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

Project acronym	LIFES50+
Grant agreement	640741
	Collaborative project
Start date	2015-06-01
Duration	47 months

Deliverable D5.5 Overall summary of the industrialization process

Lead Beneficiary	Ramboll
Due date	2019-04-30
Delivery date	2019-04-30
Dissemination level	Public
Status	Final
Classification	Unrestricted
Keywords	Large scale manufacturing, fabrication, assembly, installation, economies of scale, pre-fabrication, mobile site, production methodology, lean philosophy, design methodology, semi-submersible, load assessment, structural stress analysis, manufacturing readiness level, commercial readiness index, logistics, decommissioning
Company document number	Click here to enter text.

The research leading to these results has received funding from the European Union Horizon2020 programme under the agreement H2020-LCE-2014-1-640741.

Disclaimer

Document information

Version	Date	Description	
0A	2019-04-12	First draft for review	
		Prepared by	Friedemann Borisade, Jayesh Bhat, Denis Matha
		Reviewed by	Enter names
		Approved by	Enter names
1	2019-04-18	Final deliverable	
		Prepared by	Friedemann Borisade
		Reviewed by	Denis Matha
		Approved by	Denis Matha
Final	2015-06-30	Final version for QA before submission to EC	
		Prepared by	Friedemann Borisade
		Reviewed by	Jan Arthur norbeck
		Approved by	Petter Andreas Berthelsen
		In order to enter a new version row, copy the above and paste into left most cell.	

Authors	Organization
Friedemann Borisade	RAMBOLL
Jayesh Bhat	RAMBOLL
Denis Matha	RAMBOLL

Contributors	Organization

Definitions & Abbreviations	
CAPEX	Capital Expenditure
CRI	Commercial Readiness Index
DFMA	Design for Manufacturing and Assembly
FB	Fixed Bottom
FE	Finite Element
FEED	Front End Engineering and Design
FRP	Full Rate Production
FOWT	Floating Offshore Wind Turbine
KPI	Key Performance Indicators
LCOE	Levelized Cost of Energy
LRIP	Low Rate Initial Production
MRL	Manufacturing Readiness Level
RFID	Radio Frequency Identification
ROV	Remote Operating Vehicle
SPMT	Self-Propelled Modular Transport
TRL	Technological Readiness Level
TLP	Tension Leg Platform
OPEX	Operational Expenditure
OWT	Offshore Wind Turbine
O&G	Oil & Gas
O&M	Operations & Maintenance
WTG	Wind Turbine Generator
WP	Work package

Executive Summary

The ambition of this deliverable is to provide input for a roadmap to an industrialized development of FOWT technology by briefly summarizing on the following key objectives:

1. Industrialization of floating wind in general and differences to fixed-bottom wind
2. The development of an industrialized numerical design process for FOWTs
3. Industrialized procedure for the transition from conceptual to detailed design
4. Key areas from design conceptualization to manufacturing process development
5. Development of a generalized manufacturing methodology for the large-scale production
6. Economic considerations during offshore operations

Furthermore, information regarding the design of internal structures and opportunities for structural optimisation are provided. A proposal for a design methodology using coupled simulations combined with structural analysis is made. The application of a method based on analysis of instantaneous quasi-static states is demonstrated and used iteratively to obtain the instantaneous stresses for predefined time steps. The results are then used as inputs for Finite Element analysis. This methodology is exemplified by using a generic concept, which was designed according to the specifications of the LIFES50+ project Task 5.3 on industrialisation processes.

As the technology matures and gradually reaches the stage where it needs to be mass-produced, the manufacturability of the concept needs to be assessed. A Manufacturing Readiness Level (MRL) questionnaire was used with concept designers as part of the assessment procedure. The MRL questionnaire may be utilized as a template for future design assessments. TRLs and MRLs should ideally propagate in conjunction and any existing TRL and MRL gaps should be reduced to enable industrialisation of the designs. An overview of the current level of manufacturing maturity of selected FOWT concepts is presented and the interdependencies of the technological readiness with manufacturing and commercial readiness are described.

One of the main conclusions of the MRL assessment is the need for a manufacturing proof of concept to increase the manufacturing maturity. Ramboll in cooperation with concept designers, subcontracted third-party consulting companies specializing in offshore manufacturing and conducting a fabrication study separated for steel and concrete. This established an interactive loop between the concept designers and the experts in steel and concrete structures. An outcome is a generalized manufacturing methodology taking the manufacturing constraints into consideration. The study considered a mass production scenario for producing 50 FOWT units in 2 years, each unit supporting a 10 MW turbine. Recommendations and industrial best practices at various stages of the FOWT development life-cycle are highlighted. A comparison of manufacturing methodologies is made.

The installation procedure of a FOWT after manufacturing generally consists of load-out, transit to site and hook-up to mooring lines and dynamic cable. To facilitate the installation process and minimize costs, three main logistical aspects have to be considered: vessel requirements, distance from port to site and weather impact. The weather mainly impacts the installation procedure due to sensitivities of required marine operations to wave height and wind speed. This impact increases for larger distances. Furthermore, the floater towing speed, draft and other requirements, mooring and dynamic cable hook-up times and procedures and other technical aspects greatly influence installation, particularly for TLPs. For floating wind substructures, only limited information about the decommissioning process is available. Generally, floating devices will be detached from the mooring lines and towed to the shore for further decommissioning. Mooring lines may be recovered while pile anchors remain in the sea bed.

Contents

1 Introduction

Due to the relative novelty of FOWT (compared to onshore and bottom-fixed offshore wind [FB]), their LCOE is currently higher than that of FB. Therefore, to compete with the already mature FB market, development costs of the FOWTs must be reduced. The current FOWT industry currently is in its early pre-commercial stage and exhibits a high LCOE compared to its FB counterpart. However, FOWTs show an enormous potential for cost reduction in the future, considering the many synergies with bottom fixed and onshore wind, as well as oil and gas. To capitalize on this opportunity and speed-up its maturity, industrialization aspects and risks related to manufacturing and offshore workings need to be identified in advance. A basic methodology for the development of FOWTs is presented herein.

Design is a crucial stage in this development process and a focus is applied to develop an industry applicable design process. A numerical design process adapted from the FB design process shall be proposed for the FOWT design. The numerical design process differs from the FB since coupled analysis is required for FOWT rather than an iterative process. Due to the nature of the numerical design process of FOWT, issues related to confidentiality and sharing the risks, liabilities, warranties and responsibility, while sharing data between the Wind turbine designer and substructure designer may arise.

For further industrialization efforts to take place, a selected concept must make the transition from its concept stage to detailed design under consideration of serial production. This involves the specification of the hull structure, such as braces, girders and stiffeners in a cost-effective, industrialized manner. The industrialized numerical design procedure for making this transition from conceptual design to detailed design is proposed using a generic concept. The various loads and types of analysis involved will be presented.

As an effort to study the manufacturability of the concept so that relevant manufacturing constraints can be considered during design, it is essential to evaluate the Manufacturing Readiness Levels of the selected concepts. Ideally, the MRL must mature in tandem to the TRL, but often this is hardly not the situation. This is usually the case when the aspect of manufacturability is not addressed before a design is frozen, respectively too much emphasis is given to the technical design aspects, as often the case for demonstrator projects, where industrialisation is typically a secondary target. The non-involvement of manufacturers during the early design phases creates then a gap between the technological development and the manufacturing process development. This gap can potentially lead to delays and other unnecessary expenses when the actual production begins, respectively lead to concepts which lack the ability to industrialise them. To exemplify this, an MRL assessment was conducted using a questionnaire for the two selected concept developers. Their answers provide a good overview about the manufacturability and also provide a template for future designs. At later stages of technological maturity, a commercial readiness index (CRI) assessment for evaluating commercial readiness is also considered and the interaction between the CRI, MRL and TRL are depicted.

The MRL assessment shows exemplarily a typical gap between technological maturity and the manufacturing maturity, which in the case of a R&D project such as LIFES50+ is to be expected. For commercial projects, the early involvement of substructure manufactures is thus essential for ensuring that the manufacturing constraints associated with the site selection, equipment, capacity and supply chain are addressed during the design. Their early involvement also allows the identification of critical areas and potential bottlenecks during the process. To exemplify the benefits of such an early involvement, Ramboll in cooperation with the concept designers initiated a manufacturing study for addressing the large-scale manufacturing related aspects into the design. The study was supported by subcontractors selected for each of the steel and concrete floater concept. The study assumed the production of 50 units in a span of 2 years. Separate manufacturing methodologies for the steel and concrete floating concepts were developed. A generalized manufacturing methodology for FOWT substructures was then developed based on the individual methodology proposed in the study. Potential bottlenecks and critical areas in the manufacturing were identified and recommendations for upgrades and automation are provided. Results are transferable to all steel and concrete concepts.

