-systems and elements should be assessed throughout the manufacturing cycle (i.e. from raw materials through to final assembly) where all manufacturing risks shall be identified.

The following risk categories and their subcategories (shown in Table 25) should be considered when identifying manufacturing risks, see Section 5 for descriptions of each of the categories:

- Technology and the Industrial Base
- Design
- Cost and Funding
- Materials
- Process Capability and Control
- Manufacturing Workforce (Engineering and Production)
- Facilities
- Quality Management
- Manufacturing Management

The list of risk categories and sub-categories presented in Table 25 can be considered as the potential 'Risk Areas' with respect to manufacture. Each of the identified systems, sub-systems and elements shall be assessed against the hazard areas. Additionally, information such as standards, practice guides and design drawings can help to identify hazards. Where a hazard is reasonably foreseeable, the root cause shall be captured. Table 26 shows an example of manufacturing risk identification for the mooring chain and gravity anchor.

Table 26: Example Manufacturing Risk Identification

Function	Sub-function	Element	Risk Area	Hazard
Station keeping	Mooring	Mooring chain	Materials	Long lead times from supplier
			Quality management	Required tolerances not met
		Gravity anchor	Technology and the industrial base	Immature technology base of design for manufacture of the component
			Technology and the industrial base	No industrial base for fabrication
			Materials	Shortage of raw materials required for fabrication
			Manufacturing management	Too large for conventional transportation from fabricator facility to assembly site

5.2 Manufacturing Risk Analysis

A risk assessment should be performed on the identified manufacturing hazards. This involves assessing the consequence and probability of hazard materialisation, as illustrated in Figure 20.

Figure 20: Manufacturing Risk Analysis Process

5.2.1 Consequence of Hazard Materialisation

The manufacturing hazard materialisation consequence is related to the cost, schedule and quality of manufacturing the respective components and the manufacture of the overall substructure concept [23]. A scale has been identified where a minor consequence relates to insignificant impact to manufacture and an extensive consequence relates to severe cost and quality implications on both the component and complete substructure manufacture. Table 27 summarises the consequence categories for manufacturing risk.

The analysis of the consequence of hazard materialisation should be performed by a suitably qualified person with expert knowledge in the relevant areas of manufacturing.

Table 27: Example Manufacturing Consequence of Hazard Materialisation

Scale	Consequence (Severity)	
	Category	Description
5	Extensive	Severe cost / schedule / quality impact on the manufacture of the component. Severe impact to component interfaces. Severe impact on the manufacture of the overall substructure.
4	Major	Severe cost / schedule / quality impact on the manufacture of the component. Severe impact to component interfaces. Moderate impact on the manufacture of the overall substructure.
3	Severe	Severe cost / schedule / quality impact on the manufacture of the component. Moderate impact to component interfaces. Minor impact on the manufacture of the overall substructure.
2	Moderate	Moderate cost / schedule / quality impact on the manufacture of the component. No impact to component interfaces. Does not affect the manufacture of the overall substructure.
1	Minor	Insignificant impact on the manufacture / fabrication / assembly of the component and overall substructure.

5.2.2 Probability of Hazard Materialisation

Where possible the probability of hazard materialisation should be defined using quantitative measure, however manufacturing development typically lags technology development, hence for the scope of LIFES50+ quantitative measures for manufacturing readiness may be limited.

In the case where quantitative assessment of probability cannot be made, a qualitative measure should be used based on assessment by suitably qualified persons with expert knowledge in the relevant areas of manufacturing.

Table 28 summarises the probability categories for manufacturing risk.

Table 28: Example Technology Probability of Hazard Materialisation

Scale	Probability (Likelihood)		
	Category	**Qualitative Measure**	**Quantitative Measure (per year)**
5	Very Likely	Almost certain to occur, happens frequently either in this context or a similar context.	$p > 10^{-1}$
4	Likely	Likely to occur, happens less than once per year either in this context or in a similar context	$10^{-2} < p < 10^{-1}$
3	Probable	Probable to occur, i.e. heard of in this context or in a similar context, less than once per year but still a credible scenario	$10^{-3} < p < 10^{-2}$
2	Possible	Possible but not probable to occur given what has been observed to happen in this context or in a similar context historically. Would require a number of simultaneous failures of risk controls.	$10^{-4} < p < 10^{-3}$
1	Unlikely	Unlikely to occur. Although in theory a possibility, this event has never been observed in this or in a similar context	$p < 10^{-4}$

5.2.3 Risk Rating

Following the identification of hazard areas, consequence and probability of hazard materialisation, the manufacturing risk rating can be assessed. This shall be performed according to Section 1.3.3 of this report.

Figure 21 shows the manufacturing risk matrix which shall be used to assess the overall risk of the hazard based on the likelihood and consequence of hazard materialisation.

Consequence						
	5	M	M	H	H	H
	4	M	M	M	H	H
	3	L	M	M	M	H
	2	L	L	M	M	M
	1	L	L	L	M	M
L=Low, M=Medium, H=High		1	2	3	4	5
		Probability				

Figure 21: Manufacturing Risk Matrix

An identical split of the manufacturing risk matrix into low, medium and high risks to the technology risk matrix is used. The reasoning for the specific breakdown used in the manufacturing risk matrix is to make sure that risks with high probability and low consequence and vice versa are addressed.

At the current point of the LIFES50+ designs development stages any significant delays or materialised hazards, either due to repetitive occurrences of small consequences or one, high unlikely, but of a high consequence risk, could potentially significantly damage the investor confidence in the floating wind projects, hence further delaying and adding additional hurdles to making floating offshore wind turbines feasible.

Table 29 shows an example of the overall manufacturing risk analysis process where the relevant data has been supplied from the previously performed analysis (Table 26), and the risk levels are identified using the technology risk matrix (Figure 21).

Table 29: Example Manufacturing Risk Register with Risk Ranking

Function	Sub-function	Element	Risk Area	Hazard	Probability	Consequence	Risk
Station keeping	Mooring	Mooring chain	Materials	Long lead times from supplier	3	4	M
			Quality management	Required tolerances not met	2	4	M
		Gravity anchor	Technology and the industrial base	Immature technology base of design for manufacture of the component	4	5	H
			Technology and the industrial base	No industrial base for fabrication	2	5	M
			Materials	Shortage of raw materials required for fabrication	1	4	M
			Manufacturing management	Too large for conventional transportation from fabricator facility to assembly site.	1	3	L

5.3 Manufacturing Risk Evaluation

Manufacturing risks identified during the risk analysis phase must be evaluated. The aim of the manufacturing risk evaluation process is to compare results of the risk analysis with the risk criteria to determine whether the risk/s are acceptable, tolerable or unacceptable.

The risk evaluation shall be performed according to Section 1.3.3 of this report.

As explained by [23], care should be taken when solely relying on the MRL numbering scheme to assess manufacturing readiness, as it can be misleading. It is not the MRL number that is important but rather the degree of maturity and what needs to be done to increase maturity of a specific element being analysed. For example, a major investment in the production plant might lower the MRL, even if it improves producibility and lowers risk.

The hazards identified and analysed as part of the manufacturing risk identification and analysis are evaluated against the set criteria, as per Section 1.3.3. The ALARP process diagram in Figure 5 and risk scale in Table 3 should form the basis of the risk evaluation. For example, the manufacturing hazards that have been recognised to pose medium ("M") or high ("H") risk are assumed to be critical and require risk treatment. For those hazards that have been assigned low ("L") risk no further action is required. However, these should be kept on the risk register and monitored.

At this stage the classification of the overall concept and each critical element against the MRL can be performed. Emphasis should be placed on assessing element and sub-system level as assigning an MRL value to the whole system/technology can be of very little value. The MRL can vary extensively from element to element and while some elements may have a long record of use, resulting in a high MRL, other elements may be quite unique and innovative, resulting in a low MRL. As the MRL of the whole system/technology is only as high as its lowest element, this could be misleading and increase the overall level of risk, which would not be representative of the actual situation. To counter this, a bottom-up assessment of manufacturing readiness should be performed at the system, sub-system and element level.

Whilst all LIFES50+ substructure designs are approximately at the same TRL, there may exist large differences in the MRL. These should be identified and recorded.

5.4 Manufacturing Risk Treatment

No specific manufacturing risk treatments are suggested as technology developers are best placed to decide what kind of treatments to be used and how to implement these. However, one risk treatment method, specifically applicable in the context of manufacturing, is provided below.

