PivotBuoy

PivotBuoy

An Advanced System for Cost-effective and Reliable Mooring, Connection, Installation & Operation of Floating Wind

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D6.3: Final Reliability, Health & Safety and Environmental Assessment of the PivotBuoy system

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Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including Commission Services)	
CO	Confidential, only for members of the consortium (including Commission Services)	

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Issue Date	Version	Changes Made / Reason for this Issue
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31/03/2023	1.0	For information

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1 EXECUTIVE SUMMARY

This report is the third deliverable of Task 6.1 (Hazard and Reliability Aspects), Task 6.2 (Health & Safety Aspects) and Task 6.3 (Environmental Aspects). It presents the final version of the Failure Mode, Effects and Criticality Analysis (FMECA) and of the the HAZard IDentification (HAZID) of the PivotBuoy system. This report builds on the assessments reported in the deliverable D6.1 "Identification of failure modes and initial reliability, health & safety and environmental assessment of the PivotBuoy system" [Ref 1], which was issued in September 2019 (Project month 6) and deliverable D6.2 "Update of Reliability, Health & Safety and Environmental Assessment of the PivotBuoy system" [[Ref 2]], which was issued in June 2020 (Project month 15). This final report includes the results and feedback of the manufacturing, assembly, installation, testing and operational (up to turbine activation) phases in relation to the identified risks and hazards.

A general objective of Work Package 6 is to identify critical failure modes and de-risk the development of the PivotBuoy system. This is achieved by means of a continuous process of risk identification, evaluation and mitigation during the project lifecycle. Deliverable 6.1 presented an initial technology assessment and initial FMECA based on the design definition achieved during the first months of the PivotBuoy project. These initial assessments allowed the design team to focus their efforts on eliminating ('designing out') significant risks.

The FMECA has been updated frequently during the engineering phase as and when new design data has become available. Key milestones in this process have been the Detailed Design Reviews (DDR) during which the designs have been presented to and discussed amongst the broader PivotBuoy consortium team. In addition to these formal reviews, numerous FMECA sessions have been held with focus on a particular system component or sub-component. The responsible engineers for these components have contributed actively during these sessions.

A final FMECA session has been held in February 2023 (Project month 47) in the X1 Wind office to evaluate the identified risks based on experience gained during design, construction, installation and initial operation (up to turbine activation) and to define lessons learned with the X30 system for further concept development (X90 – X140). The final FMECA register is included in this report as an appendix. This FMECA register reflects the operational status as of mid-February 2023.

In addition to the FMECA, an initial HAZID of the offshore transportation and installation methodology was performed in conjunction with the DDR2 session. The hazards identified during this session have been addressed in the procedures that were developed and implemented for the transportation and installation of the anchoring system and the PivotBuoy floating system. Lessons-learned from these transportation and installation activities have been collected and were reviewed in conjunction with the final FMECA session in February 2023. Where appropriate, these lessons learned are also captured in the final FMECA register.

2 INTRODUCTION AND OVERVIEW

The *PivotBuoy Project: An Advanced System for Cost-effective and Reliable Mooring, Connection, Installation & Operation of Floating Wind* (referred to as PivotBuoy project) is a project that will develop a prototype of the "PivotBuoy" system to demonstrate its potential to reduce the Levelized Cost Of Energy (LCOE) of floating wind. The PivotBuoy is an innovative subsystem that aims to reduce the costs of mooring systems and floating platforms, that allows faster and cheaper installation and that supports a more reliable and sustainable operation. The system prototype has been installed at the PLOCAN test site (Gran Canaria) to validate the concept.

The objective for Work Package 6 (Risk Assessment including Reliability, Environment, Health & Safety) activities is to de-risk the system development by identifying critical failure modes and analysing system reliability. Due to the very limited application of floating wind systems world-wide, there is currently little data available in the public domain on risks and failure modes specifically relevant for floating offshore wind systems. However, there is a wealth of experience and data available from cross-cutting fields from other relevant sectors. Regarding the PivotBuoy subsystem and its components, experience from the oil & gas sector and in particular from design, installation and operation of Single Point Mooring (SPM) systems, Tension-Leg Platforms (TLP) and dynamic riser and cable systems have been applied to identify potential risks. This experience data includes relevant information on failure modes and events.

The work on Task 6.1 of Work Package 6 started during the preliminary design phase by performing a technology assessment for the concept system design following the technology qualification methodology described in DNVGL-RP-A203. This resulted in a technology categorization rating for each major component of the PivotBuoy system. Subsequently, an initial Failure Mode Effect and Criticality Analysis (FMECA) was performed to chart the probability of system and component failure modes against the severity of their consequences. Both the technology qualification assessment and the FMECA are tools to support the systematic identification and management of technical risks during a project. As stand-alone documents (registers) they have limited value. However, they are highly valuable when integrated into the overall design process where they can be utilized to assess a developing design in terms of technical risks on a continuous basis. The continuous feedback allows risks to be 'designed out' at an early stage, which is the most effective means of risk reduction and also the most cost-effective.

