

FLOATING OFFSHORE WIND
CENTRE OF EXCELLENCE

Delivered by
CATAPULT
Offshore Renewable Energy

FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

MOORING AND ANCHORING SYSTEMS TECHNOLOGY QUALIFICATION FRAMEWORK AND GUIDANCE NOTES



Photo courtesy of Principle
Power. Artist: DOCK90

Author: S. Weller

Date: 07/10/2022

Reference: PN000487-RPT-012

Status: Public

In partnership with:



DISCLAIMER

Whilst the information contained in this report has been prepared and collated in good faith, ORE Catapult makes no representation or warranty (express or implied) as to the accuracy or completeness of the information contained herein nor shall we be liable for any loss or damage resultant from reliance on same.

DOCUMENT HISTORY

Revision	Date	Prepared by	Checked by	Approved by	Revision History
REV 1	07/10/2022	Sam Weller, Tom Mackay, Ben Yeats (TTI-MR)	Ellen Jump (ORE Catapult)	Ralph Torr (ORE Catapult)	Final revision

PREFACE

Floating offshore wind (FOW) technology is developing rapidly. Offshore wind is expected to be a major contributor to the UK's clean energy mix as we move towards net zero emissions. The North Sea region is set to become the world's first floating offshore wind market of scale, propelling the UK's net zero ambitions by 2050. The first round of ScotWind lease awards is for up to 28GW of offshore wind capacity from 20 sites around the coast of Scotland. Commercial-scale floating wind projects are set to make up 65% of this total [5] [6].

A significant part of the technology proposed for deployment in floating offshore wind projects is not novel. It is adapted or has evolved from other applications, mostly fixed bottom wind and the oil and gas industry. Whilst the principles of these technologies remain the same, the specification, operating conditions, scale and volume for deployment in floating offshore wind may differ.

Mooring and anchoring systems are already an area of deep knowledge and strength for the UK supply chain. This ORE Catapult project, Floating Offshore Wind Mooring Systems – Technology Development and Qualification Programme, aims to stimulate the development and validation of relevant technologies, and to grow the capacity to deliver mooring and anchoring systems for large scale floating offshore wind cost-effectively.

This programme itself is split into three (3) separate phases:

- **Phase 1** focuses on the development of a mooring and anchoring system technology qualification framework, based on the assessment of technology risk and failure modes specific to its application in floating offshore wind.
- **Phase 2** of the project seeks to support the development and qualification of relevant technologies using the framework developed in phase 1. Both by providing direct support for such activities in the FOW Centre of Excellence (CoE) programme, and by coordinating support in other programmes.
- **Phase 3** is a parallel programme of enabling research to fill knowledge gaps required to qualify technology. Phases 2 and 3 are being carried out by ORE Catapult from mid-2022 onwards.

Phase 1 is the scope of this report. This document presents a framework for qualification of FOW mooring and anchoring components and systems, setting out clear stages of development, methods of assessing the stage of development of a technology, and methods of progressing through the stages.

The framework developed aims to summarise existing TQ processes, provide context for mooring and anchoring technologies and add an additional level of detail in order to provide a straightforward approach which facilitates relevant stakeholders to navigate the qualification landscape. In addition, it is envisaged that the framework can be utilised from early research and development to commercialisation and could also be applicable to other FOWT (or indeed offshore) equipment.

The purpose of this document is to be a companion document to the Technology Qualification Register (TQR) spreadsheet. The TQR spreadsheet does include concise specific notes and guidance for each phase of the TQ and this document is intended to elaborate on these aspects for completeness.

In addition to these guidance notes, the reader is directed to two additional resources:

- An online interactive Technology Qualification Tool (TQT) website¹



- A Technology Qualification Register (TQR) spreadsheet² available to download that can be used to formalise the planning and execution of TQ activities and also generate documentation for record keeping and/or Classification Society review.



The above work has been supported by a FMECA study covering the major mooring and anchoring reliability concerns, and a study mapping the existing qualification codes and standards. Technology qualification mapping case studies were also carried out to support development, testing and validation of the qualification framework; these focused on a mooring quick connector, a load reduction device, and a synthetic rope. These case studies are not presented in this report.

¹ www.fowmoortq.com

² <https://ore.catapult.org.uk/wp-content/uploads/2022/10/PN000487-DOC-011-Technology-Qualification-Register-Rev-1.xlsx>

CONTENTS

1	INTRODUCTION.....	1
2	EXISTING GUIDANCE.....	3
3	THE TECHNOLOGY QUALIFICATION PROCESS.....	6
3.1	DEFINING THE SYSTEM.....	6
3.2	DEFINING READINESS / MATURITY LEVELS	6
4	FRAMEWORK.....	9
4.1	STAGE 1: REQUIREMENTS DEFINITION	11
4.2	STAGE 2: TECHNOLOGY ASSESSMENT	12
4.3	STAGE 3: QUALIFICATION PLAN DEVELOPMENT	20
4.4	STAGE 4: QUALIFICATION PLAN EXECUTION	22
4.5	STAGE 5: REVIEW	22
5	CONCLUSIONS.....	25
6	REFERENCES.....	26

LIST OF FIGURES

Figure 1: Schematic showing a FOWT semi-submersible system with a semi-taut mooring system with drag anchors.....	1
Figure 2: Design development phases, with TRL definitions from [69].	7
Figure 3: TQ activities featuring in all design development phases.....	8
Figure 4: A high-level view of the developed TQ Framework, including statements and certification.....	10
Figure 5: A subset of requirements for a generic mooring connector.....	11
Figure 6: Generic mooring quick connector system diagram.	13
Figure 7: Generic mooring quick connector system decomposition.	14
Figure 8: An example three-element system with (left) linear and (right) non-linear integrations.	15
Figure 9: Potential failure modes relevant to M&A equipment.	18
Figure 10: Management of Change (MoC) at each development phase.	23

LIST OF TABLES

Table 1: Mooring and anchoring system components.....	2
Table 2: A selection of M&A component-related design and test procedures. The reader is directed to the Terminology section for explanation of the acronyms.....	4
Table 3: Non-destructive testing (NDT) techniques recommended by (29; 22) for wire ropes (WR) and chains (C) and associated hardware. Reproduced from [65].....	4
Table 4: Example system decomposition sub-set for the generic mooring connector.....	14
Table 5: Technology Maturity Levels and associated categories.	15
Table 6: Integration Maturity Levels, adapted from Integration Readiness Levels defined by Lloyds Register in <i>Guidance Notes for Certification through Technology Qualification</i> [5].....	16
Table 7: Failure impact ratings, defined by severity as low (L), medium (M) and high (H).	19
Table 8: Failure likelihood ratings.	20
Table 9: RPN matrix.	20
Table 10: RPN categories.....	20
Table 11: Typical content of the Technology Qualification Plan.....	21

NOMENCLATURE

ABS	American Bureau of Shipping
API	American Petroleum Institute
DNV	Det Norske Veritas
FOWT	Floating Offshore Wind Turbine
FSD	Functional System Decomposition
HS&E	Health, Safety and Environment
IEC	International Electrotechnical Commission
IRL \ IM(L)	Integration Readiness Level \ Integration Maturity (Level)
LCOE	Levelised Cost of Energy
LRD	Load Reduction Device
M&A	Mooring and Anchoring
MoC	Management of Change
QA & QC	Quality Assurance & Quality Control
QFD	Quality Functional Deployment
(Q)FME(C)A	(Qualification) Failure Modes and Effects (Criticality) Analysis
R&D	Research and Development
RPN	Risk Priority Number
SSD	Structural System Decomposition
TM(L)	Technology Maturity (Level)
TPV	Third Party Verification
TQ	Technology Qualification

TQR	Technology Qualification Register
TQT	Technology Qualification Tool
TRL	Technology Readiness Level

1 INTRODUCTION

To support the growing floating offshore wind industry, the need for developing reliable mooring and anchoring technologies with a secure supply chain is critical. Mooring and anchoring (M&A) components have been used in the oil and gas sector for many years, however floating wind brings with it new challenges. It is recognised that many of the components, sub-systems and systems utilised in the mooring and anchoring (M&A) of floating offshore wind turbines (FOWTs) will not be novel in themselves but the application area and operating conditions are novel; mooring spread designs, water depths, metocean conditions, and floater motions will all be different in floating wind in comparison to oil and gas. Introducing novelty into a M&A system may introduce uncertainties regarding short-and long-term performance of the complete FOWT system and hence this requires careful consideration to ensure robust and reliable products and project development.

Herein, M&A equipment is defined as any system/subsystem/component which provides station-keeping ability to a FOWT. A typical arrangement of a mooring and anchoring system and associated components is shown in Figure 1. This system could also incorporate items such as load reduction devices, ballast/buoyancy equipment, new mooring line materials, or new mooring layouts (e.g. using shared anchors or shared mooring lines).

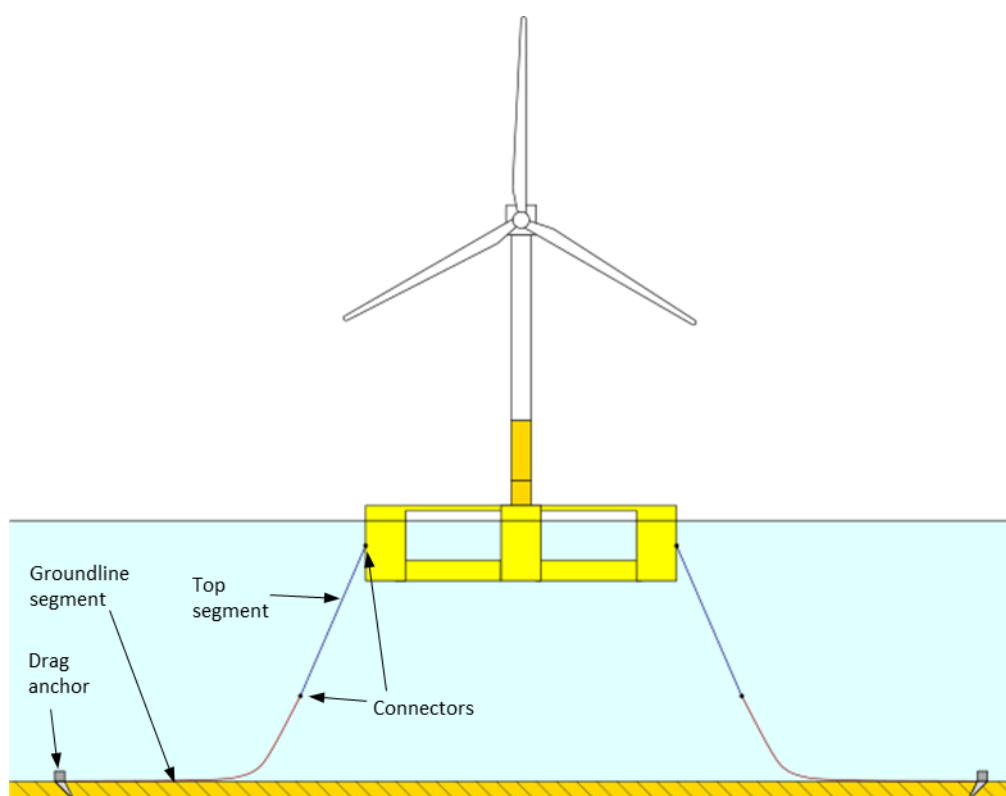


Figure 1: Schematic showing a FOWT semi-submersible system with a semi-taut mooring system with drag anchors.