The installation procedure of a FOWT after manufacturing generally consists of load-out, transit to site and hook-up to mooring lines and dynamic cable. To facilitate the installation process and minimize costs, three main logistical aspects have to be considered: vessel requirements, distance from port to site and weather impact. The weather impacts the installation procedure due to sensitivities of required marine operations to wave height and wind speed. This impact increases for larger distances. It may be, thus, beneficial to invest in closer ports and upgrade its infrastructure. High investments must be compared to the alternatives including higher risks regarding weather forecast and higher vessel costs. Furthermore, the floater towing speed, draft and other requirements, mooring and dynamic cable hook-up procedures and other technical aspects greatly influence installation, particularly for TLPs.

For floating wind substructures, only limited information about the decommissioning process is available. Generally, floating devices will be detached from the mooring lines and towed to the shore for further decommissioning. Mooring lines may be recovered while pile anchors remain in the sea bed. This is a clear advantage over fixed-bottom structures. The decommissioning can be done, after the floaters are towed back to the port followed by recycling or disposal of the employed materials like steel, concrete, synthetics, etc.

2 Industrialized development of the FOWT technology

Figure 1 indicates, cost from new and innovative technologies tend to increase from initial conception to detailed development and then decrease when the concept is optimised and industrialised. As a technology at the early stages of development, the CAPEX and LCOE estimates for floating wind may underestimate the full costs of deploying the technology. This has already been observed in the fixed-bottom industry [1] and is also evident in demonstrations at the Fukushima FORWARD project in Japan or Hywind Demo, which were very expensive. The industrialisation stage is here indicated to take place beyond TRL 7 and is characterized by considerable reductions in cost. In LIFES50+ the project aims at achieving TRL 5 for the selected concepts at the end of the project. While an actual industrialisation of the concepts in LIFES50+ is beyond the project scope, WP5 only aims at outlying the general considerations by creating a roadmap towards industrialisation.

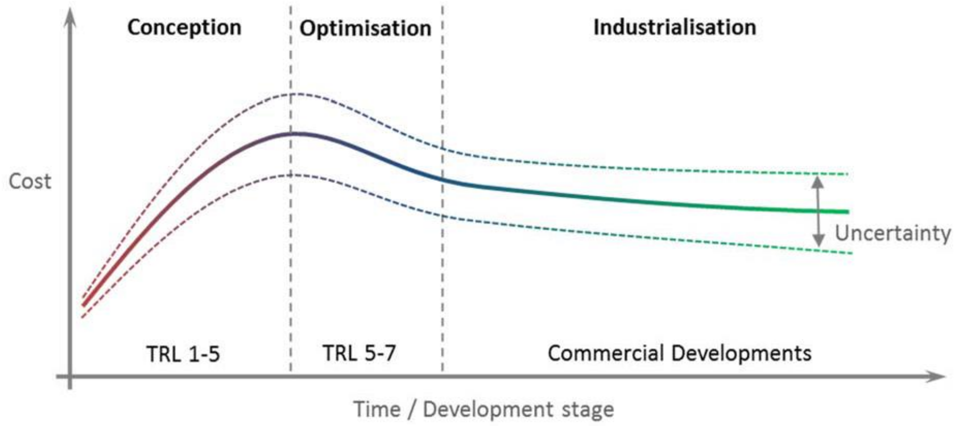


Figure 1. Potential of cost reduction in industrialisation phase [2].

Some of the lessons learnt during the last almost 30 years of experiences with offshore wind farms on fixed foundations should also be considered when envisioning an industrialized FOWT design process:

- When looking at the development of forecasts of offshore wind capacities, most predictions in the past were overly optimistic. These overinflated or unrealistic expectations were damaging for governments, developers and the supply chain. Key reasons for that were the under-estimation of the issues related to the offshore environment which resulted in major delays and massively increased construction costs. Additionally, complex environmental permitting has proven to be an important factor and source of delay.
- The learning curve in offshore wind until around 2010 was inverted [1], with costs increasing rather than decreasing regardless of the increased number of units installed. This contradicts the conventional theory and basis of industrialized markets. However, it appears to be well aligned with the statements made above.
- Development of an efficient supply chain took a considerable amount of time and many lessons were learnt to reach this level of maturity.

2.1.1 Key aspects for the industrialized FOWT design:

- **Centralization of Production:** Utilization of expensive equipment and facilities is feasible only with production performed at a single location, i.e. a harbour/shipyard for a particular region. Such a hub is ideally comprised of a large turbine assembly plant, a host of manufacturers of ancillary equipment including gearboxes, blades, nacelles and cables alongside a series of installation, logistics and operations and maintenance companies. The process will thus use the economies of scale with respect to capital investment, management and auxiliary services. From this central location the product is shipped to the various installation sites.

- **Mass Production:** The investment in equipment and facilities associated with an industrialization process can be justified economically only with a large production volume. Such volume allows a distribution of the fixed investment charge over a large number of product units without unduly inflating their ultimate cost.
- **Standardization:** Production resources can be used in the most efficient manner if processes and procedures are standardized. Then the production process, machinery, and workers' training can best be adapted to the characteristics of the product.
- **Specialization:** Large volume and standardization allow a high degree of labour, software and design procedure specialization within the production system. The process can be broken down into a large number of small homogeneous tasks. Workers continuously engaged in any of them can perform at a higher productivity level.
- **Good organization:** Centralization of production, high volume, and specialization of work teams requires a sophisticated organization capable of high quality of planning, coordination, and control functions with respect to design, production and distribution of the products. This includes incorporation of well-defined and comprehensive risk and asset management strategies, as well as quality assurance procedures (i.e. mature Design Standards and internal QA processes).
- **Integration:** To ensure optimal results, a very high degree of coordination must exist between design, production, and marketing of the product. This can be ensured in the most efficient way within an integrated system in which all these functions are performed under a unified authority.
- **Project Pipeline and Policy:** All aspects above can only be achieved if a clear and reliable pipeline of floating wind projects exists. LIFES50+ thus urges policymakers to set out ambitious goals for floating wind development on a commercial scale. Without such clear goals, the learning curve will be delayed and the road to industrialization and cost competitiveness will be blocked.

2.1.2 Main difference between FB and FOWT numerical design

While some design aspects for floaters exhibit less complexity, such as geotechnical analysis (for catenary moored systems) and individual design variations for locations within a wind farm, the complexity increases in other areas related to the detailed design of structure and moorings, where the FOWT global motions need to be accounted for. Table 1 provides some of the main differences below.

Table 1. Key differences between the numerical design procedures of FB and FOWT substructures.

Item	Difference to fixed-bottom design
Components	Mooring lines, dynamic cable / umbilical, anchors, tower, RNA, floating substructure are components that are either not present for fixed-bottom OWTs or do require modification for application in FOWTs.
Loads analysis	Limited application of uncoupled approaches in the detailed design due to the more important coupling effects and the influence of the controller that are very difficult to capture with sequential methods; tower loads, and RNA loads are significantly influenced by floating foundation and controller so that coupled models are very important.

Numerical model fidelity	Regarding hydrodynamics, potential flow methods of 1st and 2nd order are applied for most (hydro-dynamically in-transparent) concepts instead of Morison based approaches; however due to this difference the wave representation is typically less advanced and only considers irregular waves up to 2nd order.
Controller	The controller has increased importance and needs to be re-qualified and often modified for floaters. Due to the controller changing the global system dynamics, consideration in early design phases may be beneficial for compliant concepts so ULS loads can be improved
Tower	Tower needs to be re-qualified taking platform motions, increased loads and eigenfrequency changes into account
Installation	Installation procedures allow much more flexibility, but procedures are not yet well established and proven
O&M	Consideration of possibilities for tow-in; little experience over lifetime; challenges in accessibility, maintainability and workability.
Geotechnics	Not influencing dynamics (major contrast with fixed-bottom where particularly soil damping is highly relevant); only important to select anchor types (has highest relevance for TLPs);
DLC selection; wind farm clustering/lumping	Due to the expectation that in large wind farms the floating foundations will likely only differ by their mooring system, different methods will be applicable to cluster design conditions and potentially reduce simulation effort; however, directionality and wake interaction will be of increased importance (low floater yaw stiffness) and add additional, worst case conditions specific to the regarded concept may need to be added as DLCs.