The initial FMECA findings for PivotBuoy were fed into the detailed design phase so that the identified risks could be addressed and mitigated to the extent practicable. This initial work is presented in deliverable D6.1 "Identification of failure modes and initial reliability, health & safety and environmental assessment of the PivotBuoy system" [Ref 1] which was issued in September 2019.

The second deliverable under Work Package 6 is D6.2 "Update of Reliability, Health & Safety and Environmental Assessment of the PivotBuoy system" [Ref 2], which was issued in June 2020. It documents the work performed to update, to maintain and to implement the results of reliability, health and safety and environmental risk assessment up to the point of near complete design (DDR 2) and initiation of manufacturing. The main vehicle for this effort continued to be the FMECA register, which has been maintained as a 'live' document throughout the design process; i.e. the risk assessment has developed in parallel with the design itself. This has been an interactive and iterative process whereby initial designs were assessed and associated risks were identified. Identified risks were then addressed in the design, and further rounds of FMECA sessions were held to review the status. Where justified, risk ratings were adjusted to reflect the mitigating actions taken, and new actions were assigned where appropriate.

Since the issue of deliverable D6.2, various minor design optimizations have been made while the purchase of materials and components started to allow inititation of the construction process (mainly at DEGIMA). A subsequent FMECA session was held in November 2022, to discuss some minor design changes and fabrication aspects, but the main focus was on risk reducing measures for the installation and operational phase. The final design as constructed is shown in Figure 1, the installed X30 at PLOCAN is shown in Figure 2.

A final FMECA session was held in February 2023 to evaluate the feed-back and lessons learned of the various development phases up to installation and commissioning (up to activation of turbine, turbine itself is not part of the scope of this risk assessment). Per identified risk in the FMECA table experience and lessons learned have been evaluated and where relevant comments included in the table in order to combine relevant outcome with risks as perceived at the start of the project. This provides valuable input for subsequent project phases and further system development (X90 – X140).

The FMECA method is most effective when applied early in the design process of an innovative project, i.e. it focuses risk reducing efforts where they have the most effect. Such early implementation was achieved for PivotBuoy, and development and update of the FMECA during the project design phase have been documented in [Ref 1] and [Ref 2]. Modifications to the system design since the issue of [Ref 2] have been relatively minor. The risk identification, ranking and risk reducing measures as documented in the FMECA were last revised in November 2020 (Project month 20) when reviews with the responsible engineers were conducted through multiple virtual meetings. Changes to the FMECA register since that time have focused on capturing experience from the fabrication, transportation, installation and initial operation and using this information to close each individual risk for the purpose of the PivotBuoy X30 system design. These latest developments since the issue of deliverable D6.2 have been documented in this deliverable D6.3.

The FMECA process has been a collaborative effort with input from the consortium members. Sessions have been held both as part of planned project meetings and as stand-alone meetings. The results of these sessions have been documented directly in the FMECA register.