An overview of typical mooring and anchoring system components is provided in Table 1 below. The mooring line itself is described as a single component but is typically composed of a number of different sections, joining by connectors. Depending on the material, specification, purpose and applications of each section, the mooring line may need to be considered as a sub-system comprising a number of different components, each requiring separate assessment as part of the development of a technology qualification plan.

Component	Description
Anchor	Seabed interface, a number of different forms can be expected e.g. drag anchors, suction piles, drilled/driven piles, vertically loaded plate anchors, gravity anchors, etc.
Mooring Line	Main mooring line element and the tension carrying part of the mooring, typically steel chain, synthetic rope (polyester, HMPE, nylon, etc.), steel wire rope. Includes ground line, rising line, top line which may be different materials / specifications.
In-line connecting elements (e.g. shackles, end links, triplates)	Joining elements connecting different elements of the mooring spread, e.g. between different diameter or material mooring lines, or lines to anchor.
Swivel	Specific mooring jewellery item to relieve torsion at connection point. Allows assumption that torsion is not transmitted by mooring line.
Substructure connector	Fairlead / platform mooring connector / chain stopper etc. Transfers the load path from the mooring line to the primary floating structure platform. May include tensioning capability.
Buoyancy element	Incompressible modules providing buoyant force to provide vertical reaction to mooring line forces. Typically foam-filled polymer
Ballast	Typically a clump weight – a concentrated weight to be used to provide isolated weight contribution to mooring system. May also be provided using parallel chains or hanging chains.
Load reduction devices	Components designed to dampen / relieve peak tensile loads. These can take a number of forms including elastomeric, mechanically actuated, pressure actuated.
In-line tensioner	Permanent component positioned within the mooring line to allow re-tensioning of the system throughout its life
Installation aids	Temporary elements of the mooring system which can be used to assist installation, and may require qualification in their own right despite not remaining permanently in the system. For example, tensioners, reaction anchors, installation buoys.

Table 1: Mooring and anchoring system components

2 EXISTING GUIDANCE

At the time of writing, no Technology Qualification (TQ) Framework exists that has been specifically designed for M&A equipment used on FOWTs. A number of more specific relevant technology qualification guidance documents do exist which include *American Petroleum Institute: Recommended Practice on Subsea Equipment Qualification API RP 17Q 2nd Edition (2018)* and *International Electrotechnical Commission: Marine energy - Wave, tidal and other water current converters - Part 4: Specification for establishing qualification of new technology IEC TS 62600-4 (2020)* [1, 2]. However, most TQ processes presented in guidance documentation are technology agnostic. Although this means that they can be applied widely, it means a level of interpretation is required to apply to specific systems and system types.

The primary Classification Societies operating in the conventional offshore and marine renewables sectors have developed systematic TQ processes and management programmes and can also act as an independent third-party verification (TPV) for assessing TQ progress. They are:

- American Bureau of Shipping: *Guidance Notes on Qualifying New Technologies (2017)* [3]
- International Electrotechnical Commission: *Marine energy - Wave, tidal and other water current converters - Part 4: Specification for establishing qualification of new technology IEC TS 62600-4 (2020)* [2]
- Lloyds Register: *Guidance Notes for Certification through Technology Qualification (2022)* [4]
- Det Norske Veritas: *Technology Qualification DNVGL-RP-A203 (2021)*, *DNV GL type approval scheme DNVGL-CP-0338 (2015)*, *Technology qualification management and verification DNVGL-SE-0160 (2021)* [5, 6, 7]
- American Petroleum Institute: *Recommended Practice on Subsea Equipment Qualification API RP 17Q 2nd Edition (2018)* [1]
- Bureau Veritas: *Risk Based Qualification of New Technology - Methodological Guidelines NI 525 DT R01 E (2020)* [8]

In addition a list of relevant standards and guidance documents which are relevant to M&A systems is provided in Table 22 and Table 33.

	LR	DNV	OCIMF	BV	CI	ABS	API	ISO	IEC	ClassNK
Steel mooring chain	[9, 10]	[11, 12]		[13]		[14]	[15]	[16]		[17]
Steel mooring wire	[9, 10]	[18, 19]								
Manufacturing, inspection and NDT of metallic components	[10, 20]	[21, 11, 14]		[22]		[23]	[24]	[25, 26]		[27]
Synthetic ropes	[9, 10]	[28, 29, 30]	[31]	[32]	[33, 34]	[35]	[36, 37]	[38, 39, 40]		
Anchors	[10, 41]	[42, 43]	[44]			[45]				
Foundations	[41]	[46]		[47]		[48]	[49]	[50]		
Higher-level guidance	[9]	[51, 52]	[53]	[54, 55]		[56, 57]	[58]	[59]	[60]	[61, 62, 63]

Table 22: A selection of M&A component-related design and test procedures. The reader is directed to the Terminology section for explanation of the acronyms.

Test	Procedure	Relevance	
		WR	C
Magnetic particle testing of forgings	EN 10228-1, ASTM A275, using wet continuous magnetisation technique	X	X
Ultrasonic testing of forgings	EN 10228-3, ASTM A388, ISO 13588 (C)	X	X
Magnetic particle testing of castings	ASTM E709, using wet continuous magnetisation technique	X	X
Ultrasonic testing of castings	ASTM A609, ISO 13588 (C)	X	X
Magnetic particle testing of bars	ASTM E1444		X
Eddy current testing of bars	ISO 15549		X

Table 33: Non-destructive testing (NDT) techniques recommended by (29; 22) for wire ropes (WR) and chains (C) and associated hardware. Reproduced from [64].

In broad terms, the TQ frameworks used in the offshore, automotive and aerospace sectors have similar approaches:

1. Definition of the requirements of the system (and associated system elements) as well as the proposed scope of the qualification programme;
2. Decomposition of the technological elements of the system, their functions and associated levels of maturity. Assessment of technology risks, failure modes, uncertainties and mitigation measures as part of the overall system;

3. Development of a TQ plan using relevant standards (where available) and mitigation measures, which comprises qualification activities and acceptance criteria as a means of addressing uncertainties, risks and threats via design, analysis or testing;
4. Execution of the TQ plan;
5. Review of the TQ activity outcomes in order to achieve the objectives of the TQ programme.

It should be noted that some technology developers utilise TQ in order to achieve *Type Approval* (and project) certification, and it is therefore prudent to engage a Classification Society early on in the planning process. This approach however, is not always mandatory, and indeed TQ could be carried out without the involvement of a Society. (e.g., by the technology developer, the customer or anyone else). For early stage certification TQ may be a mandatory activity, and whilst it may not be necessary to have this activity facilitated by a Classification Society, the documentation produced by the technology developer or other party leading this activity must be aligned with the Classification Society requirements for the certification level sought (e.g. concept certification).

The key features of the TQ processes listed above have been described and collated in the *Technology Qualification Review and Mapping Report* [65]. Three case studies were carried out which utilised a “blend” of these processes, as reported in *Mooring and Anchoring Technology Qualification Case Studies Report* [66]. A review of facilities and infrastructure that can be used to support, or carry out TQ activities has been prepared in *Mooring and Anchoring Technology Qualification Facilities Report* [67]. The resulting Framework, described herein, draws from these activities.

3 THE TECHNOLOGY QUALIFICATION PROCESS

3.1 DEFINING THE SYSTEM

The failure of a component, sub-system or system may pose a risk to life, the environment, financial assets and/or commercial reputation. According to the NASA definitions provided in *The Systems Engineering (SE) Process* [68], these terms are defined as:

System	An integrated set of elements that accomplish a defined objective.
Sub-system	A system in its own right, except it normally will not provide a useful function on its own, it must be integrated with other subsystems (or systems) to make a system.
Components	Elements that make up a subsystem or system.

The term failure is defined herein as a technology's inability to achieve technical objectives (i.e., a failure to "perform") in addition to the customarily accepted meaning of a failure being something breaking due to some mechanism. For established technologies, the in-application reliability of large numbers of components utilised in known conditions tends to follow well-established distributions and this forms the empirical basis for the demonstration of reliability and performance. However, for sectors which feature novel technologies, or those which feature novel elements, or existing technologies used in new applications (or those that push application boundaries), a service history does not exist and hence the reliability and in-application performance of components and sub-systems must be demonstrated to an acceptable confidence level prior to full-scale commercial roll out.

This is particularly the case for the FOWT sector, as reliability and performance at all system levels can play a key role in the levelised cost of energy (LCOE) of the system, e.g., overall power generation availability of the turbine, as well as influence the definition of efficient maintenance intervals. The overarching aim of a Technology Qualification (TQ) programme is to provide evidence, through the actions of a Qualification Team and delivery of a Qualification Plan, that a technology will perform as required (in terms of performance and failure probability) when subjected to a particular application.

3.2 DEFINING READINESS / MATURITY LEVELS

The development of a technology, product or service follows four phases from idea generation to deployment (Figure 2). TQ can be applied at any development phase, and is, in essence, a structured method of incrementally increasing a product's maturity (e.g., Technology Readiness Level; TRL or Technology Maturity Level; TML) enroute to commercialisation and/or certification of that technology³.