Out of these differences, the major numerical design approach difference between bottom fixed and floating foundations are the requirements for more integrated and coupled design tools. Deliverables D4.4 [3] and deliverable D7.4 [4] are dedicated to the discussion of various numerical tools and state-of-the-art numerical design approaches for FOWTs. The current design process for bottom fixed structures is usually based on an iterative, sequential procedure, i.e. exchanging wind and wave loads, between the foundation designer and wind turbine designer to clearly distribute responsibility and risk and protect confidential information. Opposite to that, FOWTs are usually simulated with a fully coupled approach for the majority of concepts, where both load contributions are simultaneously applied, including consideration of the controller for operational loads. Otherwise the resulting load predictions may be of limited accuracy. It is essential for the industry to agree on a way to address this key issue.

Even though significant differences exist between the industrialized design of fixed-bottom and floating offshore wind turbine structures, a majority of these are focused around the design of the primary structure and the controller. Key design element synergies related to many aspects, such as secondary structures, structural analysis, mechanical and electrical design, geotechnics, and others can as well be identified and knowledge transfer from the fixed-bottom design will enable a more rapid development towards a mature floating wind industry by adopting and adapting existing methods. By making use of established best practice experience the learning curve timescales associated with cost reductions can be reduced.

3 Transition from conceptual design to detailed design

As the design reaches higher levels of fidelity, it must make the transition from its conceptualization stage to detailed design. This involves the specification of structural details, such as inner shells, girders and stiffeners to the existing conceptual design in a cost-effective manner allowing for industrialised manufacturing. The industrialized numerical design procedure for making this transition from conceptual design to detailed design is proposed using a generic concept. The flowchart in the Figure 2 represents the main stages involved in this procedure. To accomplish this task, a generalized approach described by Kräckel [5] and Tiedemann [6] is applied, which were based on existing Ramboll internal processes. This structural design and optimization studies are intended for ease of comprehension and adaptability of the proposed detailed design approach to different types of floater designs. It shall be emphasized that the below described approach is generic in the sense that for commercial detailed design projects, procedures adapted to specific commercial designs will be made containing more specific details. The below process is the process developed within LIFES50+ and not necessarily identical with Ramboll internal detailed design processes, which cannot be fully shared due to confidentiality.

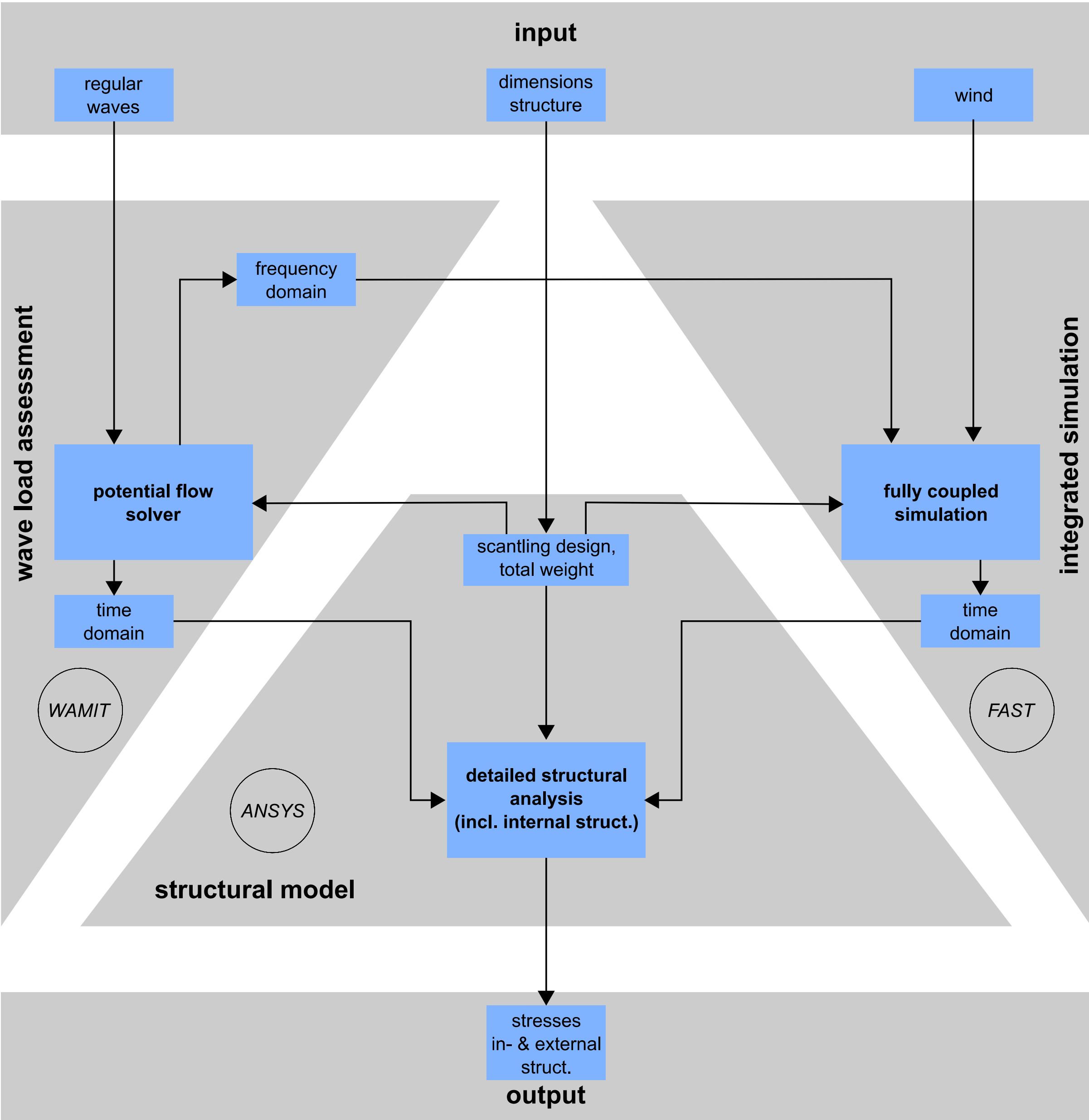


Figure 2. Flow chart representing generic numerical procedure for detailed design.

Loads are assessed based on environmental conditions of Ultimate and Fatigue Limit States. During a simulation in the frequency domain, the hydrostatic and -dynamic characteristics, as well as the pressure distribution on the hull are determined by the potential flow solver. The used model of the floater's wetted surface is a direct export provided by a macro. Subsequently, the geometry is assessed during a time domain simulation executed by a fully coupled aero-hydro-servo-elastic computer-aided engineering tool. The resulting sectional loads and states for global motion for every time step can then be applied to the FE model. Furthermore, the internal pressure, which is determined based on the flooded structure's fill level is added. A finite element model for the structural analysis is generated by a parametrized macro. Within its limitations, the script processes user input automatically to build an arbitrary model. It allows the variation of multiple parameters like general dimensions of the hull, or number and sizes of different internal structural elements. The macro offers the ability to generate automatized multiple designs with minimum effort.

3.1.1 Potential areas for cost cutting during the basic design phase

3.1.1.1 Steel floater:

- For the steel floater, the use of durable, welder-friendly and high-tensile offshore steel is recommended. A high availability on the market of this type of steel is necessary. S355J2+N represents a suitable example.
- As a non-alloy, low-carbon structural steel can be used for construction, as critical components and major structural members. It has good cold-forming properties and is available in a variety of width, length and thickness.
- For simplified construction, it would be possible to build the hull of substructures with stiffened flat panels only. Since these cause higher drag and/or drift forces, this advantage might be offset by higher costs for the mooring system. Thus, a cylindrical columnar structure is preferred.
- The main parts of a floating semi-submersible substructure— the columns and pontoons— are designed for hydrostatic pressure which is handled by internal braces, stringers and stiffeners.
- Bracings are avoided for the overall shape to cut production and maintenance costs and reduce the vulnerability to fatigue.

3.1.1.2 Concrete floater:

- On the other hand, the concrete floater can be built based on a simple design with clear load bearing, repetitive modules etc. Due to the well matured concrete construction industry, industrial best practices already exist for pre-fabricated modules of concrete sub-blocks and mechanized rebaring operations are available.
- The floating unit shall be optimized for its main purpose, namely the operation phase and minimum extra cost shall be required to solve temporary conditions.
- The floater must be designed to be manufactured at quayside to eliminate all challenges related to offshore lifting operations, future lack of suitable lifting tools etc.