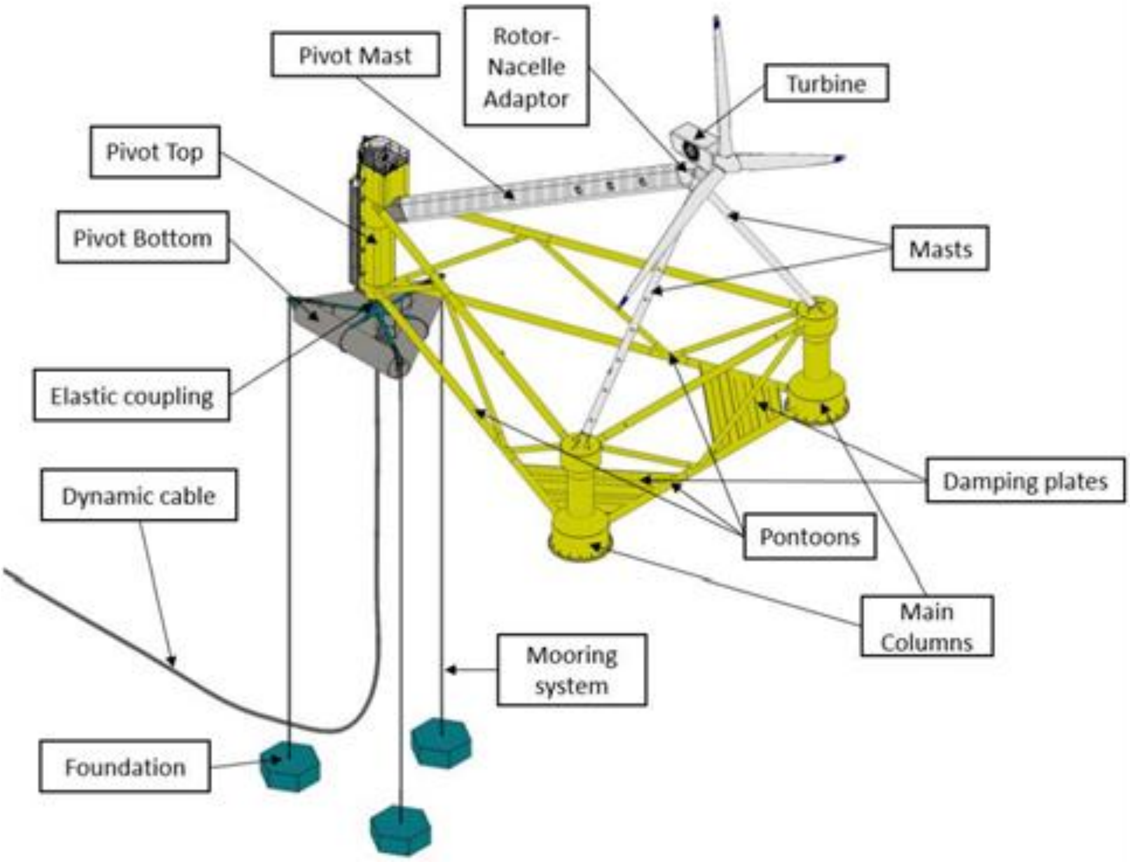

Figure 1. Final Design for Construction

Figure 2. Installed X30 (right front) near PLOCAN offshore platform (left)

Separately to the FMECA, a Hazard Identification (HAZID) review has been performed with focus on the installation methodology. This was done on 5 March 2020 in conjunction with the detailed design review and was attended by the consortium partners [[Ref 3]]. The purpose of the HAZID was to identify the risks associated with the transportation and installation of the PivotBuoy unit offshore Gran Canaria. A set of HAZID guidewords was used to stimulate the discussions and to ensure identification of typical risks. The HAZID register has served as input to the detailed installation procedures and was revisited during the review of these procedures.

The remainder of this report describes in further detail the background for the risk assessment approach taken and the results of the assessments performed.

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3 FMECA PROCESS

3.1 Purpose and method - general

To better prioritize the design development efforts, a method is required that not only categorizes the technology complexity but that also considers the consequences of component malfunction, to system performance and to the project in general. As described in D6.1 "*Identification of failure modes and initial reliability, health & safety and environmental assessment of the PivotBuoy system*" [Ref 1], the selected failure mode identification technique for PivotBuoy is the Failure Mode, Effects and Criticality Analysis (FMECA) as described in DNVGL-RP-A203.

The objective of an FMECA is to identify relevant failure modes with underlying failure mechanisms for the components of a physical system. The level of detail of the FMECA is therefore governed by the level of detail of the design. The output of the FMECA is a list of possible failure modes for each of the main components and sub-components of the PivotBuoy system and a quantification of the associated risks (risk being the combination of failure probability and consequence of failure). Subject matter experts identify the possible failure modes and their judgement is applied to assign probability and consequence values to each identified failure mode.

The entries in the FMECA register can be sorted in order of risk ranking (i.e. High to Low), and treatment of the highest risks can be given priority during the design process. As a design pogresses, the FMECA is updated by re-assessing the components and adding entries to the register to reflect the latest design details. Good practice dictates that entries are never fully deleted from the register so that traceability is maintained.

3.2 System components and sub-components

The main component breakdown applied for the FMECA has developed over time, which reflects the progression of the design. The final component and sub-component definitions are listed below. These have not changed since FMECA update documented in deliverable D6.2.

The nacelle / turbine is not included here as a component since it is not part of the project scope. This part of the structure has been purchased as fully functional (re-cycled) component and is not part of the scope of this risk identification process.

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Main Component	Sub- components
Foundation	Structure - main
	Structure - tether interfaces
	Seabed interface
	Scour protection
Mooring	Upper tether joints
	Tendons (tethers)
	Lower tether joints
Pivot Bottom	Structure - main
	Structure - tether interfaces
Yaw System	Bearing arrangement
	Elastomeric mount / coupling
	Rubbers
	Steel components
	Studbolts
Pivot Top	Structure - main
	Center shaft
	Deckhouse / technical room
	Upper deck
	Boat landing
Pontoons & Masts	Super-structure - pontoons - wetted
	Super-structure - masts - dry
	Rotor-Nacelle-Adapter (RNA)
	Walkway thru PivotMast
	Heave damping plates
Main Columns	Ballast compartments
	Filling pump
	De-ballasting pump
	Piping
	Sensors
	Control unit
	Vent
Electrical Power	Cable - RNA-buoy - dry
	Electrical transfer unit
	Riser system - wet
	Cable on seabed
	Power end location
Utilities	Control room
	Lightning protection
	Power
	Nav lights & signal
	Safety (fire)
	SCADA

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3.3 Risk categories

The risk category, as combination of probability and consequence, is assigned following the guidelines given in DNVGL-SE-0422

The probability class assignment is done based on the values given in Table 1.