³ As discussed in [65], the TRL definitions differ per offshore Classification Society and caution should therefore be exercised on comparing TRLs.

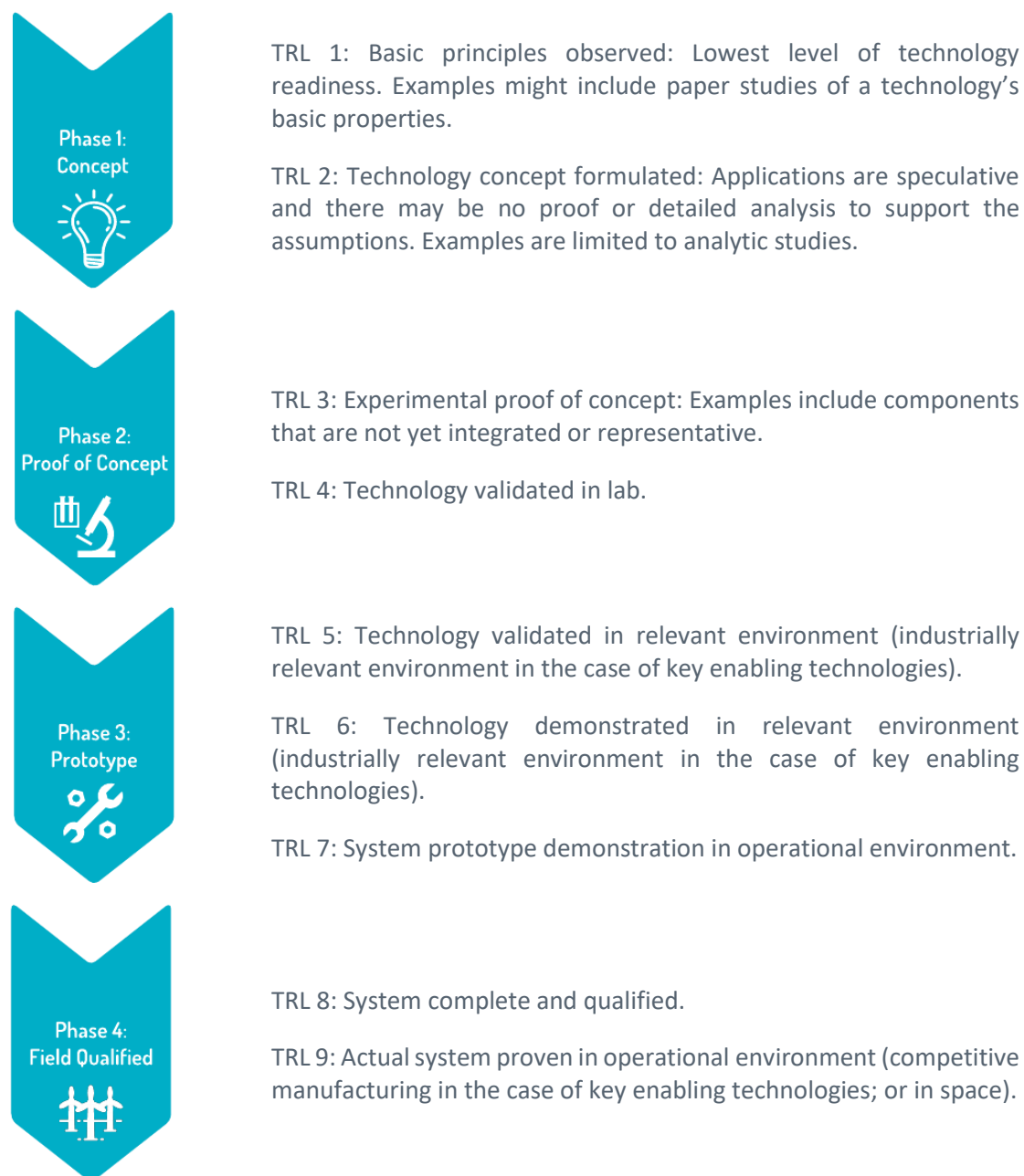


Figure 2: Design development phases, with TRL definitions from [69].

Depending on the aims of the TQ programme, available resources and technology maturity, TQ activities can take place sequentially or iteratively. For example, Figure 3 illustrates how TQ activities can be embedded within each technology development stage with a decision gate in place to determine if the predefined technology development milestones have been satisfied. Successful outcome(s) of this process allow the design to proceed to the next development phase. Failure to meet the milestone objectives is likely to result in the modification of the design, qualification activities and/or programme aims, and this may be enacted iteratively until the particular milestone has been achieved. Oversight of the TQ processes is provided by the TQ programme Management of Change (MoC) register, and this enables the impact of any modifications on interfacing equipment or overall system performance to be investigated and highlighted.

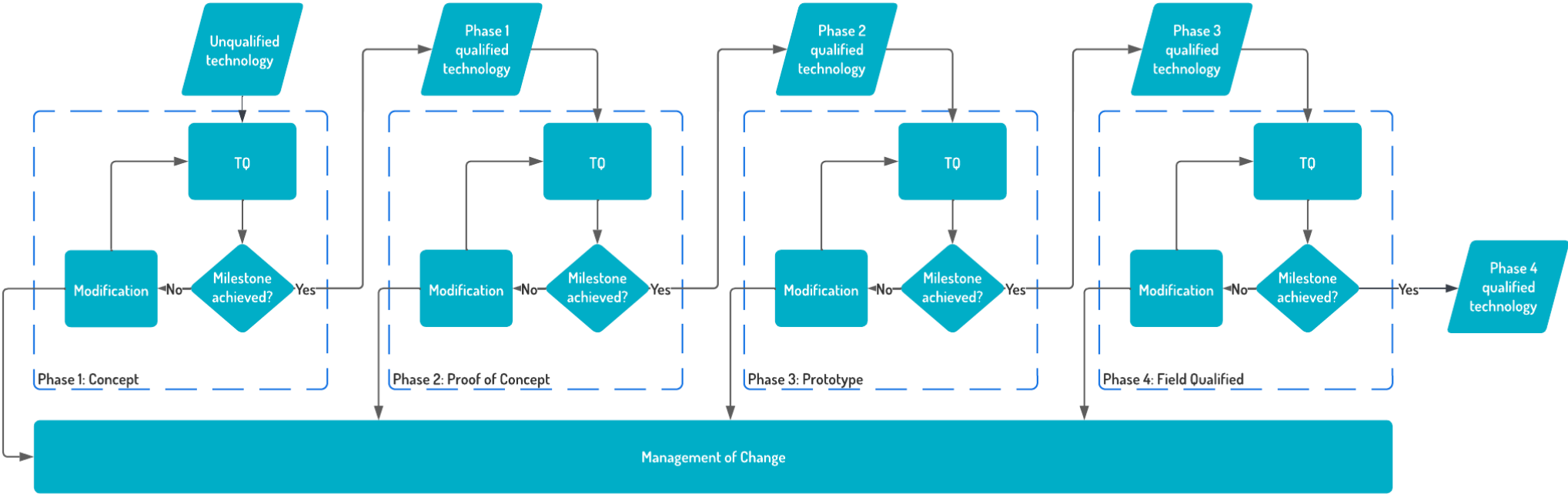


Figure 3: TQ activities featuring in all design development phases.

4 FRAMEWORK

At its highest level, the developed Framework has five principal stages, as illustrated in Figure 4. In the first instance, the stages are sequential (green arrows), culminating in *Stage 5: Review*. Should any requirements not be satisfied by the TQ activities, remedial actions may be required by revisiting earlier Stages (dark blue lines). Often, TQ processes are enacted several times during the four Technology Development phases introduced in Section 0 (dark red line). Technologies deemed to be mature in *Stage 2: Technology Assessment* can 'fast-track' the process and achieve qualification (light blue line), for example, the Lloyds Register *Certification of Mature Technology* process. Furthermore, technologies deemed to be *Proven* (defined as $TRL \geq 4$) according to the API TQ process [36] can bypass earlier stages which are geared towards immature technologies.

The following subsections describe each key stage of the TQ framework using an example of mooring line connector. Connection hardware is widely used to join mooring line elements together or connect lines to anchors and top-side equipment. Within this section, a generic mooring connector [66] is used to provide a practical example of how the Framework can be used.