3.1.2 Structural optimisation of the design

During a quasi-static structural analysis that features the loads resulting from the above-mentioned calculations, the stress distribution is assessed for the hull and all internals. This gives an overview on locations where hotspots occur during a specific wave period. The examined models can be used e.g. in sensitivity studies for the assessment of global stress distribution of internal and external structural elements. A suitable framing and compartmentation strategy is developed by following the common DNV standards, so that an economically feasible design for the internal structure is obtained. It is a critical area for cost savings and carries major implications related to the manufacturability of the substructure. Figure 3 shows a sample output from such a procedure.

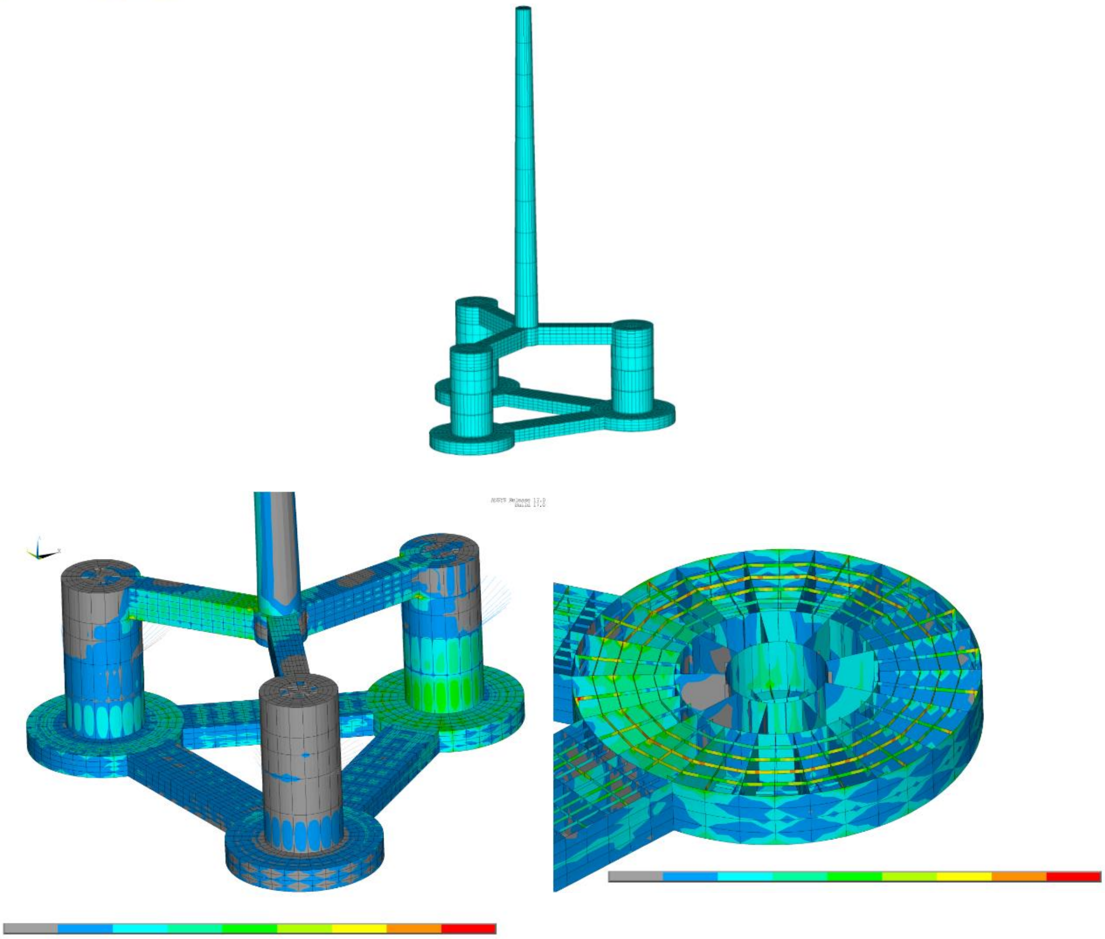


Figure 3: Top: Final design of the semi-submersible floating offshore structure (ANSYS model, no mesh); Bottom left and right: Distribution of overall stress and internal structure of lower column.

3.2 Design for manufacturing guidelines from the automotive and oil and gas industry

To standardize the simplification of design a set of design guidelines were developed and are commonly referred to as Design for Manufacturing and Assembly or DFMA in short.

In most conventional cases, the manufacturer is rarely involved during the design process even though a significant proportion of the overall costs are linked to manufacturing process-related operational expenses. This leads to many issues later and need for costly changes. Most of the issues arise only after the start of actual production, making them difficult to detect. Unfortunately, by this time it might be too late to mitigate these issues, which in turn causes problems in the form of unwanted costs and unprecedented delays. The manufacturer's input during the design will help identify manufacturing risks that the design may be subjected to.

In more general terms, using DFMA can help tackle these issues and simplifying design earlier during the manufacturing process development. DFMA has been widely accepted and successfully integrated into the design processes of many of the well-known global companies from many operating in many different industrial sectors. Moreover, these companies have reported savings worth billions in terms of manufacturing costs after successfully integrating this concept during design. The DFMA concept includes a set of guidelines to help with the simplification of the design [7] [8] and are listed as follows in Table 2

Table 2. DFMA guidelines for simplified design.

DFMA guideline	Description
Modular design	Modularization basically reduces the complexity in design. Typical manufacturing activities can be more easily applied to the modules. The biggest benefit provided by modularization is how it deals with change. Design changes of a module are simpler to adapt rather than design changes to the entire design which is more time consuming. Modules also allow the design to integrate more variety and flexibility, allowing the design to cater to varying needs without needing huge changes.
Reduce total number of parts	The total number of parts in the design have a direct relationship to the cost and time. This provides the best opportunity for reducing manufacturing costs. In general, it affects all activities related to the fabrication of the structure and not just the area of manufacturing. One way to reduce the number of parts is to identify the critical parts. The critical parts are those which fulfil a particular function and have relative motions with respect to the other parts. Parts that make the assembly and fabrication difficult should either be redesigned or eliminated.
Standardizing components	The use of standard items readily brings down costs and improves the overall efficiency of the process. The reliability and availability of the goods are also well documented, and the chances of errors are also minimum.
Multi-functional parts	When parts can be designed to handle multiple functions, then they indirectly lead to the reduction of the number of parts. For example, a part can be designed to be a structural member and a stabilizer for a ship hull design which eliminates the need for an extra component.
Design for easy fabrication	The component must be designed while considering the manufacturing process and assembly in mind. The designer must have a good idea about the different manufacturing processes that are used to produce the component. When the designer lacks details regarding the manufacturing process, it is recommended to take the inputs of the manufacturer and create an interactive feedback loop to design. This will allow the design to consider limitations of the manufacturing process and stay within manufacturing constraints. Moreover, the optimum combination of material, labour and type of manufacturing processes can also be determined using this method.
Integrate fasteners into design	Separate fasteners like screws, bolts or rivets increase the cost and time during manufacturing and assembly of a part due to the numerous handling and feeding operations that need to be performed. These operations in addition to being unnecessary, reduce the overall manufacturing efficiency. Thus, designers should avoid separating modules and if necessary, should keep the number of connection points to a minimum.
Minimize assembly movement	As much as possible, the design should encourage assembly from one direction. The best direction is considered as adding parts from above, in a vertical direction, using the effects of gravity. This way the assembly does not have to compensate for its effect while moving heavy parts.

Increase compliance	It is quite common for errors to occur during insertion or joining operations. It is particularly common for these errors to take place when the parts overshoot the specified geometric tolerances. For this reason, it is considered good DFMA practice to include compliance into the design. A popular example of built in compliance features include tapers or chamfers and moderate radius sizes to facilitate easy fitting and joining of parts.
Minimize handling	Minimize the amount of time a part spends travelling from inventory to the manufacturing area or from one place to another. This is considered to be wasteful and delays production processes.

4 Transition from design conceptualization to manufacturing process development

To help in the assessment of manufacturing maturity for FOWT technology, there exists a pre-defined set of stages referred to as the Manufacturing Readiness Level (MRL). These indicators work similarly as the Technology Readiness Level (TRL), but the evaluation procedure is oriented towards building a cost-effective and low risk manufacturing methodology. TRL and MRL should ideally mature in parallel but this rarely happens in real-life situations, as often a focus is set on technology first.

As a general disclaimer, it shall be emphasized that LIFES50+ is a H2020 RIA R&D project and the floater concepts were matured within the framework of this &D project, which inherently implies that they are focussed on TRL and only partially align with MRL, as e.g. a H2020 RI action or moreover a commercial development will be. Therefor it must be stated that the below results should be assessed on this basis and does not necessarily relate to the commercial versions of the concepts assessed below. Nonetheless, the study results provide relevant insight into typical challenges regarding MRL levels and also can provide a template for MRL assessments.