For those systems, sub-systems and elements that do not meet the target MRLs (set as part of manufacturing assessment basis (Section 5.1.1)), a manufacturing maturation plan (MMP) should be developed and implemented to eliminate or reduce risk to some predefined acceptable level. This should include a description of the approach to resolve the risk, how much it will cost, what resources are available and what impact will this have on the schedule. An MMP, as given by [23], should include:

- Statement of problem
    - Describe the element of assessment and its maturity status
    - Describe how this element of assessment would be used in the system
    - Show areas where manufacturing readiness falls short of target MRL including key factors and driving issues
    - Assess type and significance of risk to cost, schedule and performance
- Solution option
    - Benefits of using the preferred approach
    - Fall-back options and the consequence of each option
- Maturation plan with schedule and funding breakdown
- Key activities for the preferred approach
- Preparations for using an alternative approach
- The latest time that an alternative approach can be chosen
- Status of funding to execute the manufacturing plan
- Specific actions to be taken
- Prototypes and test articles to be built
- Tests to be run
    - Describe how the test environment relates to the manufacturing environment
- Threshold performance to be met
- MRL to be achieved and when it will be achieved

The MMP, as given by [23], was developed for the U.S. Department of Defense and hence is more applicable to high-technology. The overall process is sound and can be easily adjusted to meet any particular needs of any industry or technology being assessed, including those of the LIFES50+ project.

Additionally to the in-house expertise, where applicable, manufacturing expertise of others, such as contractors and sub-contractors, should be used to help reduce manufacturing risk.

5.5 Manufacturing Risk Summary

A manufacturing risk assessment procedure for evaluation of technology concepts participating in the LIFES50+ project has been developed based on the generic process of risk assessment recommended by international standard procedures. The manufacturing risk assessment developed draws heavily on the work on MRLs by the U.S. DoD [23] and DNV GL guide for technology qualification [5]. It is tailored to manufacturing of early stage MRLs by recognising that the low-level TRL concepts, such as those being explored by the LIFES50+ project, are likely to be at a similar or lower level of MRL. Hence the standard MRL threads and sub-threads applicable to MRL 4 or lower are considered and should drive the identification of manufacturing hazards. These should then highlight the difference between the four concepts of the LIFES50+ project in the context of manufacturing risk assessment. A suggested interpretation of probability and consequence scales for risks is also provided in the context of manufacturing.

In the broader context of risk management, no specific risk treatments have been suggested. However, MMP has been suggested as a valid approach for manufacturing risk treatment.

A simplified flowchart for the manufacturing risk assessment and management process, as set out in this section, is provided in Appendix D – Flowcharts.

Suggested further reading includes:

- *Manufacturing Readiness Level (MRL) Deskbook* by the U.S. Department of Defense [23]. Provides information on best practices for performing manufacturing readiness assessment.

6 Commercialisation Risk Assessment

Commercialisation risk covers those aspects of risk related to bringing a new product to market, including non-technological considerations such as regulatory environment, financial performance and proposition and market opportunities [24], [37]. A risk assessment for the commercialisation dimension of a novel wind turbine floating substructure design should account for the 'hazards' that could be encountered in each of these areas, including those related to the permitting process, certification of new technology, compatibility between wind turbine and substructure, attaining environmental consents, the regulatory environment for new or innovative designs, and the potential impact of commercial risk on Levelised Cost of Energy (LCoE). Note that particularly in the context of commercialisation there is also scope for opportunity, or upside, in each of these aspects and so although the term commercialisation 'risk' is used, it should be taken to mean an assessment of commercialisation risk and opportunity, as both hazards and strengths may be identified via this process [37].

Assessment of commercial readiness (which can be considered a high-level indicator of the residual risk of a concept being taking through the process of commercialisation) can be made with reference to the Commercial Readiness Index (CRI) [24]. The levels of this index, and their interpretations, are illustrated in Figure 22. The CRI consists of six levels of readiness ranging from that which is applicable to a technology which is still a hypothetical commercial proposition through to that which is applicable to a technology considered as a bankable asset class. A full description of each of the six levels of the commercial readiness index shown in Figure 22 is given in Table 30.

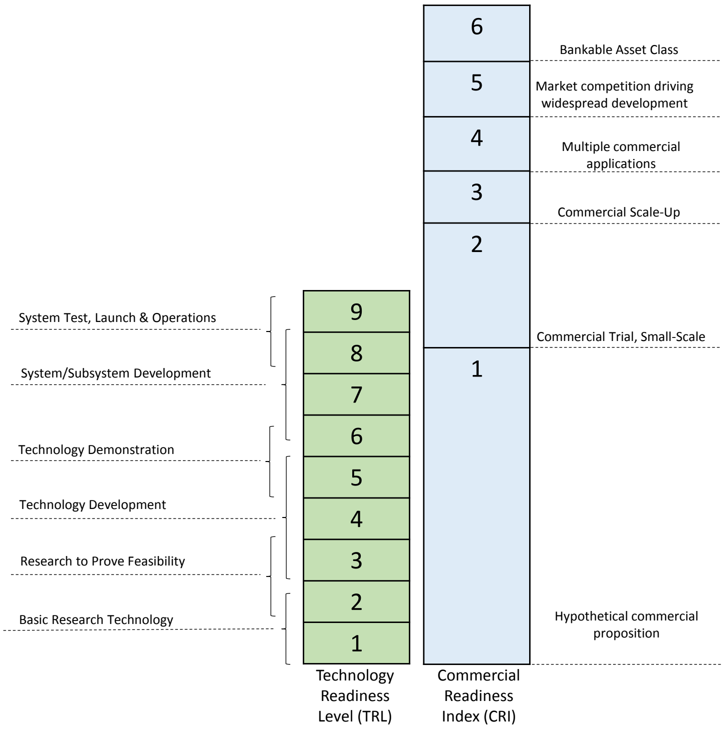

Figure 22: Relationship between Technology Readiness Level and Commercial Readiness Index [24]

Table 30: Description of CRI Levels 1-6 [24]

Status Summary Level	Description	Details
1	Hypothetical commercial proposition	Technically ready – commercially untested and unproven. Commercial proposition driven by technology advocates with little or no evidence of verifiable technical or financial data to substantiate claims
2	Commercial trial	Commercial trial: small-scale, first of a kind project. Commercial proposition backed by evidence of verifiable data typically not in the public domain
3	Commercial scale up	Commercial scale up occurring driven by specific policy and emerging debt finance. Commercial proposition being driven by technology proponents and market segment participants – publically discoverable data driving emerging interest from finance and regulatory sectors.
4	Multiple commercial applications	Multiple commercial applications becoming evident locally although still subsidised. Verifiable data on technical and financial performance in the public domain driving interest from variety of debt and equity sources however still requiring government support. Regulatory challenges being addressed in multiple jurisdictions
5	Market competition driving widespread deployment	Market competition driving widespread deployment in context of long term policy settings. Competition emerging across all areas of supply chain with commoditisation of key components and financial products occurring
6	'Bankable' grade asset class	Bankable grade asset class driven by same criteria as other mature energy technologies. Technology has known standards and performance expectations. Market and technology risks not driving investment decisions. Proponent capability, pricing and other typical market forces driving uptake.

The way in which the CRI relates to TRL is also shown in Figure 22. Even high-TRL concepts are still low-CRI concepts, i.e. even when much of the technology risk has been removed a high degree of commercial uncertainty surrounding the demonstration and deployment of that technology will remain. This is because TRL progression typically covers technology development whilst still a hypothetical commercial proposition and does not extend beyond the phases of small-scale trials [24]. Only on moving beyond the technology readiness levels does an asset class become bankable such that investment decisions are no longer driven by technology risks [38]. Nonetheless significant focus of a commercialisation risk assessment should be on early stage development of a technology to ensure that it is being developed, designed and validated in such a way that it will reduce in risk as development progresses. This will eventually enable it to satisfy the risk appetite of potential investors [39] and will also benefit the technology developers themselves, as the majority of costs of new product development are determined by decisions made at the start of the innovation process but incurred during commercialisation [37][11]. Hence an awareness of the implications of technology decisions for commercialisation at the early stages of a project will benefit the full process of innovation and development for multiple stakeholders.