Table 1: Probability classes

Class	Name	Description	Reference
1	Very low	Negligible event frequency	Accidental
2	Low	Event unlikely to occur	Strength / ULS
3	Medium	Event rarely expected to occur	Fatigue / FLS
4	High	One or several events expected to occur during the lifetime	Operation low frequency
5	Very high	One or several events expected to occur each year	Operation high frequency

The consequence classes are as defined in Table 2.

Table 2: Consequence classes (floating turbine or component)

Class	Description of consequences (impact on)				
	Safety	Environment	Operation	Assets	Cost (€)
1	Negligible injury or health effects	Negligible pollution or no effect on environment	Negligible effect on production (hours)	Negligible	1k
2	Minor injuries or health effects	Minor pollution / slight effect on environment (minimum disruption on marine life)	Partial loss of performance (retrieval not required outside maintenance interval)	Repairable within maintenance interval	10k
3	Moderate injuries or health effects	Limited levels of pollution, manageable / moderate effect on environment	Loss of performance requiring retrieval outside maintenance interval	Repairable outside maintenance interval	100k
4	Significant injuries	Moderate pollution, with some cleanup costs / Serious effect on environment	Total loss of production up to 1 m (€)	Significant but repairable outside maintenance interval	1m

The combination of probability and consequences results in a risk ranking as shown in Table 3. In general, actions required to close a specific entry in the FMECA register depend on the risk ranking, as follows :

- Low risk : Tolerable, no action required
- Medium risk : Mitigation and improvement to be considered to reduce risk
- High risk : Not acceptable, mitigation and improvement required to reduce risk

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Table 3: Risk Ranking

	Consequence				
Probability	1	2	3	4	5
5	Low	Med	High	High	High
4	Low	Med	Med	High	High
3	Low	Low	Med	Med	High
2	Low	Low	Low	Med	Med
1	Low	Low	Low	Low	Med

3.4 FMECA Update Process

As reported in deliverable D6.1 [Ref 1], the FMECA process for PivotBuoy started with the preparation by INTECSEA of an initial register, which then formed the basis for the the first plenary session involving the other consortium members. This plenary session took place in Barcelona on the 17th and 18th of July 2019, and the results of this session were used to populate and to update the FMECA register. The first formal issue of the FMECA register was as an appendix to deliverable D6.1.

Since its first formal issue, the FMECA register has been maintained as a 'live' document. This means that updates were made to the register as and when new design information became available. Furthermore, focused sessions have been held to assess in greater detail specific components of the PivotBuoy system. These sessions typically have comprised a presentation of the design by the responsible lead engineer followed by FMECA assessment facilitated and scribed by INTECSEA.

The status after (near) completion of design is reported in deliverable D6.2 [[Ref 2]]. Since then two more FMECA sessions have been held. The first, which took place through a series of virtual meetings in November 2020, addressing minor design updates and installation and operation risks. This resulted in mitigating measures related to surveys, installation procedures, testing, etc. Many of the FMECA entries were deemed closed after this update. A final session was held in February 2023 in Barcelona to evaluate all entries in the FMECA table, close out the last remaining open items, discuss lessons learned and document the process in the comment column of the FMECA to obtain a document that can be of value for the next phase of the PivotBuoy system development. Where the comment column in the FMECA table mentions observations concerning installation or operation, these are further detailed in the documentation of the system in-situ survey performed in January 2023 [[Ref 4]].

The general timeline leading up to this report has been:

Dates	**FMECA Update Activity**
June 2020	Issue of deliverable D6.2
25 November 2020	Focused FMECA session (on-line meetings) on remaining design aspects, installation and operational aspects *In attendance: X1Wind, DNVGL and INTECSEA*
November - December 2020	Desktop update based on input latest on-line session, intermediate (informal) issue to Consortium partners

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Dates	FMECA Update Activity
15 February 2023	Focused FMECA session in Barcelona on entire system, experience with operational system and lessons learned for subsequent system development phases *In attendance: X1Wind, DNVGL and INTECSEA*
February - March 2023	Desktop finalization of FMECA, prepare final deliverable D6.3 (this document)
March 2023	Issue D6.3

During November and December 2020, the focus of the FMECA process has progressed from identification of failure modes and mitigation of design risks to the documentation of actions taken to mitigate the construction, installation and operational risks for each entry in the register. For most FMECA entries, actions to be taken were noted when the entry was first made; however, the development of the project meant that some of these actions became obsolete and new actions had to be added to reflect the latest design.

Various standard mitigative actions (e.g. implementation of quality control and development of detailed procedures) were seen to reappear for each main component, so a decision was taken to label these as 'general actions'. These general actions have been copied to a separate register so that actions taken can be recorded.