4.1.1 MRL assessment

To investigate the status of the manufacturing maturity of the selected concepts, a MRL questionnaire was sent to the selected concept developers for steel and concrete. In total, the original questionnaire [9] comprises of 419 questions distributed among MRL 1 to 10. The number of questions increases with MRL maturity. This is understandable since during the early basic research phases, uncertainty is high, and a basic manufacturing methodology is not in place yet. However, since the LIFES50+ project's goal is to reach TRL 5, only questions related up to MRL 5 were deemed necessary and answered by the concept developers. The answers were later evaluated and the results from this evaluation are consolidated and presented in this section. The answers and their respective company names will not be included due to reasons related to confidentiality and to maintain brevity.

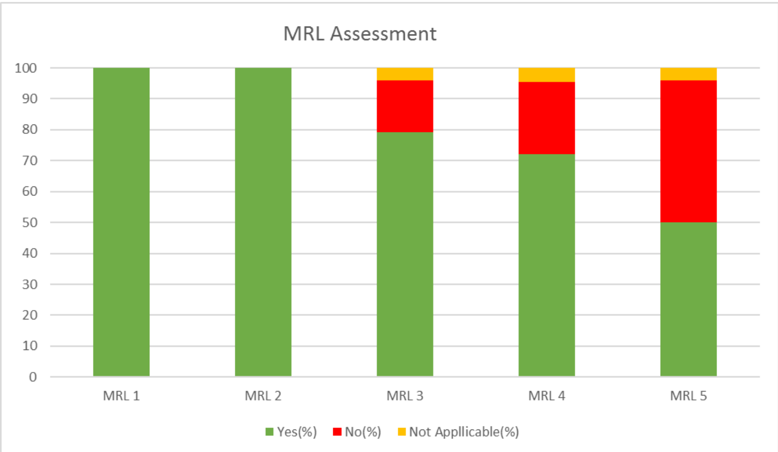


Figure 4: Exemplary, generalized results from the MRL assessment.

Figure 4 depicts the status of the MRL consolidated according to the answers by concept developers.

The structure of the questionnaire, however, needed modification to make it simpler to use and improve clarity. Responses to the previously open-ended questions were now restricted to just three replies (YES, NO or Not Applicable (N/A)). Only if a question is answered YES, then these questions transform into an open-ended form. In this case, they must be supported with reliable proofs (if applicable) or alternatively, few comments describing how that phase was achieved must be included. If all questions pertaining to an MRL are answered with a YES, then that MRL is said to be attained and the maturity passes on to the next MRL. Note that since the questionnaire has quite a general outlook and is not particularly customized to the manufacturing of floating offshore structures, there were some questions identified in each level that were not relevant to FOWT manufacturing. These were marked as N/A.

One can notice questions that were not applicable to the floater fabrication scenario represented by the yellow bar. In contrast, the green bars represent a completely mature MRL. Whereas, the red bars represent the relative percentage of questions that were answered with a NO. On closer observation, it is evident that the number of questions that received a NO increased while moving from MRL 3 to 5.

Relative inconsistencies were found between the answers given by different concept developers as well. These discrepancies can be traced back to the subjective interpretation of the questions by the concept developers. This questionnaire was originally designed with the primary intention of providing a comprehensive self-assessment in terms of manufacturability. So, using the results as a relative measure to compare the MRL maturity between concepts should not be the main goal here. It is important to factor in this subjective bias if at all a comparison between the floater concepts is to be made in terms of their respective MRL status. However, a comparison and is not recommended. The results from the questionnaire were separately sent back to concept developers for further assessment as their manufacturing technology matures and may provide useful input for commercial designs outside LIFES50+ as well.

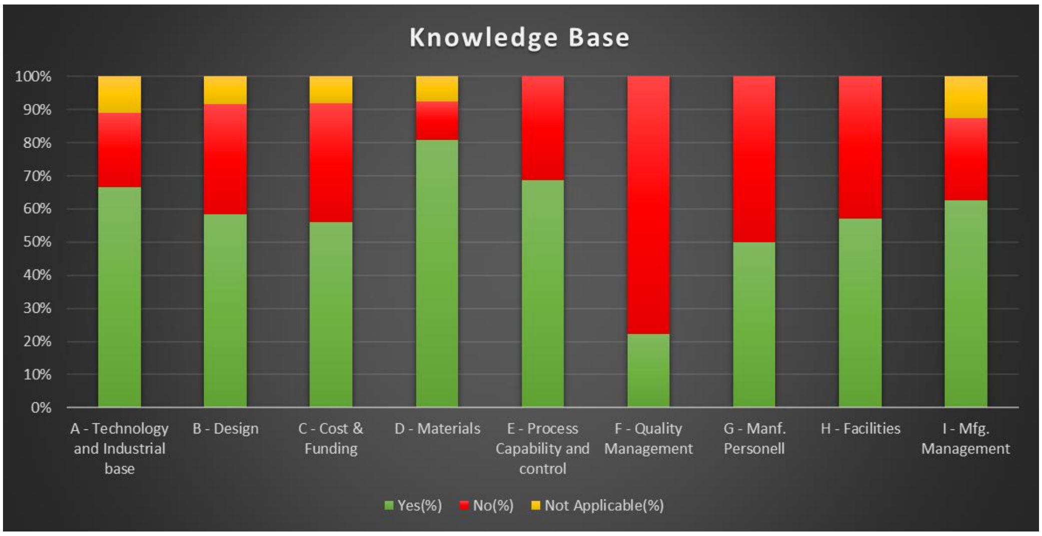


Figure 5: Exemplary graph indicating areas of knowledge scarcity.

An attempt to further analyse the information obtained was made by grouping them into separate categories as shown in Figure 5. These independent categories represent the building blocks in a typical manufacturing process development.

The main advantage of using this type of a classification is that now it is much easier to identify areas that may have been overlooked or ignored during the development process until now. A lack of research in these areas now, can potentially lead to missed process improvement opportunities or unidentified risks leading to costly changes later. Hence it is strongly recommended to acquire adequate information in these critical areas before proceeding to full scale demonstration.

Figure 5 depicts some such areas where research efforts need to be diverted. In general, the most critical area was identified as "Quality Management". On the other hand, "Process Capability", "Manufacturing

Personnel" and "Facilities" were other areas that that showed gaps which may be typical for technology focussed developments such as the LIFES50+ concepts.

One conclusion, which was very evident from the questionnaire — without being subjected to any bias— was that the current MRL lags the current TRL. To put this into perspective, it can generically be said that the rate at which the floating technology has advanced in terms of its technology is higher than the rate at which its accompanying manufacturing processes is advancing.

Although a few prototypes and one pre-commercial floating wind farm have been already developed, and basic expertise is already in place in terms of floater fabrication, the FOWT technology for the concepts generally still lacks a manufacturing proof of concept for large scale commercial serial production. Particularly, if a large-scale production scenario involving 50 units is considered, no prototypes or demonstrations exist currently. A proof of concept involves a methodological description of the operational steps needed to fabricate, assemble, load-out and install the substructures at sea. Figure 6 depicts the current state of MRL for the LIFES50+ concepts in this project, representative for many floating wind concepts at similar development stages.