The comparison of TRL and CRI given in Figure 22 shows that technologies at early stages of development typically correspond to a CRI of 1: even the most advanced floating wind concepts in development globally are at CRI 2 [38]. Consequently all technologies being evaluated within the LIFES50+ project are at CRI 1 (Figure 23) which means that this alone cannot be used as a measure of commercialisation risk to differentiate between participating technologies.

Instead, the general process of risk assessment outlined in Sections 1 and 2 has been combined with dimensions of commercial readiness derived from the CRI to arrive at a recommended process for quantifying the commercialisation risk of the floating substructure concepts being evaluated by the LIFES50+ project. This uses the eight dimensions used to judge commercial readiness as a basis also for quantifying commercialisation risk [24]:

[11] It has been reported that the cost of developing a floating wind concept from design to commercial deployment is up to £30 m [40].

- Regulatory Environment
- Stakeholder Acceptance
- Technical Performance
- Financial Performance – Costs
- Financial Proposition – Revenues
- Industry Supply Chain and Skills
- Market Opportunities
- Company Maturity.

These encompass the three key dimensions identified by [40][12] to achieve cost reduction potential for floating wind technologies and also the seven areas of commercialisation risk identified by [37][13].

	Final Score (CRI)	Regulatory Environment	Stakeholder Acceptance	Technical Performance	Financial Performance - Costs	Financial Proposition - Revenue	Industry Supply Chain and Skills	Market Opportunities	Company Maturity	Score
'Bankable' grade asset class										6
Market competition driving widespread deployment										5
Multiple commercial applications										4
Commercial scale up										3
Commercial trial										2
Hypothetical commercial proposition										1

LIFES50+

Figure 23: LIFES50+ Technology Concepts on CRI Scale

6.1 Uncertainty in Cost

Two of the eight dimensions of commercial readiness (technical performance and financial performance) will influence the Levelised Cost of Energy (LCoE) associated with the technology concept. Expressed simply, the LCoE for wind energy is the ratio of the present value of the full lifetime costs of the wind farm (including CAPEX, OPEX and decommissioning expenditure) to the present value of the net energy produced:

$$LCoE = \sum_{t=1}^{n} \frac{C_t + M_t + D_t}{(1+r)^t} \Bigg/ \sum_{t=1}^{n} \frac{E_t}{(1+r)^t}$$

where

n = the economic life of the system; C_t = Capital expenditure in year t; M_t = Operations & Maintenance expenditure in year t; D_t = decommissioning expenditure in year t; E_t = electricity generation in year t and r = discount rate.

The costs of building, operating and maintaining, and decommissioning the wind farm therefore influence the top line of this fraction, whilst the energy produced (affected by wind resource, turbine per-

[12] Namely a secure and stable regulatory framework, sufficient RD&D financing to support innovation and targeted RD&D programmes to overcome common industry challenges
[13] Namely the market need, market environment, technology, idea/value proposition, business environment, management and collaboration network

formance, availability, layout, etc.) affects the denominator. Costs will vary between substructure types depending on materials used, manufacturing methods and complexity of accessing the substructure for purposes of maintenance. Performance may also vary between substructure types depending on the way in which layout is affected by substructure and on any implications of maintenance scheduling for turbine availability.

A full assessment of levelised cost will be carried out for each of the four floating wind turbine substructure types as part of Work Package 2 of LIFES50+ via a bespoke calculation tool and a detailed assessment of the costs of development and operation. It should be noted, however, that over- or under- estimates in any of the quantities which are taken into account by this calculation, or incomplete knowledge of their likely values, will result in an uncertainty in the overall LCoE. Although this type of uncertainty is inevitable for emerging technologies, as discussed in Section 1.4, if it varies across technology types it is a useful measure (in amongst a suite of other measures) for informing technology choice.

As levelised cost is a numerical measure it lends itself well to a quantitative assessment of uncertainty. For LIFES50+ the uncertainty in LCoE will be used as one indicator of commercial risk (see Section 6.2 for a full list of proposed commercialisation indicators for floating substructure designs), with concept designers asked to identify the key drivers of cost or performance uncertainty and give indicative upper and lower limits on possible variations in these quantities for the floating wind turbine substructure types in question. These ranges will then be used to quantify overall uncertainty in LCoE, giving a measure of variation in cost to complement the central estimate of cost and to inform technology choice.

This approach is recommended even if assessing the commercial viability of a single concept.

6.2 Commercialisation Risk Identification

The process of commercialisation risk assessment should start with identification of possible commercialisation hazards or events and continue through to quantification of the likelihood and consequence of those events. As per risk assessment in other areas the end product can be a matrix of commercialisation risks which highlights those areas of commercialisation which are most risky for a given technology and which can be compared to the commercialisation risk matrix for competing substructure concepts.

Assessment of commercialisation risk should be seen as complementary to estimation of overall commercial readiness, and should extract detailed information relating to each of the dimensions of commercial readiness for each floating substructure concept. Key to this is identification of those areas which drive variation in commercialisation risk between competing technologies.

6.2.1 Hazard Identification

As per Section 1, commercialisation risks should be identified via a HAZID workshop or expert consultation. The aim of this is to specify those hazards relating to commercialisation of floating substructure technologies and to identify ways in which these can be mitigated, if possible. The hazard identification process for commercialisation risk in the case of LIFES50+ should focus on those aspects of risk that will drive choice between competing technology concepts. The key types of information that should inform the assessment of commercialisation risk include:

- Data on consenting of floating substructures and the risk around obtaining this, particularly relating to environmental consents and the way in which this may vary by technology concept.
- Technical data relating to turbine compatibility with substructure interface (this will affect both financial prospect and market outlook).
- An uncertainty assessment of the LCoE estimated for energy from turbines with floating substructures, and the key drivers of this uncertainty (accounting for both the potential range in cost estimates and the likely up- and down-side to forecast energy yield).
- Market forecasts or forecasts of the size of the offshore wind sector that can be accessed by floating substructures, and the proportion of this that could be accessed by different types of substructure design (whether spar buoy, semi-submersible or TLP)
- Policy forecasts relating to support for renewable energy technologies for the countries in which there is most scope for floating substructures to be deployed and for the countries in which the technologies are being developed.
- Business-specific data including details of financial backing and history of innovation for the technology developer in question.

An example of the categories of risk which should be considered in the hazard identification process is found at Table 31. The type of evidence that could be used to inform the risk assessment has also been identified. Note from this that the commercialisation risk assessment will draw on data provided from the technology, manufacturing and health, safety and environment risk assessments. Note also that as Task 6.5 of the LIFES50+ programme will examine three key components of commercialisation risk, namely environmental consenting requirements (sub-task 6.5.1), substructure turbine compatibility (sub-task 6.5.2) and commercial risk management (sub-task 6.5.3), the relevance of each proposed sub-category of commercialisation risk to be evaluated by the hazard identification procedure is matched accordingly. Those marked ‘All’ are those which are a dimension of commercialisation risk that will underpin commercialisation risk at a higher level than the sub-tasks are designed to assess.

The sub-categories of commercialisation risk outlined in Table 31 should be used as a framework for a commercialisation risk register. This will be a list of specific hazards that could arise in the commercialisation of floating substructures with a probability and consequence category assigned to each (see Table 32 for an example section of a commercialisation risk register). The definition of probability and consequence in this context is given in Sections 6.3 and 6.3.2.