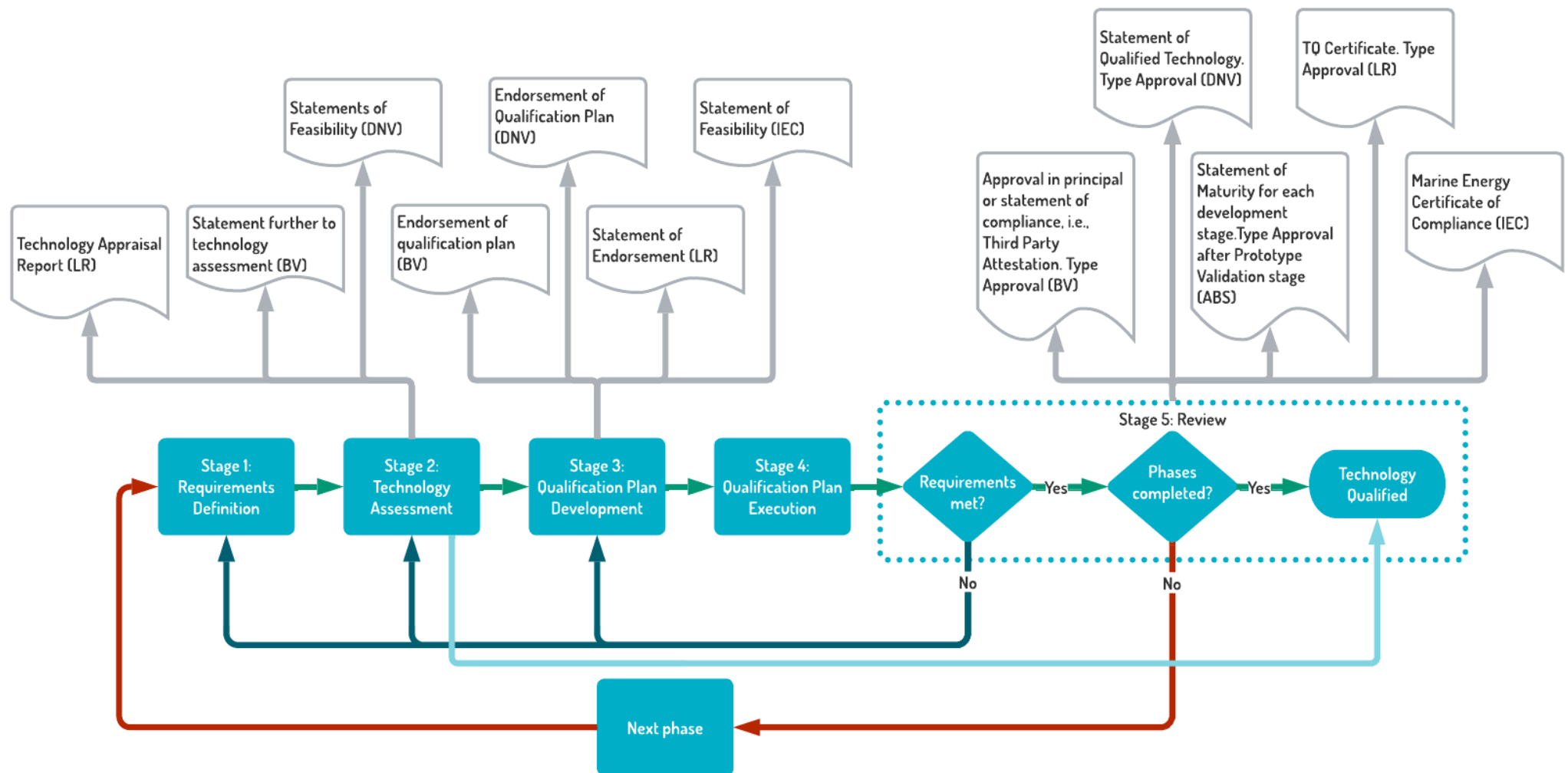


Figure 4: A high-level view of the developed TQ Framework, including statements and certification.

4.1 STAGE 1: REQUIREMENTS DEFINITION

The first stage comprises defining the basis for Technology Qualification, namely:

- What the technology is;
- How it functions;
- How it is used;
- How it is expected to perform and
- What the overall aims/targets of the qualification process are.

The different TQ processes developed by offshore Classification Societies vary in terms of how prescriptive the details introduced in this section need to be, at what development phase they are applied, and also if particular methods must be used in their definition.

This stage can be regarded as defining the inputs to the qualification plan and process. All qualification activities refer back to fulfilment of the requirements defined at this stage and/or the threats or risks identified during the next stage (Technology Assessment).

To provide an example, a subset of requirements for a generic mooring connector is shown in Figure 5 for one headline requirement *Allow handling and operation*. Clearly the connector will have other requirements, e.g., *Be sufficiently robust* etc.

The TQR spreadsheet *Stage 1 Requirements Definition* sheet has a table to fill out the requirements of the system and these can be subsequently selected from dropdown menus in the *Stage 3 TQP* and *Stage 5 Review* sheets.

At the early stages of technology development, the requirements of the technology may not be fully defined and hence, the *Requirements Definition* may include descriptive or qualitative statements. As the TRL increases, the requirements will become more specific, and include quantitative metrics that the technology must satisfy.

The description of the technology is likely to include:

- Definition of the general design concept/description and technology intent
- Current stage of development/qualification
- Functions and functional limitations
- Similarities/differences with other technologies
- Technology boundaries
- Relevant literature
- Material properties, manufacturing as well as quality assurance and quality control (QA & QC) aspects

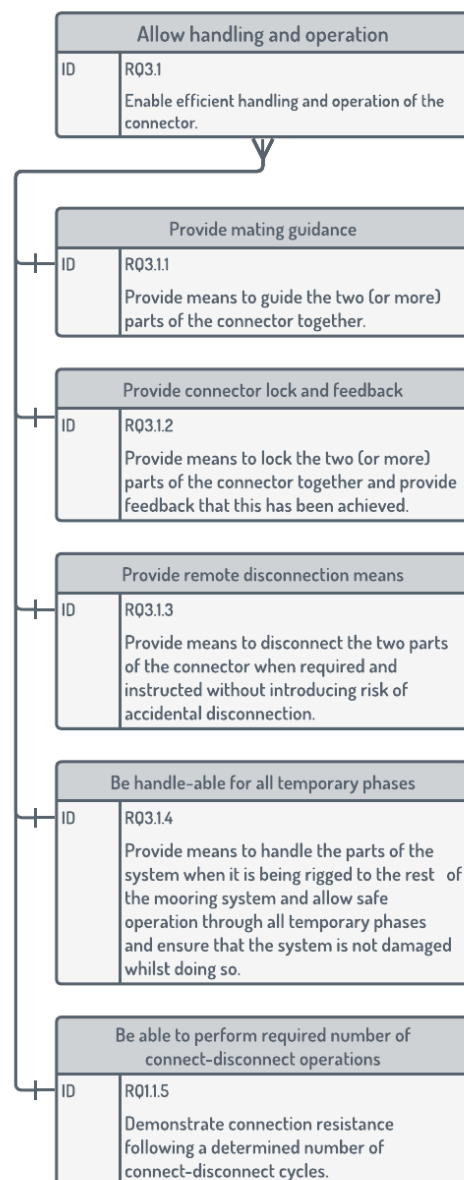


Figure 5: A subset of requirements for a generic mooring connector.

- Relevant areas of expertise required for further development (and qualification)

Performance requirements could include the following aspects:

- Acceptance criteria (i.e., Safety, functionality, reliability, availability, environmental impact, maintainability and performance goals)
- Health, Safety and the Environment (HSE) targets or constraints
- Adopted standards of reference
- Market needs
- Human system integration

The scope of TQ is defined in the context of the wider technology qualification programme (e.g., *Technology qualification management and verification DNVGL-SE-0160*) [7], including the:

- Roles and responsibilities of the Qualification Team including relevant experience and qualifications
- Goals and requirements of all relevant stakeholders (e.g., target maturity level)
- Confidentiality aspects with respect to background intellectual property
- Identification of decision gates and/or milestones
- Resources required to carry out the TQ programme
- Project management

4.2 STAGE 2: TECHNOLOGY ASSESSMENT

The second stage comprises a detailed assessment of the technology and the principal uncertainties associated with its use, in order to focus on the definition of qualification activities in Stage 3. The assessment commences with decomposition of the system into discernible elements, followed by two parallel activities: Technology Maturity Assessment and Risk Assessment. Each of these three activities should consider all lifecycle phases of the technology (i.e., from cradle to grave). The activities can be summarised in the TQR spreadsheet *Stage 2 System Breakdown*, *Stage 2 Technology Maturity* and *Stage 2 FMECA* sheets.

The granularity of information available to carry out risk and threat assessments, will depend on the technology development phase; qualitative approaches are likely to be made in the first instance, followed by quantitative assessments as more evidence (e.g., physical test data) is gathered during later development phases.

4.2.1 SYSTEM DECOMPOSITION

The system is decomposed into elements in order to determine which part(s) of the technology are novel or new to an application, where the element fits into the system, subsystem or component hierarchy and any relevant interfaces between elements or other systems.

The functions, operational modes, processes and project phases of each element are then identified in order to assist in the determination of technology maturity. A combination of approaches can be used in the technology decomposition process, including structural system decomposition (SSD) and functional system decomposition (FSD).

SSD is used to decompose the technology from the highest (system) level into lower levels (i.e., component/sub-component level) until a single maturity level can be assigned to a tangible hardware (or software) element. Similarly, FSD starts with the highest (system) level and progressively works down through the system hierarchy levels until all functions (or sub-functions) and structures, human-

machine interactions as well as team roles and responsibilities are assigned to technology elements. For each decomposed element, the usage, operating modes and integration issues are documented. FSD is more suited to procedural, or software-driven technologies (i.e., those which feature user-input).

The element functionalities are considered holistically during all project phases (i.e., transportation, installation, operation and decommissioning). For example, a sealing element needs to function during all life phases - not just operation, in order to prevent lubricant leakage. The conditions in each project phase impart different requirements or physical boundary conditions that would affect the functionality and performance of the seal.

Constructing a system diagram that illustrates interfaces between components in the system is a useful recommended step in the technology description and decomposition. A block diagram for a generic quick-release connector is illustrated in Figure 6 and has been decomposed into system elements in Figure 7. For each identified element, one or more functions can be specified at each system level (Table 44).

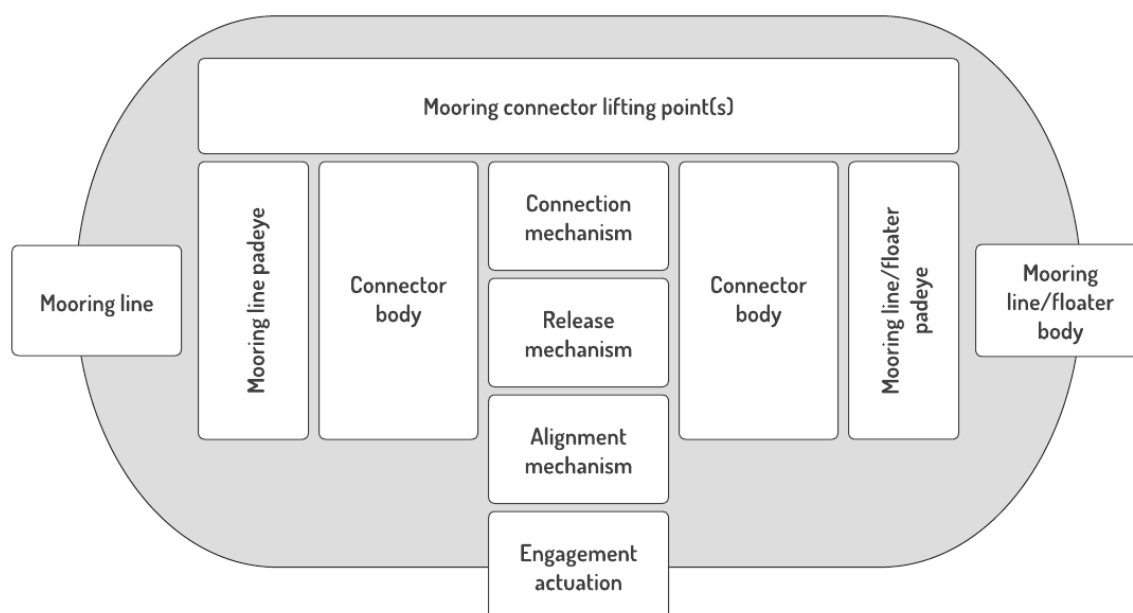


Figure 6: Generic mooring quick connector system diagram.