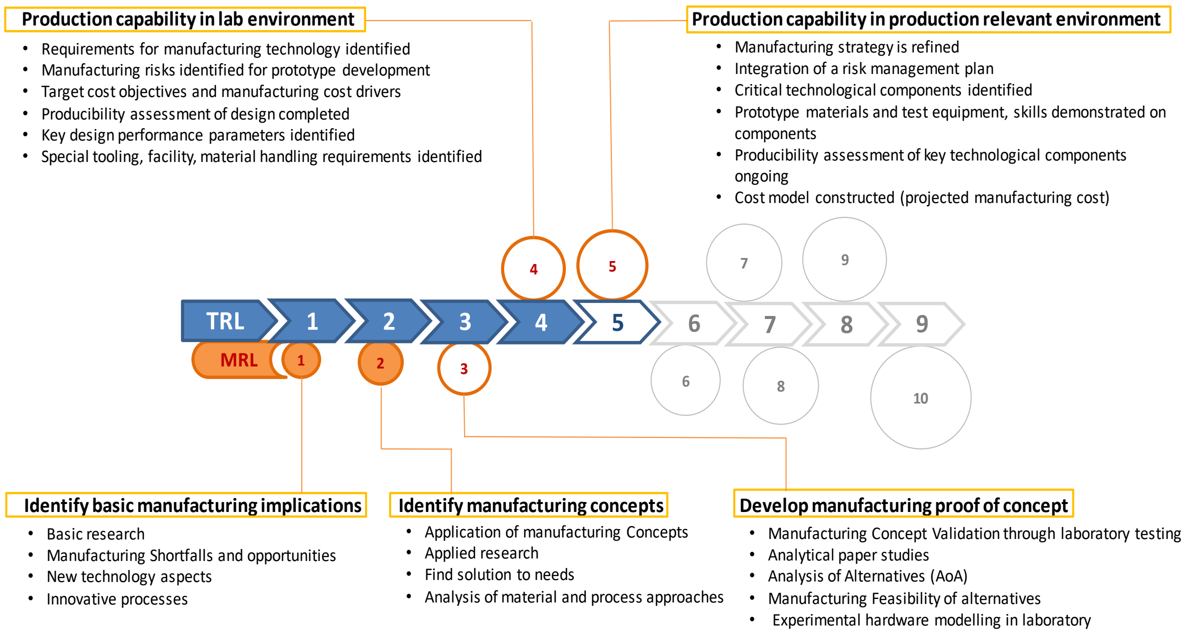


Figure 6: MRL and TRL relationship and scope of MRL assessment.

4.1.2 Future research considerations regarding MRL

To better understand the type of manufacturing risks involved and the essential steps that need to be taken to close the knowledge gap between MRL 3 to 5 (see Figure 4 and Figure 6), the following list of questions are provided.

Note that the purpose of these questions is to provide generic input to the community of FOWT concept developers regarding the challenges of commercialization and industrialization which may be addressed in the future. Although these questions are customized to be applied to the assessment of FOWT manufacturing, they are still based on the original MRL questionnaire and are divided accordingly into their respective categories as mentioned previously in Figure 5. For reasons of brevity, only the most essential questions are listed. For further details refer to the MRL questionnaire found in [9].

A. Technology and Industrial Base

- Is the available industrial technology adequate for FOWT manufacturing?
- Does the industrial base use the state-of-the-art manufacturing technology?
- Have manufacturing processes and risks been identified for the concept?
- Have required investments for technology development (for the attainment of both design and manufacturing maturity) been identified and funded?
- Have potential manufacturing sites been selected?
- Have potential constraints and limitations pertaining to the site been identified?
- Have potential obsolescence issues and site related problems been identified?
- Do the existing facilities and manufacturing technologies need substantial upgrades?
- Has manufacturing risk (availability of process, sources and materials) been considered?

B. Process Design

- Have the concepts been assessed for manufacturability?
- Have trade-offs between different manufacturing options assessed?
- Is the concept's lifecycle and technical requirements evaluated with respect to manufacturing?
- Are different manufacturing options weighed based on costs and development time?
- Have broad performance goals been identified that may drive manufacturability?
- What are the new frontiers in FOWT manufacturing where breakthroughs are likely to have a major impact to the way FOWT substructures are built?
- What are the major bottlenecks (critical areas) in the FOWT substructure manufacturing process?
- Which new manufacturing concepts are being explored and how do they tackle bottlenecks?
- Is a high-level process chart developed?
- Have the basic steps and work centres in the process been defined?

C. Cost & Funding

- Is a heavy investment needed in setting up the manufacturing facility?
- Who are the major investors for manufacturing and which programs are they funding?
- Have relevant approaches for the design of a cost model been defined?
- Which is the cost-intensive areas in the FOWT substructure manufacturing process?
- Is a dedicated cost model for analysing manufacturing costs already in place? (The parameters for this model could include costs associated with design, transition, ramp/learning, hidden factory costs, logistics, supplier, after-market, O&M, disposal, etc.).
- Have areas with the highest cost reduction potential been identified in the manufacturing process?
- Have different solutions to make the process more affordable been analysed?
- Do the cost estimates consider the costs associated to rework, scrap and repair? (Production cost estimation can be conducted by using several means, including formal Production Cost Models, parametric estimates, sensitivity analysis, cost risk bands based on technical maturity, etc.).
- Are relevant cost drivers such as material, labour, overhead, tooling, yields, rework, repair, etc. for each part of the product life-cycle cost identified?
- Has the uncertainty involved in the cost drivers been quantified? (Process variables need to be quantified based on costs).
- Are critical issues involving large cost items with large variations or new items with unknown costs identified? (Variability in costs can be visualized using sensitivity analysis)
- Has a value stream mapping been conducted for the process? (It shows the high-level breakdown of the process with different work centres and its associated cost centres).

D. Materials and Supply Chain Base

- Does the type of material being used by the substructure affect the manufacturing process drastically?
- Is it likely that new materials would replace the existing materials used in the near future?
- Are there new manufacturing processes needed to produce the FOWT substructure?
- Have make/buy decisions been initiated?
- Do the make/buy evaluations include production considerations reflecting the pilot line, Low Rate Initial Production (LRIP), and Full Rate Production (FRP) needs?
- Have potential supplier survey/ supplier selection strategies been identified?
- Have on-site assessment of potential suppliers been conducted?
- Have the lead time estimates related to material procurement estimated?
- Has the feasibility of the supply chain been demonstrated in other industrial projects?
- Are proper mitigation strategies in place for addressing risks associated with the supply chain?

E. Process Capability and Control

- Have initial simulation models pertaining to the manufacturing process been developed?
- Have model parameters, variables and boundary conditions been specified?
- Are existing models available which can be adapted to FOWT floater manufacturing?
- Have initial estimates of the yields and rates based on assumptions been completed?
- Have critical processes and pathways been identified?
- Have process capability requirements been identified for pilot line, Low Rate Initial Production (LRIP) and Full Rate Production (FRP) scenarios?
- Have the risks associated with the critical process been identified?
- Have potential production scale up issues been identified?

F. Quality Management

- What data is available from similar, more mature systems to assist in quality planning?
- Are there any lessons learned on quality strategies from other similar industrial sectors?
- What is the effect of quality control on costs, schedule and performance?
- What are the critical areas in FOWT manufacturing that need effective quality control?
- Are inspection and acceptance testing strategies already in place?
- Is an investment in new tooling and test/inspection equipment required?
- Are quality control procedures for weight restrictions and dimensional tolerances available?
- Is the quality of the raw materials controlled?
- Which areas do not need strict compliance to quality and does slacking in these areas have implications to cost and time reduction?
- What feature/key components need total quality control? (E.g. Critical joint sections)
- Have supplier quality issues been addressed? (if any).

G. Manufacturing Personnel

- Have new manufacturing skills been identified?
- Have the manufacturing skills needed to produce, test and support the proposed concepts been assessed in the required number and time frame?
- Do existing personnel have similar skills to those required and/or can they be cost-effectively cross-trained?
- Have production workforce requirements (technical and operational) been evaluated?
- For high tolerances and quality requirements, are skilled workers fulfilling such requirements difficult to find and how does it influence cost?
- Have special skills, certification and training requirements been established?

H. Facilities

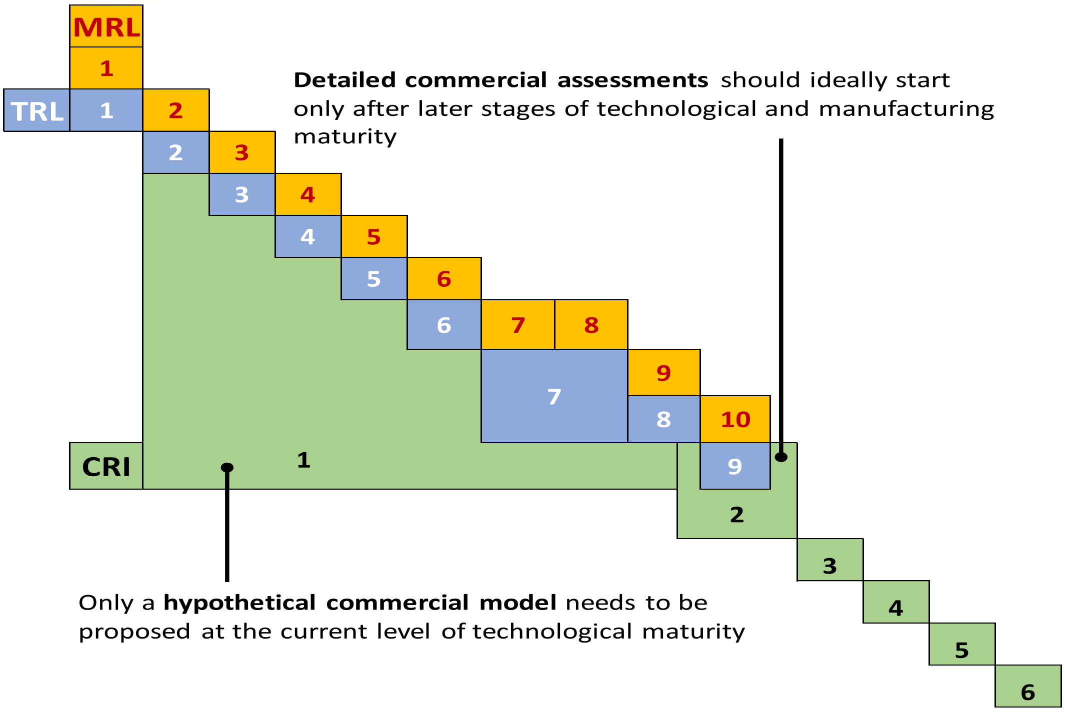
- Has the availability of manufacturing facilities for prototype development and production been evaluated?
- Is available capital enough for required facilities, test equipment and tooling?