The responsibility for implementing mitigative actions for a system component is primarily with the responsible lead engineer for that component. The update of the FMECA register, to show the actions taken, therefore has been done largely by the lead engineers themselves as a desktop exercise.

3.5 Treatment of High Risk Findings

All entries in the FMECA register that were initially scored as High risk (see Table 3) were re-assessed to determine whether the mitigative actions taken (or to be taken) are sufficient to reduce the risk rating to Medium or Low. This is further discussed below. Entries that were initially rated Medium or Low risk have not been re-scored; however, mitigative actions have been identified for these, and actual actions taken have been recorded in the register. Also valuable lessons learned related to Medium or Low risk are identified in the FMECA table and in this document (see Section 3.7)

3.6 FMECA findings

The final FMECA register is included as Appendix A to this report. All actions are closed. It contains a total of 336 entries, this is including 41 entries that have been set to 'inactive' (indicated by gray color shading); primarily due to changes in the design that have made them irrelevant for the PivotBuoy X30 system. This leaves 295 'active' entries remaining in the register. Note that the inactive entries are maintained visible in the FMECA register since they may be relevant for future designs (i.e. X90 – X140).

The following figures present the number and type of FMECA findings :

- Figure 3 summarizes the findings as per September 2019 at the time of issue of deliverable D6.1 [Ref 1].
- Figure 4 summarizes the findings as per June 2020, that is at the time of issue of deliverable D6.2 [[Ref 2]], based on the unmitigated risk
- Figure 5 summarizes the findings based on the mitigated risk (for entries originally designated as High risk, High risks that are no longer 'active' are in the mitigated risk table arbitrarily set at consequence 1 and probability 1 to keep the total numbers consistent).

In each figure the risk categories are color-coded : low=green, medium=yellow, and high=red.

Number of occurences total risks 278

Increase in consequence →

Increase in prob ↓

Conseq	1	2	3	4	5	total
Prob						
1	-	-	11	27	10	48
2	-	2	12	110	51	175
3	-	3	4	33	11	51
4	-	-	-	4	-	4
5	-	-	-	-	-	0
total	0	5	27	174	72	

Figure 3. Summary of FMECA findings – as per Ref 1 (September 2019, M6)

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Number of occurences — total risks 336

Increase in consequence →

Conseq / Prob (↓ Increase in prob)	1	2	3	4	5	total
1	-	-	11	21	15	47
2	-	6	17	131	64	218
3	-	2	11	42	10	65
4	-	-	2	4	-	6
5	-	-	-	-	-	0
total	0	8	41	198	89	

Figure 4. Summary of FMECA findings – Unmitigated Risk - as per Ref 2 (June 2020, M15)

Number of occurences — total risks 336

Increase in consequence →

Conseq / Prob (↓ Increase in prob)	1	2	3	4	5	total
1	1	-	11	22	15	49
2	-	6	17	135	71	229
3	-	2	11	43	-	56
4	-	-	2	-	-	2
5	-	-	-	-	-	0
total	1	8	41	200	86	

Figure 5. Summary of FMECA findings – Mitigated Risk – as per Ref 2 (June 2020, M15)

The above figures show that the FMECA process has successfully reduced the number of high risk entries. By looking in detail at the mitigative actions taken for each entry (ref Appendix A), it is also evident that the FMECA process has contributed to achieving a more robust, lower risk design overall.

During this final phase, between the issue of deliverables D6.2 and D6.3, no new risks have been added and no re-scoring has taken place. The intention of the FMECA process is to identify risks at the start of an innovative project such that the highest risks can be given priority during the design process. Adding risks or re-evaluating scores in hindsight has no added value in the FMECA process. The intention of this last step is rather to compare project outcome against identified risks at the start of the project. To identify significant outcomes of the completed FMECA process that can be of value for subsequent phases (development of X90 – X140).

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3.7 FMECA findings in relation to lessons learned

When evaluating the entries in the FMECA, it is recognized that the probability of occurrence is relative. Even events categorized with probability 'high' are not necessarily expected to occur, especially given the limited operational time of the X30 system. Rather, it is considered of interest to evaluate significant project outcomes and experience against the identified failure modes, the perceived risks and the affect and adequacy of the implemented mitigating measures.

From Table 3 it can be concluded that risks with probability 3 to 5 can lead to High risks. As shown in Figure 4, no failure modes with probability 5, and a total of 6 failure modes with probabililty 4 were identified in the unmitigated risk table. Of these 6 failure modes, 4 were resulting in a High risk and 2 in Medium risk. None of these failure modes have occurred to date.

When looking at all high risk failure modes (the above 6, plus 10 failure modes with probability 3 and consequence 5, a total of 16 failure modes), they are all related to structural strength or fatigue failure or functional failure of the slip ring assembly. None of these failure modes have occurred to date .

Most relevant mitigating measures applied related to these failure modes include:

- Separate pad-eyes / connection points on the concrete foundation blocks for handling and transportation on one hand and for use during operation on the other hand, which is considered a robust risk reducing measure.
- Specification of better quality pumps for (de-)ballasting which is an essential control tool during installation, operation and decommissioning.