Table 31: Example Categories of Risk for Commercialisation Risk Register

Dimension of Commercial Risk		Subcategory	Illustration/Issues to Consider for Commercialisation Risk Assessment	Example Data Sources/Evidence	Relation to LIFES50+ SubTasks
1	Regulatory Environment	Permitting process	Any special considerations in the permitting process for a substructure design of each type	Evidence of permitting requirements	6.5.1
		Certification	Any areas of risk identified by **Technology risk assessment** which are likely to affect or delay certification	Technology risk assessment – risk register & risk matrix	6.5.1
		Environmental consents	Any areas of **HSE risk assessment** identified where environmental impact requirements are unlikely to be met or additional work needed to meet environmental standards	Health and safety risk assessment – risk register relating to environmental hazards & positioning on risk matrix	6.5.1
2	Stakeholder Acceptance	'External' stakeholder acceptance	Political climate both globally and locally to the technology developer and likely support for renewable technology. Analysis of implication of this for far-shore offshore wind farms and backing for development of floating substructures		All
		'Internal' stakeholder acceptance	Company history of supporting innovations in floating substructure design or in other areas of innovation	Estimate of size of local market and ongoing political backing for innovation	All
		Warranty	Likely requirements of financial backers when providing project finance during construction phase to guarantee technical performance and integrity of substructure throughout lifetime (20 years)	Will be linked to technical performance (see below)	6.5.3
3	Technical Performance	Compatibility with turbines (current and next generation)	Flexibility/adaptability of substructure design to changes in turbine design & interface requirements	Engineering design demonstrating those aspects of the technology that would be replaced if turbine technology were to progress	6.5.2
		Compatibility with grid connections/array cabling	Degree of modification to array cable connections and substations to enable compatibility with substructure design	Engineering design data	6.5.2

		Warranty	Likelihood of being able to warrant substructure design for 20-year design life, based on engineering data and maturity of design.	Technology risk assessment and technical certification.	6.5.3
4	Financial Performance – Costs	Cost drivers of LCoE, and uncertainty on these	Range of uncertainty on cost estimates and resulting range of uncertainty on LCoE from energy produced from turbines with floating substructures	Range of uncertainty on cost estimates for **LCoE calculator** (WP2). This should include both Capex and Opex items and take into account the primary materials being used for the substructure and their price volatilities. This should also include costs associated with turbine design modifications required to make the substructure suitable and account for the return on investment required by financiers when backing an early-stage technology.	6.5.3
5	Financial Prospect – Revenue	Competition	Potential for substructure design to become redundant due to developments in competing technologies	Assessment of developments in all types of floating substructure [28], [40]–[42]	6.5.3
		Turbine compatibility	Degree of compatibility with larger turbine types (i.e. potential to increase energy yield and drive down LCoE)	Engineering data	6.5.3
		Site compatibility	Potential to access areas with increased wind resource (relating to flexibility in design)	Evidence of substructure adaptability from **Technical Risk Assessment.** Estimate of increase in wind speed that come with deeper waters relative to test sites – reference site conditions identified in WP1 and any available estimates of wind speed vs. depth in UK and EU waters.	6.5.3
6	Industry Supply Chain and Skills	Opportunities for serial manufacture	Any areas of risk around serial manufacture identified by **Manufacturing Risk Assessment**		6.5.3
		Availability of skills and expertise	Any areas of risk (e.g. relating to skills gap or lack of engineering capability in supply chain) identified by **Manufacturing Risk Assessment**	Link to share of floating substructure market accessible by technology type (see below)	6.5.3

7	Market Opportunities	Size of market for floating substructures	Estimated size of global market and long-term stability	Estimate of size of global market for floating wind, including site specific characteristics (water depths, distances from shore, wind speeds and wave heights) and ongoing support for innovation	6.5.3
			Estimated size of local market (market for floating substructures within the sovereign state of the technology developer)	Estimate of size of local market and ongoing political backing for innovation	6.5.3
		Share of total market which could be captured by substructure type in question	Suitability of substructure type to identified future market(s)	Linked to industry supply chain and skills (see above)	6.5.3
8	Company Maturity	Business model	Degree to which estimates of cost and revenue put forward by technology developer is supported by industry forecasts	Business models for substructures in question demonstrating estimates of cost and revenue for each given design, including ongoing costs of operation, has been seen and sense-checked against best estimates of costs for the floating offshore wind sector (for example [28], [40])	All
		Financial backing/company structure	Company history of developing innovations in offshore wind, limited access to support subsidies and limited or no history of securing funding for innovation projects	Company data	All
		History of innovation	Company history of commercializing innovations either in offshore wind or other areas of engineering	Company data	6.5.1
		Scale of company	Ability to deliver contract for foundations	Scale of balance sheet required to be able to undertake a contract and associated liabilities	6.5.1

Table 32: Example Commercialisation Risk Register

Dimension of Commercial Risk		Subcategory	(Example) Hazard	Probability	Consequence	Overall Risk Rating
1	Regulatory Environment	Certification	*The substructure design features new or novel elements which delay technology certification*			
4	Financial Performance - Costs	Drivers of LCoE	*Costs of key components are unknown and under-estimated in business plan, introducing uncertainty into financial prospect*			

6.3 Commercialisation Risk Analysis

6.3.1 Probability Scale

Each commercialisation hazard recorded in the risk register (see Table 32) should be placed on a 5-point probability scale. The suggested interpretation of this scale in the context of commercialisation risk assessment is given in Table 33. In this context the categories have a qualitative, rather than a quantitative, interpretation.

Table 33: Example Probability of Occurrence Scale for Commercialisation Risk Assessment

Probability of Occurrence of Harm

Scale	Category	Description
5	Very Likely	Almost certain to occur, happens frequently in wind energy, offshore or other related industry when developing new or innovative technologies
4	Likely	Likely to occur, happens often in wind energy, offshore or other related industry when developing new or innovative technologies
3	Probable	Probable to occur, heard of in wind energy, offshore or other related industry when developing new or innovative technologies, but does not happen often, credible scenario
2	Possible	Possible to occur, but not known in wind energy, offshore or other related industry when developing new or innovative technologies, foreseeable though would require multiple market failures
1	Unlikely	Unlikely to occur, never heard of in wind energy, offshore or other related industry when developing new or innovative technologies, very little credibility as scenario

The likelihood of all hazards recorded in the risk register can then be placed on this scale. For example, a hazard that '*The substructure design features new or novel elements which will delay technology certification*' may be considered likely, as the LIFES50+ project is focussed on innovative designs and so would be rated as a 4 according to the above scale. This will, of course, be substructure-specific and depend on the architecture of the design and may not be consistent across all technologies.

Similarly, the example hazard that '*Costs of key components are unknown and under-estimated in business plan, introducing uncertainty into financial prospect*' may also be likely given the early stage at which development of concepts sits. This will, however, very much depend on what the key components of the design are and the novelty of these, on how much historic data is available on costs, and on the level, detail and development of the business plan for the technology in question. That is, there is likely to be variation across proposed substructure technologies. If the concept is very novel and uses components in its design which are previously unproven then this would be 'Very Likely', and could be rated as a 5.

6.3.2 Consequence Scale

The general severity of harm scale (see Table 1) should be interpreted in the context of commercialisation hazards as per Table 34. In this context severity of harm is considered in terms of short term project delays and delay to full scale commercial deployment. Again using the example hazards from Table 32 it may be reasonable to consider delays due to technology certification as only moderate, and so this particular risk would be placed at a 2 on the consequence scale, i.e. it will delay commercialisation of the project but should not substantially impact on long term prospect. In comparison if cost under-estimates were particularly severe then severity of harm to financial prospect could also be severe, and ranked as a 3 on this scale.

Table 34: Example Consequence Categories for Commercialisation Risk Assessment

Severity of Harm

Scale	Category	Description (Commercialisation)
5	Extensive	Concept extremely unlikely to reach bankable asset class without major intervention (or, if no intervention is possible, harm would be catastrophic to commercial prospects). Should not proceed with development of technology concept until this has been addressed.
4	Major	Hazard could result in major delay (several years) to commercialisation or damage to commercial prospect/reputation of the technology concept. Immediate intervention needed to address this and reduce risk. Proceed only with risk mitigation plan in place.
3	Severe	Could result in severe (but manageable) delays to technology concept becoming a bankable asset class including damage to financial prospects. Proceed only with plan to address this risk in place.
2	Moderate	Moderate delays in bringing commodity to market or moderate impact on financial viability. Interventions can be used to mitigate delay and to enable earlier commercialisation but only if the benefit outweighs the cost.
1	Minor	Slight delays to full scale commercial deployment or achieving 'bankable asset class' status. Full commercial readiness likely to be achieved even without intervention. Any costs of intervention should outweigh benefit of earlier commercialisation.

6.4 Commercialisation Risk Evaluation

6.4.1 Commercialisation Risk Matrix

The categorisations of risk as low, medium and high developed for technology risk should also be used for the evaluation of commercialisation risk, when placed into the risk matrix format (Figure 24).

Consequence						
	5	M	M	H	H	H
	4	M	M	M	H	H
	3	L	M	M	M	H
	2	L	L	M	M	M
	1	L	L	L	M	M
L=Low, M=Medium, H=High		1	2	3	4	5
		Probability				

Figure 24: Commercialisation Risk Matrix

The example hazards would now be interpreted as per Table 35: probability score and consequence score are added to arrive at an overall risk score which falls into one of three categories (Low, Medium or High).