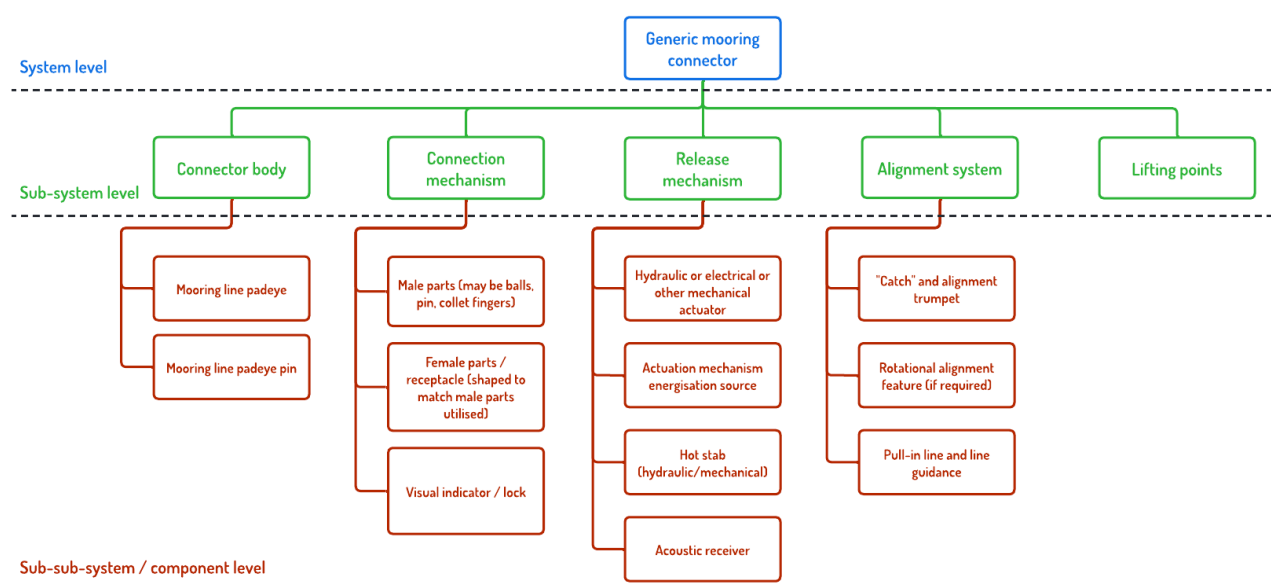


Figure 7: Generic mooring quick connector system decomposition.

System	Function	Subsystem	Function	Sub-sub-system / component	Function
Mooring connector	Remotely connect two parts of mooring system for long-term mooring	Connector body	House/support other sub-systems	Mooring line padeye	Provide connection to mooring line
			Provide mooring tensile load path	Mooring line padeye pin	
			Resist out-of-plane forces/moments	N/A	N/A

Table 44: Example system decomposition sub-set for the generic mooring connector.

4.2.2 TECHNOLOGY MATURITY ASSESSMENT

The level of maturity of a technology is ranked based on its degree of novelty, its current scope of application in the sector and the novelty of interfaces between interacting technology elements. Referring to Table 5Table 55, Technology Maturity Levels (TMLs) can be determined by the degree of novelty of the technology and the intended application area, with the following definitions:

Degree of Novelty of Technology - The level of novelty of the technology itself. Modifications to one or more technology elements from a *Known* state are likely to introduce performance and/or reliability uncertainties. In this scenario the novelty can be classified as *Limited Field History* or *New or Unproven* depending on the level of analysis and/or experimentation that has been conducted to assess the impact of any change(s).

Application Area - The level of accumulated experience of the expected operational conditions or environment of interest i.e., if a technology has never been used in a particular environment before there are high levels of uncertainty on how it will perform (i.e., it is *New*). Conversely, if sufficient evidence exists that a technology has been operated in a particular application then performance uncertainties are likely to be minimal, hence the application area is *Known*. The category *Limited Knowledge* is positioned between these two extremes.

Categorisation – A maturity category based on the combination of *Degree of Novelty of Technology* and *Application Area* ratings which can be used to determine appropriate TQ actions.

		Degree of Novelty of Technology			TML	Categorisation
		Proven	Limited Field History	New or Unproven		
Application Area	Known	1	2	3	1	Proven Technology
	Limited Knowledge	2	3	4	2	New Technology Uncertainties
	New	3	4	4	3	New Technical Challenges
					4	Demanding New Technical Challenges

Table 55: Technology Maturity Levels and associated categories.

The maturity of any integrations between system elements may influence the overall technology maturity of interfacing systems, sub-systems or components. For example, non-novel components being combined in a novel way. The Framework includes TML adjustment factors which range from 0.5-1.0 for linear systems which comprise elements connected in series (see Figure 8), which has been adapted from the approaches defined by Bureau Veritas and Lloyds Register in *Risk Based Qualification of New Technology - Methodological Guidelines NI 525 DT R01 E* and *Guidance Notes for Certification through Technology Qualification* [8, 4]:

$$TML_{mod} = \max \left\{ TML_{init} \left(\frac{IML}{14} + 0.5 \right)^{-1}, TML_{init} \right\}$$

Where TML_{init} and TML_{mod} are the initial and modified maturity ratings, and IML is the relevant integration maturity level (Table 66). IMLs greater than 6 are deemed to be mature and hence do not influence the TML. The Technology Qualification Tool (TQT) website, has interactive content to explore the maturity levels.

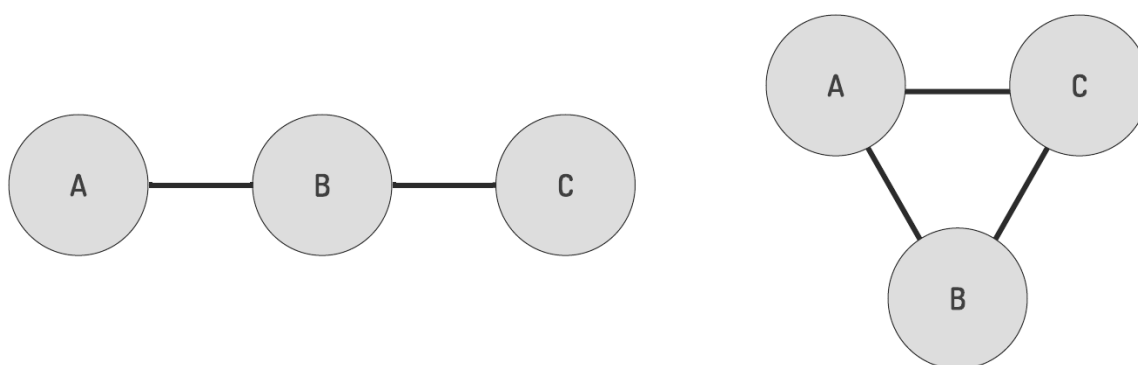


Figure 8: An example three-element system with (left) linear and (right) non-linear integrations.

The justification for this approach is that even if a technology is currently at a high TML, when applied to a new interface, performance and reliability uncertainties are likely to increase and hence requalification may be necessary. Adjustment factors to account for linear integrations are included in

the TQR spreadsheet⁴. Adjustment factors can also be applied to Technology Readiness Levels (TRLs), for example in [8, 4].

Focusing on the system decomposition example provided in Table 44, the *Mooring line padeye* is a widely used component in the offshore sector, therefore it can be classed as *Proven*. FOWT mooring systems are a comparatively new application, with a small number of deployments conducted to-date, hence there is *Limited Knowledge* of how they will perform in the long-term. Assuming that the integration maturity level is well understood (IML > 6), the overall TML will therefore be 2 (*New technical uncertainties*). It is important to approach the maturity assessment conservatively to ensure a robust qualification plan is developed and all key risks addressed. It would be easy to say that the padeye is totally known but this might then miss a particular load combination or risk specific to FOWT that later transpires to be an important failure mode. This might be, for example, due to a more dynamic load and motion regime at a mooring connection than similar components are normally exposed to in existing applications.

IML	Description
0	Interface not yet identified
1	Interface identified with sufficient detail to allow characterisation of the relationship
2	Some level of specificity to characterise the interaction
3	Technology compatibility allowing integration and interaction
4	Sufficient detail in the quality and assurance of the integration
5	Sufficient control to establish, manage and terminate the integration
6	The integrating technologies can accept, translate and structure information for the intended application
7	Integration verified and validated with sufficient detail to be actionable
8	Integration completed and mission qualified in the system environment
9	Integration mission proven

Table 66: Integration Maturity Levels, adapted from Integration Readiness Levels defined by Lloyds Register in *Guidance Notes for Certification through Technology Qualification* [4].

According to Lloyds Register and API, technologies which are deemed to be mature can 'fast-track' the TQ process towards qualification. Applying this logic to the Framework, technologies which are

⁴ Components which have multiple interfaces at different IMLs are classed as non-linear systems and methods for addressing this type are included in the *Guidance Notes for Certification through Technology Qualification* published by Lloyds Register [4].

assessed to have a *Proven* degree of novelty and used in a *Known* application area could be classed as mature as long as any integrations are well understood (IML > 6).

4.2.3 RISK ASSESSMENT

In order to focus qualification efforts, a quantitative failure analysis method, such as failure modes and effects criticality analysis (FMECA) can be used to assess threats and also identify failure modes and their associated risks. As the name implies it considers the root causes, failure mechanisms and both localised and global effects (such as cascade failures). A key aspect of the approach is that it can provide an early indication for the need to make design modifications prior to carrying out any qualification activities (as part of MoC system, see Section 4.5.1). It is therefore prudent to carry out such analyses at early technology development phases in order to design out risks; potentially reducing the need for significant (and potentially costly) TQ activities further down the line.