These are considered valuable measures to be considered for subsequent development phases.

Based on Figure 4, a total of 238 active Medium risks were identified. The remedial actions applied and/or the lessons learned that are associated with these Medium ranked risks include:

- Sheathed tethers, and well defined and executed tether handling procedures can reduce risks and extend functional life of tethers.
- Limit the number of (auxilliary installation) lines connected to the foundation blocks to avoid tangling during handling, transport and installation, separate connection points for installation and operational phase reduces risks by providing redundancy. Having additional connection points also reduces risk during removal of the blocks at the time of system decommissioning and removal.
- Ballast tank design can be improved, this will result in better control during installation and operation and ensures functionality during decommissioning, this includes internal baffles to reduce free-surface effect, marking and means to ensure full removal of water (low point) or alternatively use of nitrogen or biocides to mitigate the risk of internal corrosion / degradation.
- Coating / paint quality and QA/QC of application, also consider the pre-operational phase in wall thickness corrosion allowance or in specifying when to apply the coating (immediately after manufacturing, before transport).
- Type and use of bend restrictors installed onto the cable beneath the Pivot Bottom, not all types are adequate for dynamic offshore applications, position along the cable determines its functionality.

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- Consider functionality of added fairings and “sail” to reduce fibration due to direct wind load and improve weather-vaning under wind load.
- Good ventilation in closed spaces is of great importance for workability.
- Maintenance and / or replacement of some components is required for longer operational lifetime, such as topsides davit and winch cable.
- QA/QC and testing of manufactured components.

Finally, also for what were considered Low risks failure modes at the start of the project, some valuable lessons were learned that are worth considering in the subsequent development phases, these are:

- Use of ultra-short baseline (USBL) beacons on the foundation blocks connected to an industry standard differential global positioning system (DGPS) or real-time kinematic global positioning system (RTK) for accurate placement.
- Operational status of ballasting components such as access points and fittings later in life, such as during decommissioning and removal, also after years of in-activity.

3.8 Decommissioning

At the time of decommissioning, the most significant failure modes threatening system integrity and the load bearing capacity of the structure will be degradation due to accumulated fatigue damage and/or corrosion. In order to limit the risks during decommissioning and removal of the system, essential remedial actions during the lifetime are inspection, maintenance and repair or replacement of components observed to have deteriorated. The risk for the X30 system is considered low due to the intensive monitoring of the pilot system performance and the relative short operational life. However, for subsequent development phases this step in the system lifetime cycle is something to be given due consideration already in the design phase. The end of life system integrity and performance, and thus the feasibility of safe removal of the system is to a large extent determined by the ballast system, tethers and anchors. During the development of the subsequent development steps of the PivotBuoy system (X90 – X140), due consideration should be given to the design lifetime, inspection, maintenance and repair procedures of these systems. Good offshore industry practice for ensuring load-bearing capacity upon removal is to assume extended design life for key lifting and handling components (e.g. pad-eyes, access points) beyond the general design life of the overall operational system. This typically translates to additional corrosion allowance, additional cathodic protection and/or selection of specialized materials or coatings for key lifting and handling points. It may also require consideration of means for future refurbishment or replacement of such components.

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4 HEALTH, SAFETY & ENVIRONMENT

4.1 General

Both Health & Safety (H&S) and environmental aspects have been considered when developing the FMECA.

In general, it is a principal objective of the project to ensure that the design of the PivotBuoy facilities complies with applicable safety, health, working environment and environmental requirements. This applies during all phases of the project execution: from design through to installation and offshore operations. In addition, the ALARP principle will apply, meaning the risk will be reduced to "as low as reasonably practicable".

Ensuring a compliant design, has been achieved through implementation of the following design considerations:

- Identifying risks early in the design process so that they can be managed. This is being done on PivotBuoy through the risk assessment activities described in this report.
- Apply 'Inherently Safe' design principles. This means that, where practicable, decisions are taken to 'design out' the identified risks. Passive solutions that reduce the probability component of a risk are preferred over active solutions that mitigate the consequence component of a risk. In other words, it is better to prevent an undesirable event altogether than to try to manage the consequences of such event once it has occurred. The FMECA register includes numerous examples of risks that have been effectively designed out.
- Minimizing the potential environmental impact during all phases of the project by considering environmental aspects.
- Maximizing the benefits of protection measures; both environmental and safety-related. This means selecting protection measures that are cost-effective, robust and practical to implement.

4.2 Health & Safety Aspects - HAZID

While an FMECA includes assessment of risk to personnel in the event of a component failure, it is not the best tool for assessing the direct risk to personnel (and environment) as a result of activities; e.g. activities required to transport and to install the PivotBuoy unit.