I. Manufacturing Management

- Has a manufacturing strategy been developed and integrated with the project's commercialization goals and acquisition strategy?
- Have prototype schedule risk mitigation efforts been incorporated into this commercialization strategy?
- Is there a well-documented roadmap to achieve manufacturing maturity?
- Has the manufacturing strategy been able to refine and fine tune based upon this MRL evaluation?
- Has the manufacturing strategy been refined based upon the preferred concept?
- Is a baseline risk mitigation strategy in place to identify and mitigate all kinds of risks in the different life cycle stages of the floater?
- Have the technology development components been associated to lead time and cost estimates?

4.1.3 Commercial readiness and its implications to TRL and MRL

During later stages of technological maturity, it is also recommended to assess the commercialization aspects related to the technology using the Commercial Readiness Index (CRI). Although the CRI certainly does not concern itself with the design, it may have major implications at later stages of the concept development at higher levels of TRL and MRL maturity. As technology matures and more complicated large-scale demonstration starts, it becomes increasingly important to find the necessary investments for the development of these projects. Finding investors and presenting them with a clear overview of the process and the design then becomes crucial to maintain transparency and funding. One way to tackle this issue presents itself in the form of Commercial Readiness Index (CRI) developed by the Australian Renewable Energy Agency (ARENA) [10], see Figure 7.



	TRL
1	Basic principles observed and reported
2	Concept/application formulated
3	Concept Demostrated (analytically or experimentally)
4	Key elements demonstrrated in laboratory
5	Key elements demonstrrated in operationallaboratory environments
6	Representative of the deliverable demonstrated in relevant environments
7	Final development version of the deliverable demostrated in operational environemnt
8	Actual deliverable qualified through test and demonstration
9	Operational use of deliverable

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

	CRI
1	Hypothetical commercial proposition
2	Commercial trial, small scale
3	Commercial Scale up
4	Multiple commercial applications
5	Market competition driving widespread deployment
6	Bankable asset class

Figure 7: Scheme demonstrating integration of TRL, MRL and CRI in various stages.

5 Key areas relevant to the large-scale production of FOWT

This deliverable covers the development of a conceptual manufacturing methodology for the large-scale manufacturing of FOWT substructures. A manufacturing study was conducted for each of the two selected concepts for steel floater, developed by NAUTILUS Floating Solutions (hereafter NAUTILUS), and the concrete floater, developed of Dr. Techn. Olav Olsen (hereafter OLAV OLSEN). The studies were supported by subcontracted companies with relevant practical hands-on expertise in handling the production of offshore structures. Ramboll with close cooperation with the concept developers ensured that the objectives of this study were always being met. A generalized manufacturing methodology focussing on the large-scale manufacturing of multiple floating units was later developed by taking the proposed methodologies from the subcontractors. The scope of the study was an industrial production of 50 units in 2 years.

5.1 Manufacturing

Both steel and concrete floater manufacturing are considered, and relevant recommendations are provided. Firstly, a generalized methodology is presented based on proposed methodologies for steel and concrete by the subcontractors. Then the main items in the proposed methodologies for steel and concrete are separately highlighted. Please note that the optimal design, material and fabrication strategy is highly market dependent (existing supply chain, infrastructure) and site-specific and, thus, difficult to obtain through a basic study. Therefore, the results of this study should be considered highly generic and may be different for individual cases. A detailed investigation on a case-by-case basis must be conducted for optimal values.

5.1.1 Basic Manufacturing methodology for the large-scale manufacturing of FOWT substructures

The generalized manufacturing methodology is based on the results from the comprehensive manufacturing studies conducted for the steel and concrete floating concepts respectively. The steps encompassing this methodology are applicable to the mass production of any floating concept. Figure 8 depicts the sequence of steps, and the key inputs and outputs from each step. The start of production is indicated by "RUN", which initiates after the production scheduling step. Once production begins, the process must be continuously monitored and improved in order to achieve a lean and optimised process.

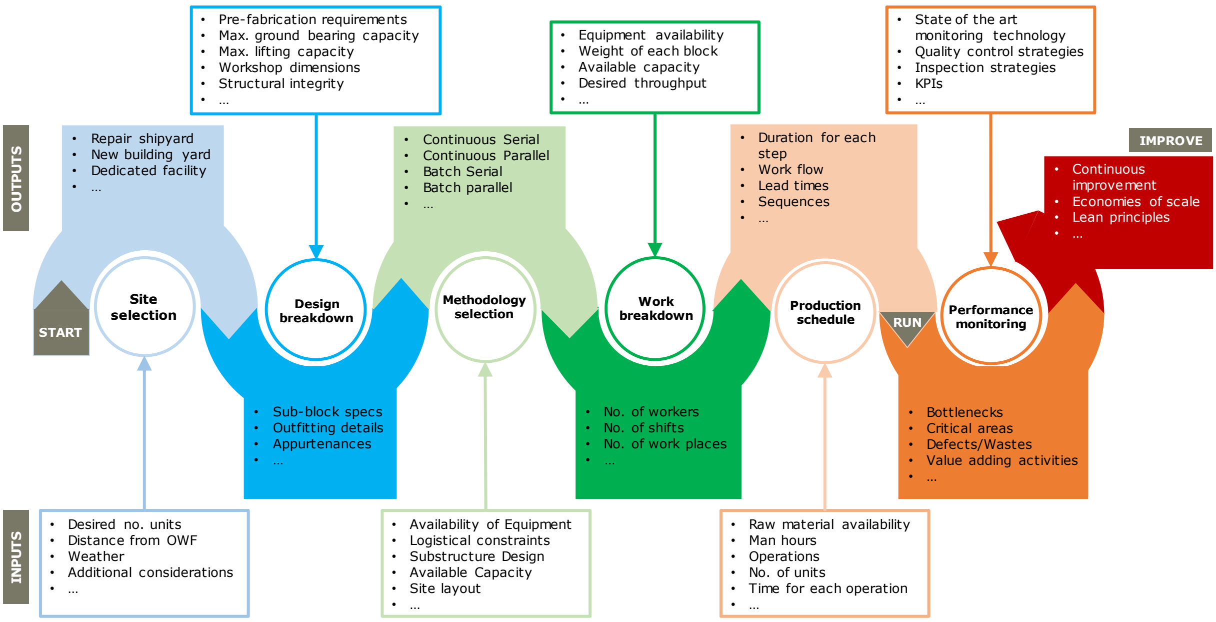


Figure 8. Generalized production methodology for floater manufacturing.

5.1.2 Conceptual production methodology for steel floater

Two shipyards were proposed for the production of 50 units for LIFES50+ reference site A [11]. The first site was chosen as the Chantier Naval de Marseille shipyard situated in Marseille, France. The fabrication of blocks takes place in the workshops and then the completed blocks are transported to the final assembly dry dock as shown in Figure 9. The shipyard is a repair yard consisting of many dry docks, which means that workshops need upgrades and that it has limited capacity in terms of storage and manufacturing. Due to the limitations, this shipyard alone cannot manufacture the entire set of 50 units in 2 years, as required in this study. So, the production of only 30 units is assumed from this yard.