Table 35: Example Commercialisation Risk Register with Risk Ranking

Dimension of Commercial Risk		Subcategory	(Example) Hazard	Probability	Consequence	Score	Overall Risk Rating
1	Regulatory Environment	Certification	*The substructure design features new or novel elements which delay technology certification*	4	2	6	Medium
4	Financial Performance - Costs	Drivers of LCoE	*Costs of key components are unknown and under-estimated in business plan, introducing uncertainty into financial prospect*	5	3	8	High

Given the scope for external factors to influence commercialisation risk the actions to be taken to manage and mitigate these risks should take into account both the risk rating and the degree to which each risk is within the control of the project.

6.5 Commercialisation Risk Treatment

The appropriate treatment of commercialisation risk should be identified by dividing the risks identified by the process outlined in Sections 6.2 to 6.4 into three categories:

1. Those over which the project has some control, for which risk reduction measures can be enacted, and which will not change without direct intervention;
2. Those over which the project has some control but which is also expected to naturally reduce as the technology matures;
3. Those which are driven by external influences outside of the control of the project.

These three types, and the proposed level of treatment, are summarised in Table 36. If there is uncertainty over the category then the highest level appropriate (i.e. the level which implies most control) should be assigned and the associated risk reduction measures considered. If these are not practical then the risk should be moved to the lower category of control.

Table 36: Commercial Risk Categorisation and Treatment

Category of Commercialisation Risk	Description	Treatment
Controllable	Within the immediate control of the technology developer. Actions can be taken now to mitigate the risk. If no action is taken the risk will remain the same, or increase, by later stages of development. Not a risk that will naturally reduce over time.	Take action to reduce risk, based on Risk Scale and Action Matrix.
Reducing	A risk that should reduce over time as the technology matures. Some scope to control but some natural reduction also expected via progression through levels of technology maturity.	Assess and monitor risk over time, take action to reduce if periodic reductions are not observed.
Beyond Control of Project	Outside of the control of the project. A risk influenced by decisions taken by others, but with direct consequence for this technology.	Assess and monitor over time. Ensure risk is communicated and understood within the technology developer.

Table 37: Risk Scale and Actions for Commercialisation Risk

	Scale	Category	Description
Risk	8-10	High	Intolerable risk. Risk reduction is required. Do not proceed until risk has been addressed, or until it has been accepted that this is a high risk area but currently outside of the control of the project.
	5-7	Medium	Risk reduction may be required. Cost/Benefit analysis recommended. Eliminate hazard or introduce protective measures if possible. Only proceed with measures in place to mitigate risk, or if it has been accepted that this is a medium risk area but currently outside of the control of the project.
	2-5	Low	Level of risk is regarded as negligible. Advise as to whether risk can be reduced further with reasonably simple measures.

An example of a 'Controllable' risk could be turbine compatibility. If a substructure type was likely to be incompatible with most large-scale turbines then steps could be taken to reduce this risk via re-design and consultation with turbine manufacturers. This risk would not decrease otherwise.

The certification risk due to the use of new components, or the novel use of established components presented in Table 35, could also be considered controllable to a certain extent and so on an initial assessment would fall into the 'Controllable' category. If review of the design then indicated that there were no practical ways to reduce risk via the technologies being used this risk would be moved to 'Reducing', as technology maturity and the corresponding improvement in understanding and acceptance of the components used should result in an implicit risk reduction. The risk should be tracked over time to ensure that this is observed.

Similarly, assuming that work on quantifying the likely costs of novel components being used in the substructure design had already been done, then the example cost risk described in Table 35 would fall into the 'Reducing' category. Again it should be ensured that this risk is communicated within the technology developer and tracked over time. At the time of the commercialisation risk assessment this measure of risk would be fixed to 'High' and compared against the level of risk assigned to the same or similar hazards for other technology concepts.

Risks driven by external influences outside of the control of the project cannot be treated but should be recognised within the risk assessment process given their importance for commercial success. For example, the size of the potential market for a technology will be driven by some decisions made beyond the control or influence of a single technology developer. This type of risk should be included in the risk assessment and established as being relevant to the project, but recognised as being within limited control. The communication and understanding of such risks, rather than the actions directly taken to reduce them, is key.

6.6 Commercialisation Risk Summary

A commercialisation risk assessment procedure for evaluation of technology concepts participating in the LIFES50+ project has been developed based on the generic process of risk assessment recommended by international standard procedures. This is tailored to commercialisation of early stage technologies based on the concept of the Commercial Readiness Index (CRI) [43], whilst recognising that low-TRL concepts such as those being explored by LIFES50+ are likely to be at a similarly low point on this scale given the slow progression of technologies within CRI until a TRL of 8 or 9 is reached. Hence the standard dimensions of CRI have been used as a starting point for characterising commercialisation risk but split into additional subcategories which should drive the identification of commercialisation hazards and which should highlight the key differences between competing technology concepts when developing a commercialisation risk register. A suggested interpretation of probability and consequence scales for risks in the context of commercialisation is also provided and the ranking of risks and their placement on a commercialisation risk matrix has been demonstrated. A commercialisation risk matrix for each of the four competing technologies being developed within the LIFES50+ project should be derived in this way. Actions to treatment of each type of commercialisation risk should be taken whilst giving consideration to the degree of control that the technology developer has over each risk.

A simplified flowchart for the commercialisation risk assessment and management process, as set out in this section, is provided in Appendix D – Flowcharts.

Further suggested reading includes:

- *Commercial Readiness Index for Renewable Energy Sectors* by the Australian Renewable Energy Agency (ARENA) [24]. Provides an overview of the commercial readiness index, its dimensions, its relationship to technology readiness level, and a template for assessing the CRI of a developing technology.

7 Summary

This report provides an overview of risk management for deep water floating wind turbine substructures. It includes a description of a risk identification, analysis, evaluation and treatment process which can be applied to any floating wind substructure concept. The process utilises a number of standardised tools and references, including a risk register, risk impact and likelihood scales, and a risk matrix.

The methodology developed draws on good practice for risk assessment and risk management and is designed to be flexible enough to apply to different types of risk. This document deals with four categories of risk - technology risks, manufacturing risks, health, safety and environmental risks, and commercial risks. Each of these areas of risk is considered for all stages of the technology's lifecycle process - from design through to decommissioning. Although each of these types of risk has different dimensions or key indicators of risk to be measured, the principles of the risk assessment are the same for each. This is important as only the use of a consistent framework allows risks to be drawn together to form an understanding of overall risk.

- In the area of technology risk assessment, a functional composition analysis of floating wind technology has been used to develop a standard functional taxonomy. This taxonomy allows a structured review of specific concepts to identify the relative novelty of each functional element. Risk assessment is then focused on the novel elements of the technology.

- In health, safety and environmental (HSE) risk assessment, standard parts of the technology lifecycle have been set alongside standard types of HSE risk. These can be utilised to perform a structured assessment of HSE risks.

- In the area of manufacturing risk assessment, the concept of manufacturing readiness levels (MRLs) has been used to develop a structured framework for assessment of manufacturing risks (including socio-economic risks).

- To assess commercialisation risks, the concept of a commercial readiness index (CRI) has been employed to relate commercial and technology readiness levels (TRLs) and develop a structured approach to identifying and assessing commercialisation risks.

In the context of the LIFES50+, the methodology developed shall be used to produce deliverables 6.2 – 6.5 (*Risk assessment of the substructure*, *HAZID risk report for the specific HSE implications of the design*, *O&M risk register* and *Review of key commercial risks*). Additionally, the produced methodology will also form an integral part of deliverable 2.5 (*Global evaluation procedure including risks*) concerned with developing a truly representative Levelised Cost of Energy (LCoE) tool that accounts for the risks associated with the uncertainties related to floating wind substructures.

Finally, whilst the methodology for risk assessment was developed for the purpose of assessing four different floating wind substructure designs of the LIFES50+ project, the process is applicable to other new floating wind substructure designs and, in theory, other floating substructures outside wind energy.