Risk to personnel during transportation and construction activities is better assessed and managed through Hazard Identification (HAZID) and Hazard & Operability Review (HAZOP). The former can be applied at a high level before detailed plans and procedures are in place, while the latter is best suited for assessment of detailed procedures and work plans.

In conjunction with the second Detailed Design review session held in March 2020 in Barcelona, INTECSEA facilitated a HAZID session centered around the draft general PivotBuoy transportation and installation methodology [[Ref 3]]. In general, the objectives of a HAZID are to identify main hazards, to review the effectiveness of selected safety measures and, where required, to expand the safety measures in order to achieve a tolerable residual risk. Given the status of the installation methodology at the time of the session, the main focus of the HAZID was on the first of the aforementioned objectives.

In advance of the HAZID session, INTECSEA prepared a list of guidewords (see Appendix B). These guidewords serve to trigger the participants to consider various potential hazard sources and thereby to propose specific hazard events. During the HAZID session, the responsible lead engineer for the installation methodology presented each of the main transportation and installation activities, and the attendees discussed specific relevant hazard events. These were recorded in the HAZID register (see Appendix C) and proposals were made on how to address the hazards. A total of 84 hazard scenarios were identified during the plenary session.

The HAZID register was used as input to the development of the detailed transportation and installation procedures. These procedures were subsequently reviewed to confirm that adequate risk reducing measures had been implemented based on the hazard scenarios.

4.3 Environmental Aspects

Risks to the environment were considered during the initial risk assessment activities; however, the technology assessment and FMECA processes (being based on review at the component level), do not always identify all relevant environmental risks. A separate desk-top exercise has therefore been conducted with the specific objective to identify environmental risks during the three main phases of the project offshore; namely, installation phase, operating phase and removal phase.

The identified risks for each of these phases are listed below. These risks have been considered during the design process. Furthermore, environmental assessments have been performed as part of project Task 6.3, lead by PLOCAN, and where applicable the findings included in deliverables D6.2 and D6.3 as updates of subject report.

Environmental Impact Risks during Installation Phase:

- Potential for spills (e.g. fuels or hydraulic fluid) from installation or tug vessels, or installation equipment
- Above-water noise emissions from installation or tug vessels exceeding established limits
- Below-water noise emissions from installation or tug vessels, including the installation of the mooring system (anchor, cables, etc.), exceeding established limits
- CO_2 and NOx emissions from installation or tug vessels and installation equipment exceeding established limits
- Disturbance of the seabed sediments and benthic communities (for example during placement of gravity based structures or cables)

Environmental Impact Risks during Operationing Phase:

- Potential for spills (e.g. bearing lubricant) from PivotBuoy system
- Potential for spills from operational support vessel
- Above-water noise emissions from turbine exceeding established limits

- Below-water noise emissions (vibrations) from turbine and mooring system exceeding established limits
- Above-water noise emissions from operational support vessel exceeding established limits
- Below-water noise emissions (vibrations) from operational support vessel exceeding established limits
- CO_2 and NOx emissions from operational support vessel exceeding established limits
- Harm to aquatic fauna (fish, cetaceans, turtles, etc)
- Harm to bird life
- Disturbance of the water quality parameters, exceeding established limits
- Interaction with other users of the marine space (fishing, shipping, etc.)

Environmental Impact Risks during Removal Phase:

- Potential for spills (e.g. fuels or hydraulic fluid) from marine vessels or equipment
- Above-water noise emissions from marine vessels exceeding established limits
- Below-water noise emissions from marine vessels, including the decommissioning of the mooring system (anchor, cables, etc.), exceeding established limits
- CO_2 and NOx emissions from marine vessels and equipment exceeding established limits
- Disturbance of the seabed sediments and benthic communities (for example during removal of gravity based structures or cables)

It is worthy to note that an Environmental Impact Assessment has been outsourced by PLOCAN to fulfill the requirement stipulated by the Law to manage the electrical consenting of national administration. Taking advantage of this document, these risks have been reviewed and updated.

5 CONCLUSIONS AND WAY FORWARD

This report presents the final hazard identification and potential failure modes, reliability and health and safety and environmental assessment of the PivotBuoy system. The Failure Mode, Effects and Criticality Analysis (FMECA) process has been the primary vehicle for this assessment. In addition, the HAZard IDentification (HAZID) process has been used to assess risk for transportation and installation activities.

After the initial issue of the FMECA register [[Ref 1]], significant effort has been made to expand and to update the register to reflect the latest design status. More importantly, the findings of the FMECA process have continually been fed back into the design so that risks could be assessed. This iterative, interactive process has resulted in a design for the PivotBuoy system that is more robust and with lower risk. A significant number of risks identified through the FMECA process have been successfully "designed out" (i.e. eliminated), and most risks initially characterized as 'High' have been mitigated such that the residual risk is Low or Medium.