The first step is to assign potential failure modes, mechanisms or causes and consequences to each technology element. Example failure modes that are relevant to mooring and anchoring systems are shown in Figure 9. The TQR spreadsheet *Stage 2 FMECA* sheet allows the user to assign the failure categories and modes shown in Figure 9 to the system elements identified in the *Stage 2 System Breakdown* sheet. The selected failure modes automatically populate a Pareto chart, to assist in the prioritisation of TQ activities (i.e., it might be prudent to focus on common failure modes, particularly on critical component paths). Failure mechanisms or causes and the respective consequence of that failure mode occurring can then be documented in the *Stage 2 FMECA* sheet.

All lifecycle stages should be considered when the technology and risk assessments are carried out – potential failure modes during installation, disconnection, or maintenance activities must also be identified in addition to those during operation.

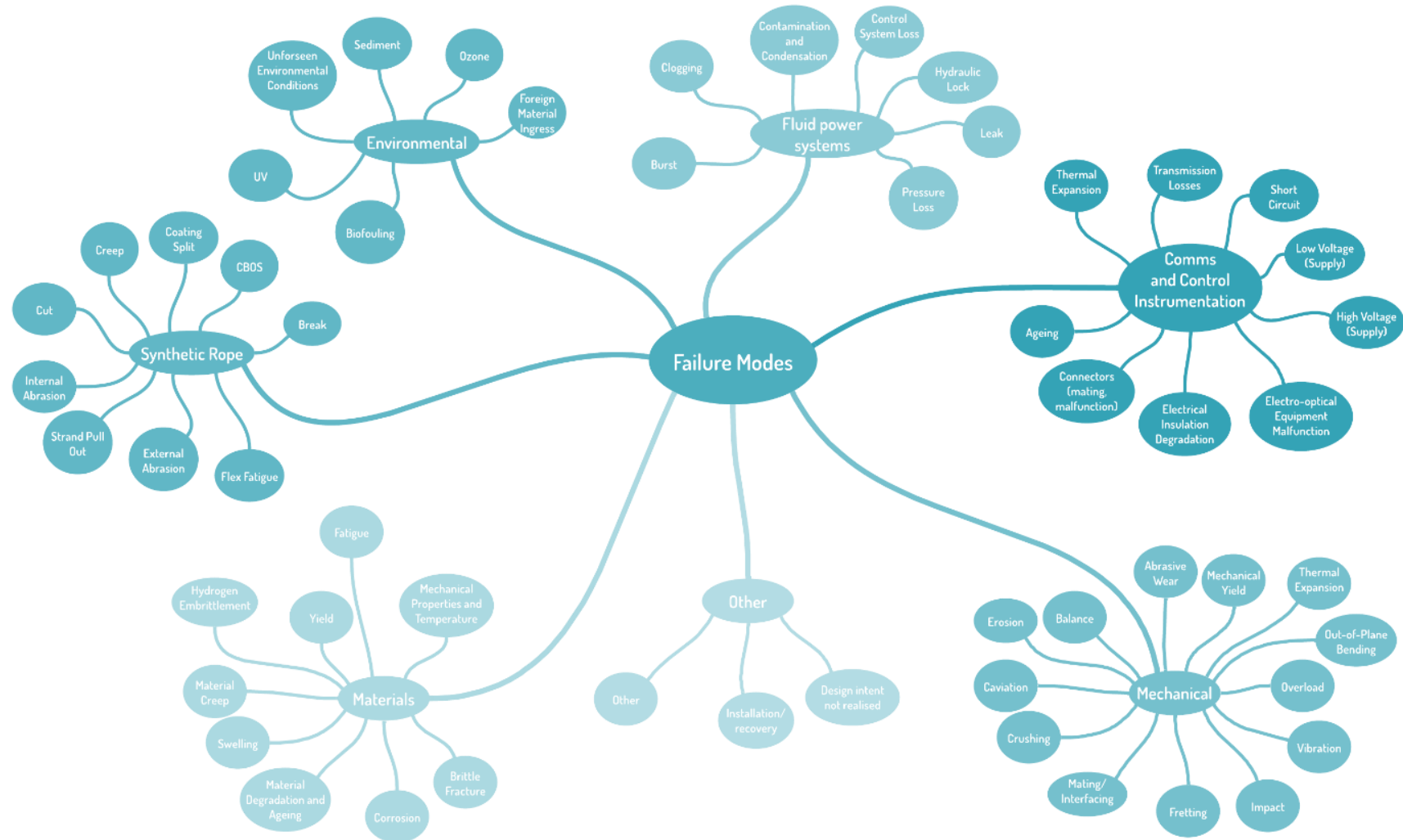


Figure 9: Potential failure modes relevant to M&A equipment.

The risks associated with each failure mode are then categorised, depending on their impact and likelihood. Referring to Table 77, different ratings can be applied to a risk depending on the expected impact of a failure occurring. Risk likelihood is defined by the estimated probability (p) of occurrence during a one year period (% per annum), see Table 88. Failure probabilities may originate from numerical analyses of physical test data obtained in a laboratory environment or from field trials, be estimated from numerical models or based on failure databases (e.g., the *Offshore and Onshore Reliability Data (OREDA) Handbook* [70]). Caution must be exercised in applying the reliability performance of a component to different operating environments, duty cycles etc. [71]. The risk priority number (RPN) is calculated as the product of the impact and likelihood ratings (Table 99). The categories listed in Table 1010 are used to translate the resulting risk priority score into a criticality category. This can then be used to inform what subsequent TQ actions are required to mitigate the risk. The Technology Qualification Tool (TQT) website has interactive content to explore the risk scoring system.

The TQR spreadsheet *Stage 2 FMECA* sheet allows initial risk impact and likelihood ratings to be assigned to each failure mode, and the resulting RPN is automatically calculated. The user can also specify mitigating actions as well as residual risk ratings.

Score	Rating	Meaning	Description
0	-	None	Impact removed
1	L	Insignificant impact	Tolerable delays, tolerable reduction in function/performance
2	L/M	Minor impact	Some delay, reduced performance or increased cost impacts project
3	M	Moderate impact	Delays, considerable impact on performance and cost
4	M/H	Major impact	Significant delays, non-achievement of function/performance
5	H	Severe impact	May cause aspects to fail

Table 77: Failure impact ratings, defined by severity as low (L), medium (M) and high (H).

A potential failure mode for the *Mooring line padeye* from Table 44 would be material yield, caused by overloading. Clearly the consequence of this occurring could be total failure of the connector, and if redundancy has not been provided in the mooring system, subsequent loss of the station-keeping ability. The impact of a *Mooring line padeye* failing could therefore be classed as very high. Assuming that the design load conditions are well understood and the system/component has been designed properly, the likelihood of this event occurring would be low. Referring to Table 99, in this example, a high impact (5) and low likelihood (1) ratings result in a RPN of 5, which according to the categories listed in Table 1010 falls within the *Medium* category, which may be acceptable.

Score	Rating	Meaning	Description	Probability (% per annum)
0	-	None	Impact removed	$p < 0.01\%$
1	L	Insignificant impact	Tolerable delays, tolerable reduction in function/performance	$0.01\% < p < 0.1\%$
2	L/M	Minor impact	Some delay, reduced performance or increased cost impacts project	$0.1\% < p < 1\%$
3	M	Moderate impact	Delays, considerable impact on performance and cost	$1\% < p < 10\%$
4	M/H	Major impact	Significant delays, non-achievement of function/performance	$10\% < p < 50\%$
5	H	Severe impact	May cause aspects to fail	$p > 50\%$

Table 88: Failure likelihood ratings.

			Likelihood				
			1	2	3	4	5
			L	L/M	M	M/H	H
Impact	1	L	1	2	3	4	5
	2	L/M	2	4	6	8	10
	3	M	3	6	9	12	15
	4	M/H	4	8	12	16	20
	5	H	5	10	15	20	25

Table 99: RPN matrix.

Rating		Criticality
$R \leq 4$	Low	Acceptable
$4 < R \leq 9$	Medium	May be acceptable
$9 < R \leq 19$	High	Unacceptable
$R > 19$	Critical	Requires immediate action

Table 1010: RPN categories.

4.3 STAGE 3: QUALIFICATION PLAN DEVELOPMENT

Within this stage a qualification strategy is developed that demonstrates that technical objectives are satisfied, according to the system requirements defined in Stage 1 and the failure modes and risks identified in Stage 2. The main outcome is a Technology Qualification Plan (TQP) document, which outlines the activities that will be carried out in order to obtain the evidence required to support the aims of the TQ programme. It also details the outcomes of the System Decomposition and Technology and Risk Assessments carried out in the previous stage and may also include aspects of TQ programme management.

For completeness, and to support later certification, it is good practice to include all elements of the system in the TQP, even those which have been deemed to have *No new technical uncertainties* from a Technology Maturity standpoint or an *Acceptable* risk category and hence require minimal TQ activities. Adopting this approach is also important in case any design modifications need to be made to a particular technology element which may impact other elements in the system, e.g., via interfaces, or a change to system operational ranges. Specific requirements for the content of the TQP are

required from the Classification Societies. However, in broad terms most require similar aspects to be included (Table 1111).

Aspect	Description
Activity List	Summary of all activities considered within the scope of TQ efforts. For example, engineering analysis (recognised experience, analytical and numerical), testing, maintenance, surveys and inspections.
Justification	Explanation of how the qualification methods are mapped to the requirements set in the technology qualification basis, i.e., how each activity will provide evidence for each uncertainty/failure mode.
Parameters	Determine the selection of the type, period of execution, frequency, limits and required accuracy of the activities. These aspects may be based on the respective risk level of the equipment, e.g., highly-critical equipment is likely to involve a combination of qualification activities and intensive monitoring requirements in order to quantify and then mitigate performance uncertainties.
Acceptance Criteria	Quantify the acceptance criteria for each activity and how each criteria will be assessed and by whom (e.g., TPV). The benchmarks or standards used to either define the acceptance criteria (or specify test/analysis procedures) tend to be based on the current best practice(s) or state-of-the-art knowledge in the sector. A list of example M&A guidelines can be accessed on the Standards page of the Technology Qualification Tool (TQT) website and also via the search facility in the TQR spreadsheet.
Traceability	Identify how the traceability of each activity will be established, including the collated evidence (e.g., test data and calibration of test equipment). The use of historical evidence may also be used to support qualification activities if the evidence is robust and traceable.
Qualification Plan Schedule	Define the overall TQ programme milestones. Summarise the roles and responsibilities associated with the defined TQ activities. The plan may have to be updated if design changes are made and/or qualification activities reveal unexpected behaviours (i.e., an iterative TQ process) and particular TQ guidelines suggest how MoC can be organised and carried out, see Section 4.5.1.