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Appendix A – Terminology

The following terminology, mainly based on ISO Guide [8] but also based on DNV GL Recommended Practice [5] (marked with an asterisk) and Manufacturing Readiness Level (MRL) Deskbook [23] (marked with a double asterisk), has been adopted for the use in this report.

consequence	outcome of an event affecting objectives
control	measure that is modifying risk
failure*	termination of the ability of an item to perform a required function
failure mechanism*	the physical, chemical, temporal or other process that leads or has led to a failure
failure mode*	the observed manner of failure
hazard	source of potential harm
level of risk	magnitude of a risk or combination of risks expressed in terms of the combination of consequences and their likelihood
likelihood	chance of something happening
manufacturability**	the characteristics considered in the design cycle that focus on process capabilities, machine or facility flexibility, and the overall ability to consistently produce at the required level of cost and quality.
monitoring	continual checking, supervising, critically observing or determining the status in order to identify change from the performance level required or expected
probability	measure of the chance of occurrence expressed as a number between 0 and 1, where 0 is impossibility and 1 is absolute certainty
producibility**	the relative ease of producing an item that meets engineering, quality and affordability requirements.
residual risk	risk remaining after risk treatment
risk	effect of uncertainty on objectives
risk acceptance	informed decision to take a particular risk
risk analysis	process to comprehend the nature of risk and to determine the level of risk
risk appetite	amount and type of risk that an organisation is willing to pursue or retain
risk assessment	overall process of risk identification, risk analysis and risk evaluation
risk avoidance	informed decision not to be involved in, or to withdraw from, an activity in order not to be exposed to a particular risk
risk criteria	terms of reference against which the significance of a risk is evaluated
risk description	structured statement of risk usually containing four elements: sources, events, causes and consequences
risk evaluation	process of comparing the results of risk analysis with risk criteria to determine whether the risk and/or its magnitude is acceptable or tolerable
risk financing	form of risk treatment involving contingent arrangements for the provision of funds to meet or modify the financial consequences should they occur
risk identification	process of finding, recognising and describing risks
risk management	coordinated activities to direct and control an organisation with regard to risk
risk management process	systematic application of management policies, procedures and practises to the activities of communication, consulting, establish the context, and identifying, analysing, evaluating, treating, monitoring and reviewing risk
risk matrix	tool for ranking and displaying risks by defining ranges for consequence and likelihood
risk owner	person or entity with the accountability and authority to manage a risk
risk profile	description of any set of risks
risk sharing	form of risk treatment involving the agreed distribution of risk with other parties
risk register	record of information about identified risks
risk retention	acceptance of the potential benefit of gain, or burden of loss, for a particular

	risk
risk source	element which alone or in combination has the intrinsic potential to give rise to risk
risk tolerance	organisation's or stakeholder's readiness to bear the risk after risk treatment in order to achieve its objectives
risk treatment	process to modify risk
technology*	the scientific study and use of applied sciences, and the application of this to practical tasks in the industry
technology risk[14]	the effect of uncertainty on the application of scientific study and use of applied science to achieve its desired practical objective
uncertainty*	a state of having limited knowledge that makes it impossible to exactly describe the existing state of future outcome(s)

[14] Combination of ISO standards [1] and [3] and DNV GL definitions [5] and [6].

Appendix B – FMECA

Shown below is an example of a FMECA worksheet.

Table 38: FMECA worksheet example

FMECA process																											
												Initial score									Revised score						
No.	Function	Sub-function	Element	Hazard	Potential failure mode	Failure mechanisms	Root cause of failure	Effect(s) of failure	Life cycle phase	TRL	Novelty category	Probability	Consequence (local)	Consequence (global)	Consequence (economic)	Risk (local)	Risk (global)	Risk (economic)	Current controls	Action taken	Probability	Consequence (local)	Consequence (global)	Consequence (economic)	Risk (local)	Risk (global)	Risk (economic)
1																											
2																											
3																											
4																											
5																											
6																											
7																											
8																											
9																											
10																											
11																											
12																											
…																											

Appendix C – MRLs

The table below gives a full description for each MRL as given by the U.S. DoD [23].

Table 39: Full MRL Definitions [23]

MRL 1	**Basic Manufacturing Implications Identified** This is the lowest level of manufacturing readiness. The focus is to address manufacturing shortfalls and opportunities needed to achieve program objectives. Basic research (i.e., funded by budget activity) begins in the form of studies.
MRL 2	**Manufacturing Concepts Identified** This level is characterized by describing the application of new manufacturing concepts. Applied research translates basic research into solutions for broadly defined needs. Typically this level of readiness includes identification, paper studies and analysis of material and process approaches. An understanding of manufacturing feasibility and risk is emerging.
MRL 3	**Manufacturing Proof of Concept Developed** This level begins the validation of the manufacturing concepts through analytical or laboratory experiments. This level of readiness is typical of technologies in Applied Research and Advanced Development. Materials and/or processes have been characterized for manufacturability and availability but further evaluation and demonstration is required. Experimental hardware models have been developed in a laboratory environment that may possess limited functionality.
MRL 4	**Capability to produce the technology in a laboratory environment** Technologies should have matured to at least TRL 4. This level indicates that the technologies are ready for the Technology Development Phase of acquisition. At this point, required investments, such as manufacturing technology development, have been identified. Processes to ensure manufacturability, producibility, and quality are in place and are sufficient to produce technology demonstrators. Manufacturing risks have been identified for building prototypes and mitigation plans are in place. Target cost objectives have been established and manufacturing cost drivers have been identified. Producibility assessments of design concepts have been completed. Key design performance parameters have been identified as well as any special tooling, facilities, material handling and skills required.
MRL 5	**Capability to produce prototype components in a production relevant environment** Technologies should have matured to at least TRL 5. The industrial base has been assessed to identify potential manufacturing sources. A manufacturing strategy has been refined and integrated with the risk management plan. Identification of enabling/critical technologies and components is complete. Prototype materials, tooling and test equipment, as well as personnel skills have been demonstrated on components in a production relevant environment, but many manufacturing processes and procedures are still in development. Manufacturing technology development efforts have been initiated or are ongoing. Producibility assessments of key technologies and components are ongoing. A cost model has been constructed to assess projected manufacturing cost.
MRL 6	**Capability to produce a prototype system or subsystem in a production relevant environment** Technologies should have matured to at least TRL 6. It is normally seen as the level of manufacturing readiness that denotes acceptance of a preliminary system design. An initial manufacturing approach has been developed. The majority of manufacturing processes have been defined and characterized, but there are still significant engineering and/or design changes in the system itself. However, preliminary design has been completed and producibility assessments and trade studies of key technologies and components are complete. Prototype manufacturing processes and technologies, materials, tooling and test equipment, as well as personnel skills have been demonstrated on systems and/or subsystems in a production relevant environment. Cost, yield and rate analyses have been performed to assess how prototype data compare to target objectives, and the program has in place appropriate risk reduction to achieve cost requirements or establish a new baseline. This analysis should include design trades. Producibility considerations have shaped system development plans. The Industrial Capabilities Assessment has been completed.

	Long-lead and key supply chain elements have been identified.
MRL 7	**Capability to produce systems, subsystems, or components in a production representative environment** Technologies should be on a path to achieve TRL 7. System detailed design activity is nearing completion. Material specifications have been approved and materials are available to meet the planned pilot line build schedule. Manufacturing processes and procedures have been demonstrated in a production representative environment. Detailed producibility trade studies are completed and producibility enhancements and risk assessments are underway. The cost model has been updated with detailed designs, rolled up to system level, and tracked against allocated targets. Unit cost reduction efforts have been prioritized and are underway. Yield and rate analyses have been updated with production representative data. The supply chain and supplier quality assurance have been assessed and long-lead procurement plans are in place. Manufacturing plans and quality targets have been developed. Production tooling and test equipment design and development have been initiated.
MRL 8	**Pilot line capability demonstrated; Read to begin low rate initial production** Technologies should have matured to at least TRL 7. Detailed system design is complete and sufficiently stable to enter low rate production. All materials, manpower, tooling, test equipment and facilities are proven on pilot line and are available to meet the planned low rate production schedule. Manufacturing and quality processes and procedures have been proven in a pilot line environment and are under control and ready for low rate production. Known producibility risks pose no significant challenges for low rate production. Cost model and yield and rate analyses have been updated with pilot line results. Supplier qualification testing and first article inspection have been completed. The Industrial Capabilities Assessment has been completed and shows that the supply chain is established to support low rate initial production.
MRL 9	**Low rate production demonstrated; Capability in place to begin full rate production** Technologies should have matured to TRL 9. This level of readiness is normally associated with readiness for entry into Full Rate Production (FRP). All systems engineering/design requirements should have been met such that there are minimal system changes. Major system design features are stable and have been proven in test and evaluation. Materials, parts, manpower, tooling, test equipment and facilities are available to meet planned rate production schedules. Manufacturing process capability in a low rate production environment is at an appropriate quality level to meet design key characteristic tolerances. Production risk monitoring is ongoing. LRIP cost targets have been met, and learning curves have been analysed with actual data. The cost model has been developed for FRP environment and reflects the impact of continuous improvement.
MRL 10	**Full rate production demonstrated and lean production practices in place** This is the highest level of production readiness. Technologies should have matured to TRL 9. This level of manufacturing is normally associated with the Production or Sustainment phases of the acquisition life cycle. Engineering/design changes are few and generally limited to quality and cost improvements. System, components or items are in full rate production and meet all engineering, performance, quality and reliability requirements. Manufacturing process capability is at the appropriate quality level. All materials, tooling, inspection and test equipment, facilities and manpower are in place and have met full rate production requirements. Rate production unit costs meet goals, and funding is sufficient for production at required rates. Lean practices are well established and continuous process improvements are ongoing.