The FMECA register included in this report provides the final version including feedback and lessons learned from the full PivotBuoy pilot system development up to operation (just before turbine activation) as per mid-February 2023. All of the 295 active entries in the register are considered closed (i.e. the actions identified to address the risk have been implemented). This final product is considered of value for the future further development of subsequent Pivot Buoy systems (X90 – X140). It is therefore recommended that the X90 development team takes notice of the final FMECA and implements lessons learned and recommendations for improvement in the design, specifications and procedures.

This project has received funding from the European Union's Horizon H2020 research and innovation programme under grant agreement No 815159

6 REFERENCES

[Ref 1] D6.1 “Identification of failure modes and initial reliability, health & safety and environmental assessment of the PivotBuoy system”, September 2019.

[Ref 2] D6.2 “Update of reliability, health & safety and environmental assessment of the PivotBuoy system, June 2020

[Ref 3] D2.3 “Detailed design review”, March 2020

[Ref 4] Documentation of system survey of 30th January 2023

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7 LIST OF ABBREVIATIONS

ALARP – As Low As Reasonably Practicable

DDR – Detailed Design Reviews

DGPS – Differential Global Positioning System

FLS – Fatigue Limit State

FMECA – Failure Mode, Effects and Criticality

HAZID – HAZard Identification

HAZOP – Hazard & Operability Review

H&S – Health & Safety

LCOE – Levelized Cost Of Energy

RNA – Rotor Nacelle Adaptor

RTK – Real-Time Kinematic

SCADA – Supervisory Control And Data Acquisition

SPM – Single Point Mooring

TLP – Tension Leg Platform

USBL – Ultra Short Base Line

ULS – Ultimate Limit State

APPENDIX A – FMECA Register

This Appendix has not been made publicly available due to IPR reasons.
In case third parties would like to request access to more detailed information, please contact the project coordinator directly or through the project website:

Project Website: http://pivotbuoy.eu/contacts/

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APPENDIX B – HAZID Guidewords

HAZID Guideword	Examples of Potential Hazard Event Scenario
ACCESS	1. Difficulty to access during transport or installation 2. Potential for impeded access due to third party activities 3. Blocked evacuation routes 4. Work in confined spaces
BARRIERS	1. Absense of barrier 2. Reliability of barrier 3. Valve positioning error
COLLISION	1. Vessel positioning system failure
COMMUNICATION	1. Loss of communication
CONNECTIONS	1. Connection difficulty or failure because of ROV / Divers installation error 2. Connection difficulty or failure due to poor alignment or hydrodynamic forces 3. Complex connection, difficult installation or retrieval for the divers or ROV
CORROSION	1. Corrosion during storage / transport
DEBRIS / FOULING	1. Debris during transport → impact 2. Debris preventing flooding or venting
DESIGN LOADS	1. Excessive loads during lifting / installation 2. Excessive loads from temporary hose connections 3. Excessive loads from third party interaction
DIVING	1. Release of pressure 2. Sharp edges 3. Trapped air 4. Umbilical tangling or snagging points 5. Pinch points 6. Heavy components or activities requiring force (also absence of hold-fasts)
DROP / IMPACT	1. Impact loads 2. Exposure of personnel and equipment in the water
ELECTRICAL ISOLATION	1. Residual or stored energy
FLOWRATE	1. Insufficient flowrate 2. Excess flowrate
HOT WORK / IGNITION	1. Fire / explosion
INGRESS / FLOODING	1. Uncontrolled flooding
LEAK / RELEASE	1. Leak to environment 2. Contamination (air or water)

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HAZID Guideword	Examples of Potential Hazard Event Scenario
LIFTING / HANDLING	1. Dropped load 2. Impact 3. Loss of control 4. Lifting over personnel / equipment 5. Handling of heavy objects by persons
LOSS OF BUOYANCY	1. Unplanned flooding of compartments
MOVEMENT – UNPLANNED	1. Shifting load on deck 2. Loss of stability 3. Load imbalance
POSITION	1. Vessel positioning error 2. Survey error 3. Incorrect placement of equipment onto seabed
PRESSURE	1. Over pressure 2. Trapped pressure 3. Under-pressure → collapse
SPEED	1. Excessive speed 2. Insufficient speed
STABILITY	1. Inability to maintain stability during transport / installation (lifting) 2. Unstable foundation due to soil conditions 3. Instability due to connection failure
STUCK	1. Stuck rigging 2. Stuck valve
TEMPERATURE	1. Expansion / contraction of structural elements 2. Pressure fluctuations
THIRD PARTY	1. Interaction with others
TOLERANCES	1. Too tight 2. Too loose
VESSEL	1. Collision with structure or other vessels 2. Extreme motions
WEATHER	1. Harsh weather conditions during installation 2. Complex installation or operation requires strict weather limitations 3. Loss of visibility
WORKING ENVIRONMENT	1. High noise levels 2. Insufficient ventilation 3. Work at heights 4. Work over open sea 5. Seasickness

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APPENDIX C – HAZID Register

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