Table 1111: Typical content of the Technology Qualification Plan.

The selection of qualification activities is likely to be driven by the need to generate robust evidence in a cost-effective way and is determined by the aims of the TQ programme and development phase. Technologies at low maturity levels tend to undergo laboratory-based and numerical analysis (i.e., virtual prototypes/Digital Twins and/or material testing and analysis), which in the first instance, focuses on reducing the largest uncertainties. It is likely that the Classification Society will require justification (and perhaps TPV) that the simulated environment is representative, as far as practicable, of the operating environment. At low maturity levels, the intended deployment environment may not be fully defined, or sufficient field data obtained. If appropriate, a stepwise approach could be adopted. Initially conservative estimates (such as fatigue analyses) could be used to qualify the technology for a short time period (e.g., 3-5 years) and then operational field data, perhaps combined with laboratory test data would be used to qualify the technology for its full service life.

The equivalence between the simulated testing environment and real-world application increases with the progress of technology development. At later development phases, assembled components, subsystems and/or systems are likely to be subjected to more extensive testing and analysis programs, e.g., functional, cyclic and durability tests. The selection of TQ activities should be based on the optimum combination of value, complexity and probability of success in obtaining the required evidence within the constraints of project duration and budget. The Technology Qualification Tool (TQT) website has an interactive map showing open water sites, component test facilities as well as wave and current tanks in the UK and beyond which may have the capability to carry out the determined activities. A summary of relevant facilities can also be found in the facility review [67].

The TQR spreadsheet *Stage 3 TQP* sheet allows the user to associate TQ activities with the identified failure modes and system requirements. Details for each TQ activity can be entered, e.g., activity type, purpose, parameters, acceptance criteria, relevant standards, required evidence, success criteria and justification and it is important to do so. A search facility of relevant M&A guidelines and standards is provided on the *Standard Search* sheet. These should only be selected when they are directly relevant and applicable to the activity type being considered and novel/bespoke tests outwith the standardised norms may be required for certain systems.

4.4 STAGE 4: QUALIFICATION PLAN EXECUTION

Within this stage the TQ activities outlined in the TQ plan are carried out and the resulting evidence documented (e.g., data and insights through experience, numerical analyses and tests). It is possible that during the execution of an activity, deviations from the plan are necessary, due to an unforeseen event occurring, such as in the event of premature failure of a component. In this case the TQ plan would be updated in accordance with the MoC system, see Section 4.5.1.

The traceability of the collated evidence is key to supporting the conclusions of each qualification activity. For example, in the case of performance tests investigating a particular failure mode, failure occurrences and their statistical margins in the context of expected performance would be recorded. To facilitate the assessment taking place in *Stage 5: Review*, the evidence will be documented in a logical and coherent way in order to demonstrate that the TQ activities have been carried out in a systematic manner. For example, in the case of a quantitative assessment of technology reliability, performance data, which could be taken from many hundreds or thousands of tests would need to be fully traceable (i.e., detailing the test conditions, sample identifiers etc.).

A thorough mindset enables independent reviews of the qualification process to take place at a later date, perhaps in the form of due diligence of the technology or *Class Type Approval*. The format of the performance reports may include the following aspects: component identifier, test (or analysis) conducted, supporting documentation as well as key findings.

The TQ plan should be updated at defined intervals (that are aligned with the stage gates of the programme) to include the status of the qualification activities. To facilitate the oversight of qualification progress, the *Stage 4 TQE* sheet in the TQR spreadsheet allows the progress of each TQ activity (automatically populated based on the *Stage 3 TQP* sheet) to be tracked by allowing the user to set a target completion date and percentage progress. The sheet provides a visual indicator of activity status and level of achievement with respect to the target completion date.

4.5 STAGE 5: REVIEW

The TQ Framework culminates with a detailed assessment of whether the qualification activities have been implemented as planned, and hence whether the collated evidence satisfies all of the acceptance criteria defined in the TQ plan. Viewed collectively, the outputs of the qualification activities should demonstrate that the goals of the TQ programme have been achieved and provide an overall picture of the development stage reached. The TQR spreadsheet *Stage 5 Review* sheet includes a means of tracking the status of each TQ activity in terms of its relationship to the overall requirements of the TQ programme.

Depending on the objectives of the TQ programme and selected Classification Society, according to *Technology Qualification DNVGL-RP-A203* [5] TPV may be required to:

- Assess the relevance and completeness of the Technology Qualification Programme and the activities in the TQP;

- Review and perform independent analyses and tests to verify the validity of the qualification evidence and conclusions;
- Confirm compliance with specified standards.

4.5.1 MANAGEMENT OF CHANGE (MoC)

The qualification activities may result in a failure to achieve a particular milestone. This may necessitate remedial actions to account for design shortcomings or residual risks, e.g., changes to the design, system operating conditions, qualification activities and/or programme aims. Such actions may be carried out iteratively until the milestone is achieved. Based on the *ABS Guidance Notes on Qualifying New Technologies* [3], the motivation for carrying out remedial actions could be to:

- Remove (or reduce the probability of occurrence or consequence) of failure mode(s);
- Improve confidence (regarding system performance);
- Redefine the operating envelope (e.g., safe operation at an acceptable level of risk);
- Modify operations and maintenance strategies;
- Reduce cost(s).

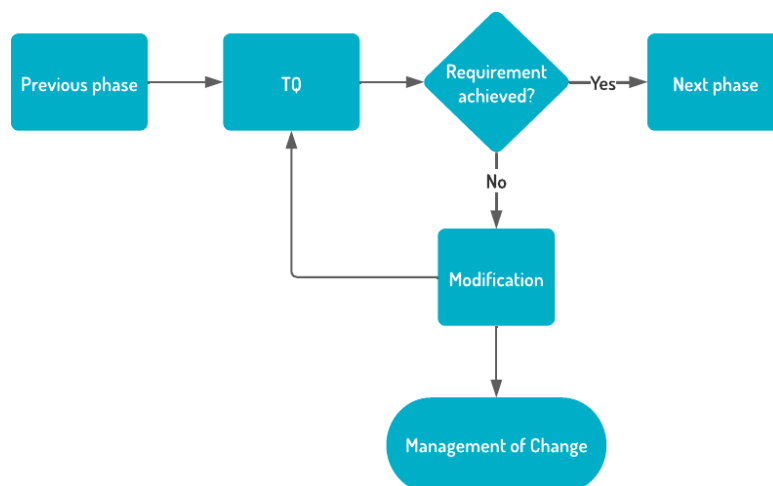


Figure 10: Management of Change (MoC) at each development phase.

Oversight is provided by the TQ programme MoC register, and this enables the impact of any modifications on interfacing equipment or overall system performance to be accounted for. Another approach that can be used to analyse the effect of design trade-offs is Quality Functional Deployment (QFD; otherwise known as “House of Quality”). Significant design changes made to a particular element are likely to lead to a reduction in the TML of the element necessitating corrective measures to be carried out, such as further requalification activities. Furthermore, such modifications may have an impact on the performance of interfacing components and/or subsystems, possibly even necessitating requalification of these associated systems, e.g., adjustment of risk assessment scores, further testing and analysis. It is therefore prudent to ensure that the proposed design changes do not result in unacceptable risks.

4.5.2 CERTIFICATES AND STATEMENTS

Technology maturity, risk and overall TQ progress can be reviewed in any of the TQ stages to make sure that the activities are on track. Formal reviews can be carried out by the Classification Society or other independent third-party, resulting in the issue of certificates or statements (see Figure 4). For example, several Societies can endorse the TQ plan following review of the activities in *Stage 3 Qualification Plan Development*. Following successful completion of TQ activities and verification of all reports and evidence, the ABS will issue a *Statement of Maturity*, allowing the developer to proceed to the next development stage. A common end goal for technology developers is *Type Approval* of their product following successful completion of TQ activities. Accordingly, the product is assessed against the defined performance requirements from Classification Society Rules, and/or recognized national/international standards. The certification awarded at the end of the TQ process may have a particular period of validity. For example, a Lloyds Register *TQ Certificate* is valid for 5 years, although this period can be extended, if appropriate, following a subsequent review carried out by the Classification Society.

Should it be desired to re-assess a previously qualified component for use in a new project, the technology developer would be required to review the operating envelope and identify any areas outside the previous assessment scope. They should then consider how far out of the operating envelope, the anticipated impact on loading, performance, and system behaviour. Additional technology qualification activities (numerical or physical) can then be defined as required.

5 CONCLUSIONS

Although synergies exist between FOWT M&A systems, components and practices with the existing offshore sector, the long-term performance of these technologies when used in FOWT applications is unknown. Furthermore, several new technologies have been proposed for FOWT M&A systems, such as load reduction devices (LRDs). The reliability of M&A components and sub-systems can play a key role in the LCOE of a FOWT system and hence must be demonstrated to an acceptable confidence level for both existing technologies used in new applications or in the development of novel technologies. TQ can be used to provide evidence, that a technology will perform as required (in terms of performance and failure probability) when subjected to a particular application.

It has been the purpose of these Guidance Notes to outline a TQ Framework which has been developed as part of the Floating Offshore Wind Centre of Excellence (FOW CoE) PR28 Floating Offshore Wind Mooring and Anchoring Systems – Technology Development and Qualification Programme. The purpose of the Framework is to assist stakeholders, including M&A technology developers, to navigate the TQ landscape. It comprises five key stages: Requirements Definition, Technology Assessment, TQ Plan Development, TQ Plan Execution and Review. Two additional resources have also been developed in this project: an online interactive Technology Qualification Tool (TQT) website as well as a Technology Qualification Register (TQR) spreadsheet which can be used to facilitate the planning and execution of TQ activities.