Appendix D – Flowcharts

Technology

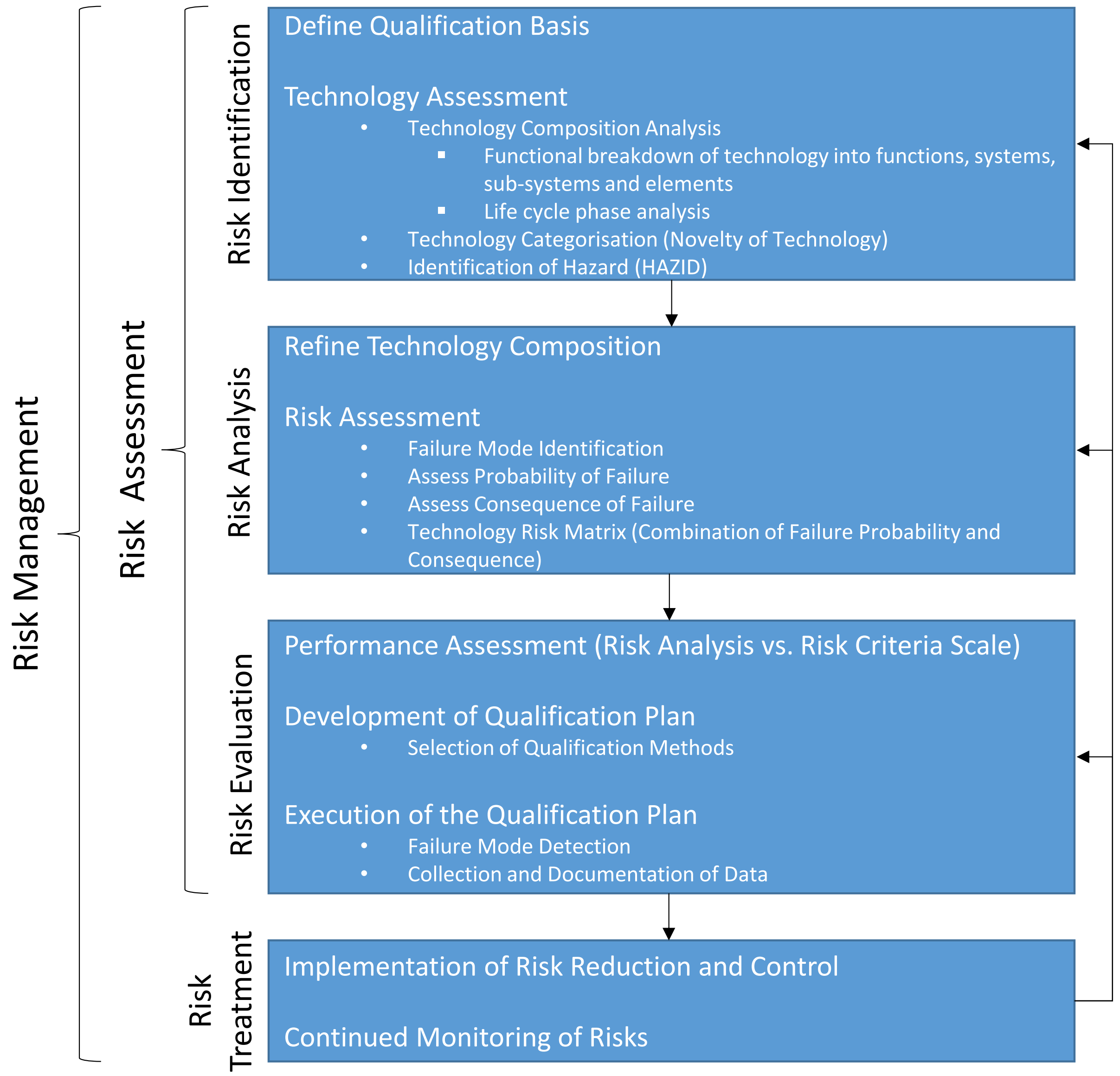

Figure 25: Technology Flowchart

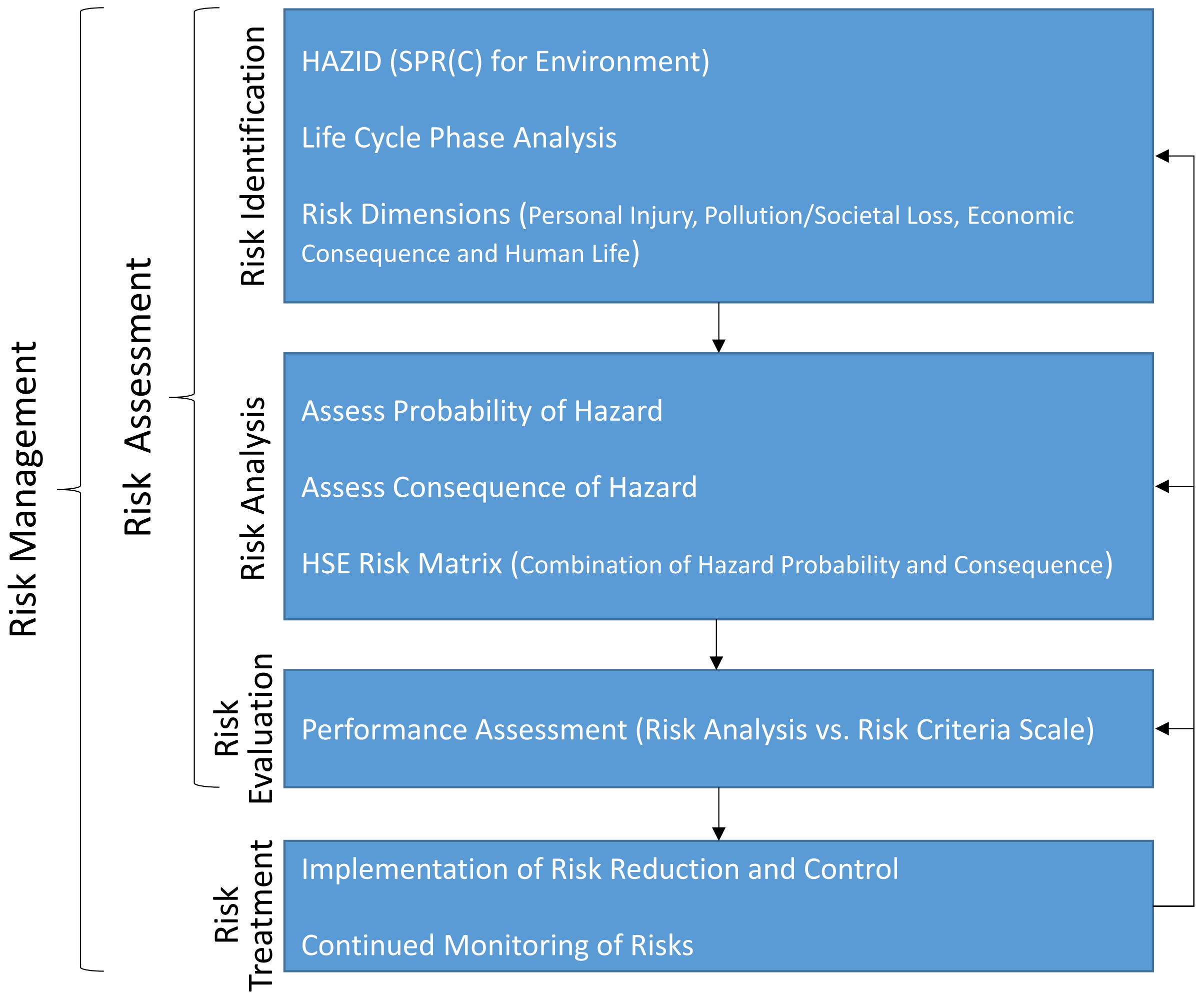

Figure 26: HSE Flowchart