Several key sources of information have been used to develop the Framework, including TQ processes developed by the primary Classification Societies operating in the conventional offshore and marine renewables sectors, stakeholder feedback as well as experience of the TTI-MR team in applying TQ processes. The case studies carried out during this project resulted in several noteworthy outcomes:

- The TQ Framework was developed to provide structured guidance through the TQ process and examples of this
- TQ is a process – not a standard. It is necessarily open to interpretation and the TQ team may tend towards more conservative or less conservative approaches
- The important point is to use it as a tool to aid product development and de-risking and generating the evidence and justification of fitness-for-purpose
- It is crucial to understand the system requirements and decomposition and a system diagram can aid this
- It is useful to consider integration maturity as well as technology maturity
- Technology risk assessment is crucial step and the value depends on experience of risk assessment team
- A fairly exhaustive list of possible failure modes has been developed and integrated into TQ Framework tool
- Qualification activities should be related to specific failure modes and product requirements. It is useful to split qualification activities into desk-based and testing and leverage existing standards as much as possible

6 REFERENCES

- [1] American Petroleum Institute, “Recommended Practice on Subsea Equipment Qualification API RP 17Q 2nd Edition,” 2018.
- [2] International Electrotechnical Commission, “Marine energy - Wave, tidal and other water current converters - Part 4: Specification for establishing qualification of new technology IEC TS 62600-4:2020,” 2020.
- [3] American Bureau of Shipping, “Guidance Notes on Qualifying New Technologies,” 2017.
- [4] Lloyds Register, “Guidance Notes for Certification through Technology Qualification,” 2022.
- [5] Det Norske Veritas - Germanischer Lloyd, “Technology Qualification DNVGL-RP-A203,” 2021.
- [6] Det Norske Veritas, “DNV GL type approval scheme DNVGL-CP-0338,” 2015.
- [7] Det Norske Veritas - Germanischer Lloyd, “Technology qualification management and verification DNVGL-SE-0160,” 2021.
- [8] Bureau Veritas, “Risk Based Qualification of New Technology - Methodological Guidelines NI 525 DT R01 E,” 2020.
- [9] Lloyds Register, “Rules and Regulations for the Classification of Offshore Units, Pt3 Ch10 Positional Mooring System,” 2022.
- [10] Lloyds Register, “Rules for the Manufacture, Testing and Certification of Materials, Ch10 Equipment for Mooring and Anchoring,” 2022.
- [11] Det Norske Veritas, “Offshore Mooring Chain (DNV-OS-E302),” 2018.
- [12] Det Norske Veritas, “Offshore mooring chain and accessories DNVGL-CP-0237,” 2018.
- [13] Bureau Veritas, “Fatigue of top chain of mooring lines due to in-plane and out-of-plane bendings NI604 R00,” 2014.
- [14] American Bureau of Shipping, “Guide for the certification of offshore mooring chain,” 2021.
- [15] American Petroleum Institute, “Specification for Mooring Chain API SPEC 2F,” 1997.
- [16] International Organisation for Standardisation, “Ships and marine technology — Offshore mooring chains (ISO 20438:2017),” 2017.
- [17] ClassNK, “Anchor chain cables and accessories including chafing chain for emergency towing arrangements W18,” 2021.
- [18] Det Norske Veritas, “Offshore Mooring Steel Wire Ropes (DNV-OS-E304),” 2020.
- [19] Det Norske Veritas, “Offshore mooring steel wire ropes and sockets DNVGL-CP-0256,” 2020.

- [20] Lloyds Register, “Rules and Regulations for the Classification of Offshore Units, Pt3 Ch20 Guidelines on the Inspection of Positional Mooring Systems,” 2022.
- [21] Det Norske Veritas - Germanischer Lloyd, “Metallic Materials (DNV-OS-B101),” 2020.
- [22] Bureau Veritas, “Approval of the manufacturing process of metallic materials NR480,” 2021.
- [23] American Bureau of Shipping, “Guide for Nondestructive Inspection,” 2020.
- [24] American Petroleum Institute, “In-service Inspection of Mooring Hardware for Floating Structures API RP 2I,” 2008.
- [25] International Organisation for Standardisation, “Steel wire ropes -- Test method -- Determination of measured breaking force (ISO 3108:2017),” 2017.
- [26] International Organisation for Standardisation, “Steel wire ropes -- Determination of the actual modulus of elasticity (ISO 12076:2002),” 2002.
- [27] ClassNK, “Guidance for the approval and type approval of materials and equipment for marine use,” 2021.
- [28] Det Norske Veritas - Germanischer Lloyd, “Offshore Standard – Offshore Fibre Ropes (DNV-OS-E303),” 2019.
- [29] Det Norske Veritas, “Recommended Practice – Damage Assessment of Fibre Ropes for Offshore Mooring (DNV-RP-E304),” 2021.
- [30] Det Norske Veritas - Germanischer Lloyd, “Design, testing and analysis of offshore fibre ropes (DNVGL-RP-E305),” 2021.
- [31] Oil Companies International Marine Forum, “Guidelines for the purchasing and testing of SPM hawsers,” 2000.
- [32] Bureau Veritas, “Certification of Fibre Ropes for Deepwater Offshore Services (NI 432 DTO R01E),” 2007.
- [33] Cordage Institute, “Fiber Rope Inspection and Retirement Criteria (CI 2001-04),” 2001.
- [34] Cordage Institute, “Determination of marine finish on synthetic fiber yarns. Technical Report TR2009,” 2000.
- [35] American Bureau of Shipping, “Guidance notes on the application of fiber rope for offshore mooring,” 2011.
- [36] American Petroleum Institute, “Recommended Practice for Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring (API RP 2SM),” 2014.
- [37] American Petroleum Institute, “Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring. API Recommended Practice 2SM,” 2014.

- [38] International Organisation for Standardisation, “Fibre ropes for offshore station keeping – Polyester (ISO 18692),” 2007.
- [39] International Organisation for Standardisation, “Fibre ropes — Determination of certain physical and mechanical properties ISO 2307,” 2019.
- [40] International Organisation for Standardisation, “Fibre ropes for offshore station keeping Polyarylate. ISO/TS 19336,” 2015.
- [41] Lloyds Register, “Rules and Regulations for the Classification of Offshore Units, Pt3 Ch14 Foundations,” 2022.
- [42] Det Norske Veritas, “Design and installation of fluke anchors DNV-RP-E301,” 2021.
- [43] Det Norske Veritas, “Geotechnical Design and Installation of Suction Anchors in Clay (DNV-RP-E303),” 2021.
- [44] Oil Companies International Marine Forum, “Anchoring Systems and Procedures,” 2010.
- [45] American Bureau of Shipping, “Guidance Notes on Design and Installation of Drag Anchors and Plate Anchors,” 2018.
- [46] Det Norske Veritas - Germanischer Lloyd, “Offshore soil mechanics and geotechnical engineering DNVGL-RP-C212,” 2019.
- [47] Bureau Veritas, “Geotechnical and foundation design NI605,” 2014.
- [48] American Bureau of Shipping, “Guidance Notes on Design and Installation of Dynamically Installed Piles,” 2018.
- [49] American Petroleum Institute, “Geotechnical and Foundation Design Considerations. ANSI/API Recommended practice 2GEO. ISO 19901-4:2003 (Modified), Petroleum and natural gas industries—Specific requirements for offshore structures, P4 Geotechnical and foundation design considerations,” 2011.
- [50] International Organization of Standards, “Petroleum and natural gas industries - Specific requirements for offshore structures - Part 4: Geotechnical and foundation design considerations ISO 19901-4,” 2016.
- [51] Det Norske Veritas - Germanischer Lloyd, “Position Mooring DNVGL-OS-E301,” 2020.
- [52] Det Norske Veritas - Germanischer Lloyd, “Floating wind turbine structures DNVGL-ST-0119,” 2018.
- [53] Oil Companies International Marine Forum, “Mooring Equipment Guidelines (MEG4),” 2018.
- [54] Bureau Veritas, “Classification of mooring systems for permanent offshore units NR493 R04,” 2021.

- [55] Bureau Veritas, “Classification and Certification of Floating Offshore Wind Turbines NI 572 DT R02 E,” 2019.
- [56] American Bureau of Shipping, “Guide for Position Mooring Systems,” 2020.
- [57] American Bureau of Shipping, “Guide for Building and Classing Floating Offshore Wind Turbines,” 2020.
- [58] American Petroleum Institute, “Design and Analysis of Stationkeeping Systems for Floating Structures API RP 2SK,” 2005.
- [59] International Organization of Standards, “Petroleum and natural gas industries - Specific requirements for offshore structures - Part 7: Stationkeeping systems for floating offshore structures and mobile offshore units ISO 19901-7,” 2013.
- [60] International Electrotechnical Commission, “Marine energy - Wave, tidal and other water current converters - Part 10: The assessment of mooring system for marine energy converters. IEC-TS 62600-10 Ed.1.0 (In-Progress),” International Electrotechnical Commission, 2014.
- [61] ClassNK, “Guidelines for Offshore Floating Wind Turbine Structures,” 2012.
- [62] ClassNK, “Anchoring Equipment A1,” 2020.
- [63] ClassNK, “General design parameters D3,” 2018.
- [64] Tension Technology International, “Cost Reduction in Supporting Infrastructure - Moorings and Foundations,” 2018.
- [65] Offshore Renewable Energy Catapult, “PN000487-RPT-009 - Mooring Technology Qualification Review and Mapping Report,” 2022.
- [66] Offshore Renewable Energy Catapult, “PN000487-RPT-009 - Mooring and Anchoring Technology Qualification Case Studies Report,” 2022.
- [67] Offshore Renewable Energy Catapult, “PN000487-RPT-XXX - Mooring and Anchoring Technology Qualification Facilities Report,” 2022.
- [68] National Aeronautics and Space Administration, “Chapter 2: The Systems Engineering (SE) Process,” [Online]. Available: https://www.nasa.gov/pdf/598887main_Auburn_PowerPoints_SE.pdf. [Accessed 2022].
- [69] Offshore Wind Innovation Hub, “EC scale of technology readiness as adapted by Offshore Wind Innovation Hub,” 2018.
- [70] OREDA Consortium, “Offshore RELiability Data Handbook 6th Edition,” 2015.
- [71] S. D. Weller, P. R. Thies, T. Gordelier and L. Johanning, “Reducing Reliability Uncertainties for Marine Renewable Energy,” vol. 3, 2015.

FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

ORE Catapult
Inovo
121 George Street
Glasgow, G1 1RD

+44 (0)333 004 1400

Disclaimer

While the information contained in this report has been prepared and collated in good faith, ORE Catapult makes no representation or warranty (express or implied) as to the accuracy or completeness of the information contained herein nor shall be liable for any loss or damage resultant from reliance on same.