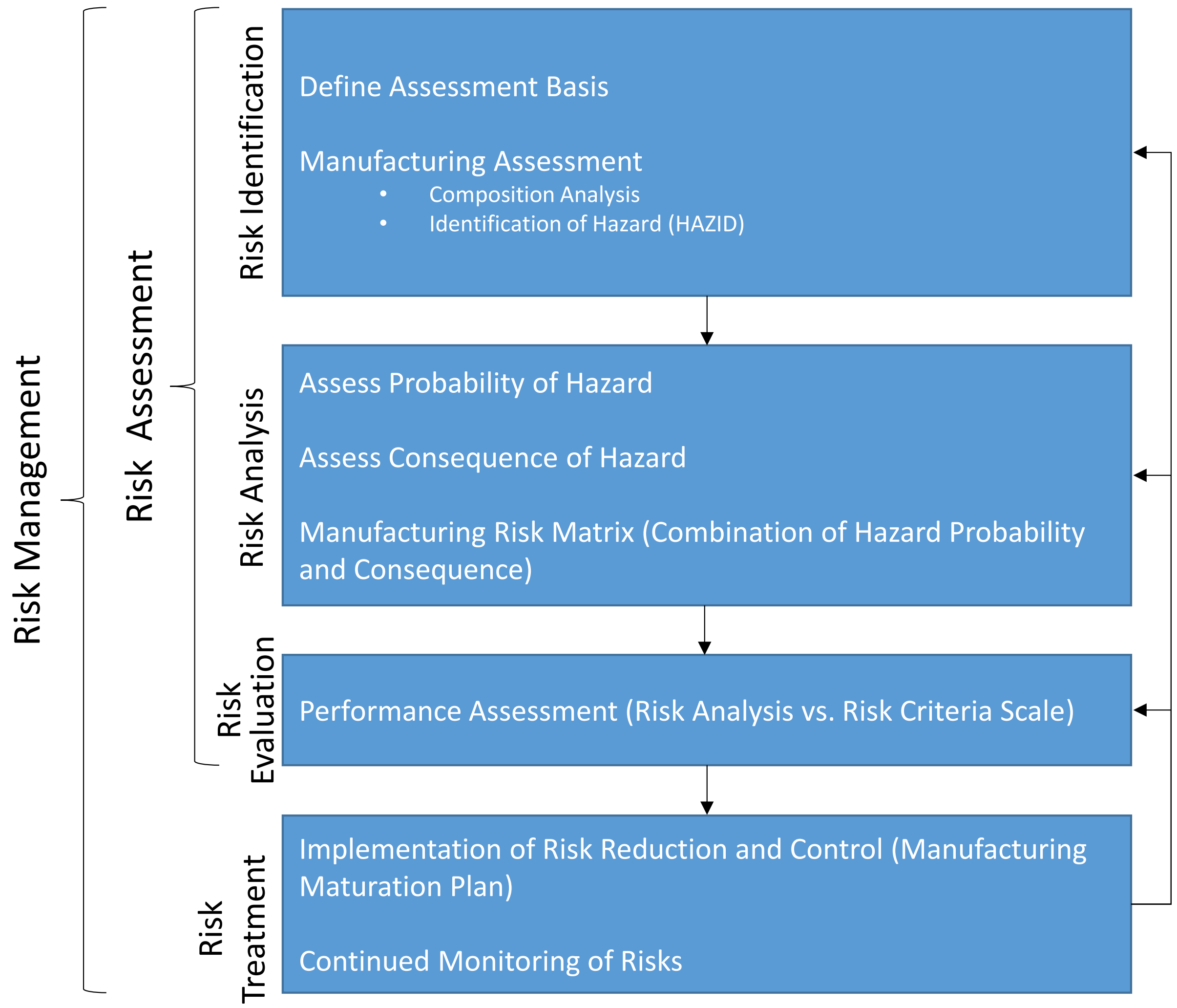

Figure 27: Manufacturing Flowchart

Commercialisation

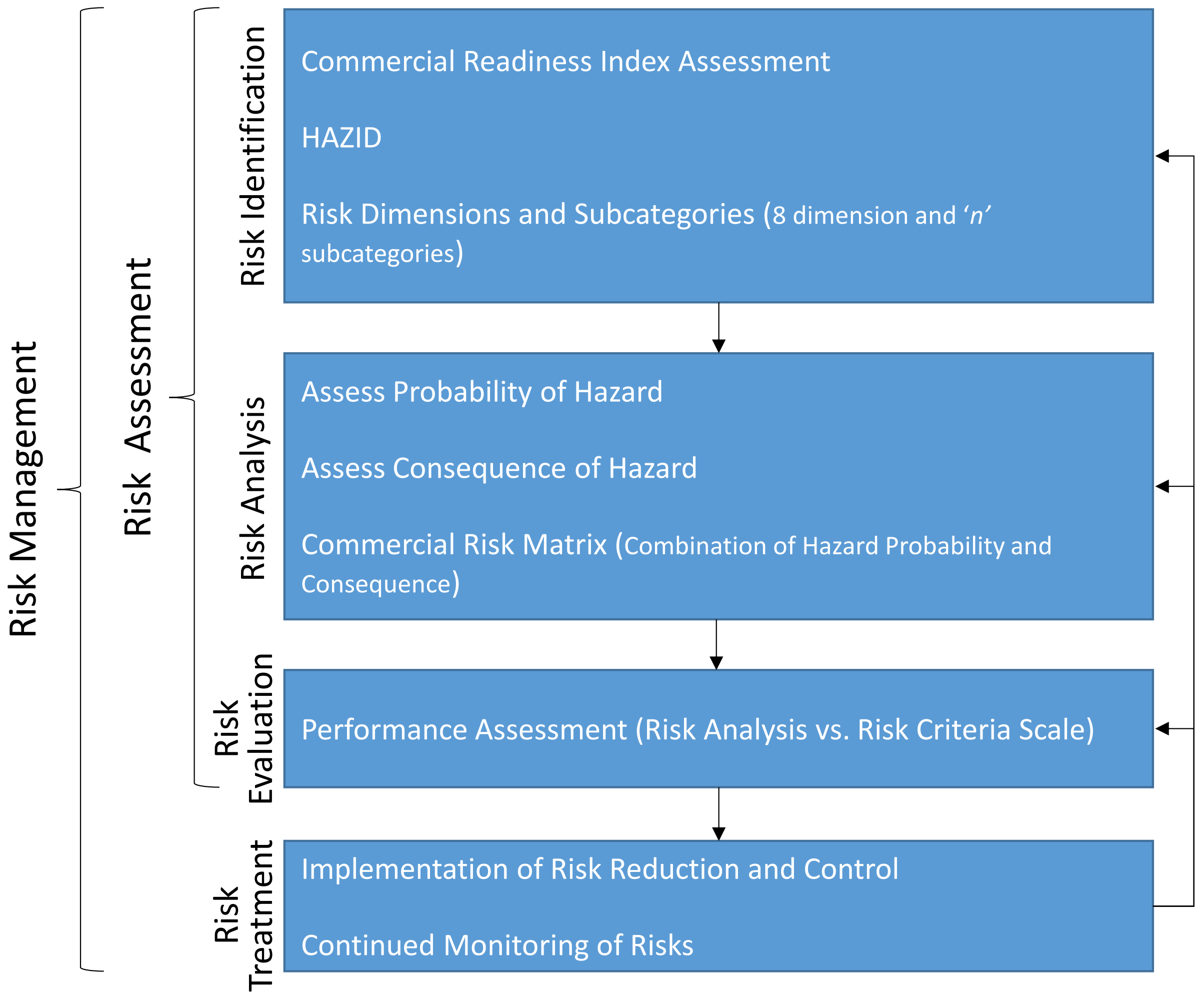

Figure 28: Commercialisation Flowchart