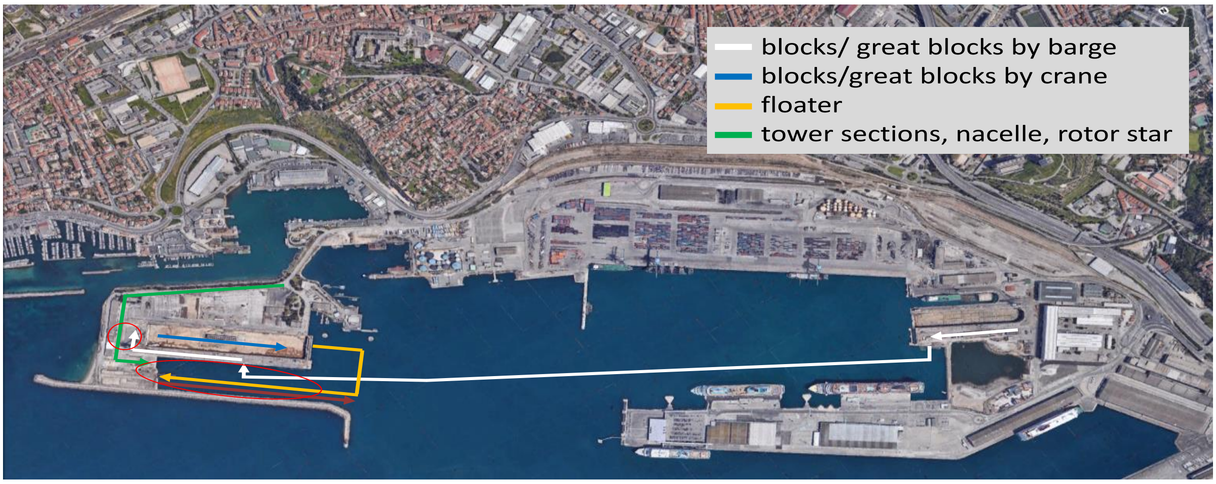


Figure 9. The main fabrication and assembly sites at Chantier Naval de Marseille (steel).

To meet the capacity requirements, another yard in Cadiz, Spain was chosen as well. The Navantia yard is a new building yard, which unlike Marseille, is well equipped with on-site manufacturing facilities and required equipment and dry docks. It is also well experienced at handling offshore wind projects as shown in the Figure 10 below. The production of the remaining 20 units is assumed to take place in this yard in this study. Note that the production at both sites start simultaneously to reduce lead time.

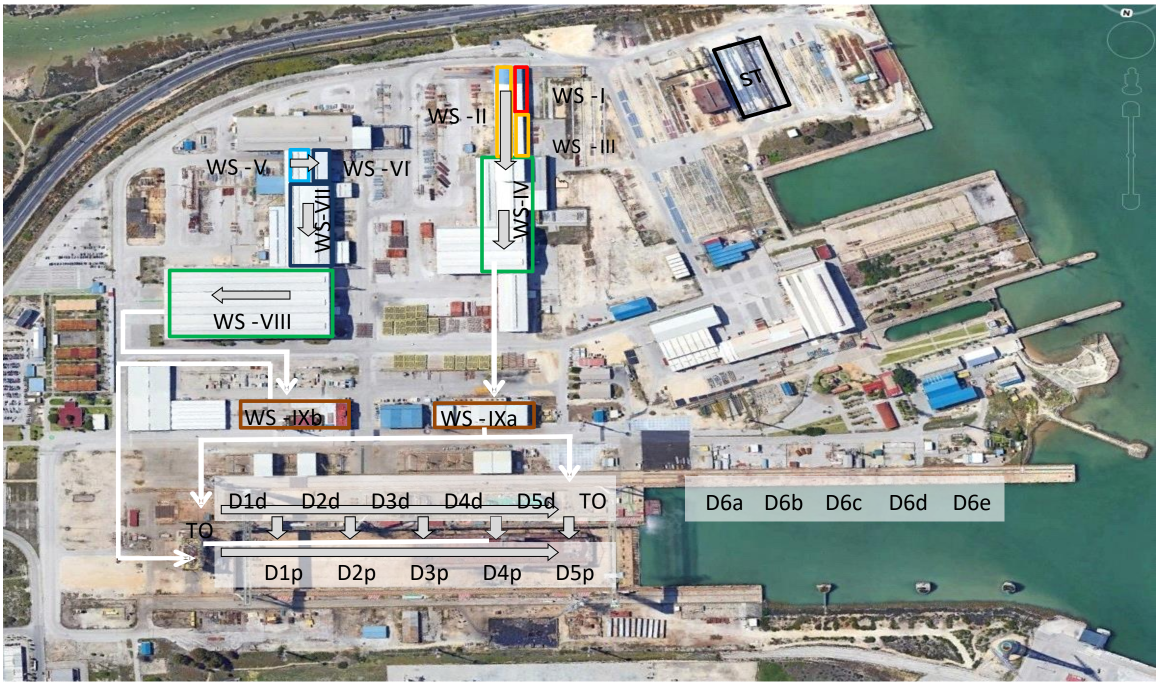


Figure 10. Dedicated fabrication and assembly sites at the Navantia shipyard in Cadiz, Spain (steel).

The key figures for both these yards are summarized in the following Table 3.

Table 3: Overview of the assumed production capacities of the selected sites.

Particulars	Marseille	Cadiz
Floaters to be built	30	20
Output of floaters	1.5 floater/month	1 floater/month
Steel throughput	5700 t/ month	3800 t/ month
Lead time to installation offshore	20 months	17 months

The schedule for the final assembly at Marseille follows a serial production setup for assembling 5 floaters in series in 100 days in dry dock and is depicted in Figure 11 below.

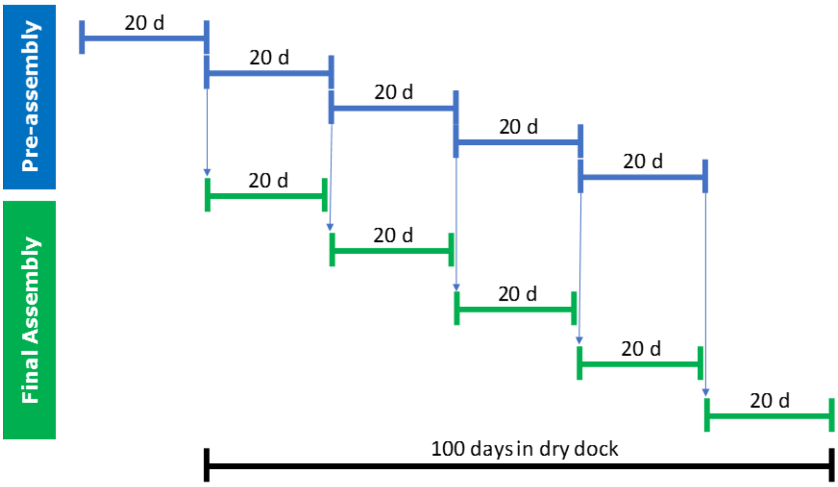


Figure 11. Final assembly schedule at Marseille (serial production, steel).

In contrast, the final assembly at Cadiz follows a batch parallel setup for assembling a batch of 5 floaters at a time in 125 days in dry dock and is depicted in the Figure 12 below.

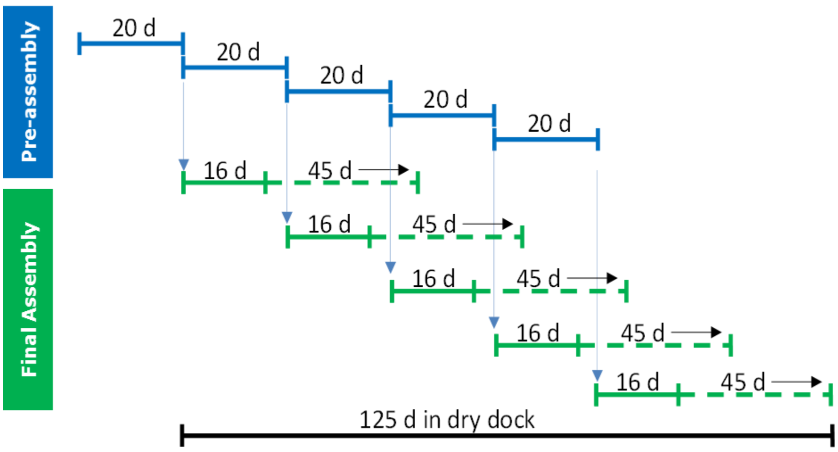


Figure 12. Final assembly schedule at Cadiz (batch parallel production, steel).

By comparing the assembly schedules with each other, it can clearly be seen that the serial production setup at Marseille (100 days) is faster compared to the batch parallel production setup in Cadiz (125 days). The batch wise assembly suffers from intermittent delays due to the uneven utilization of the workforce and equipment (painters, welders, etc.), as the resources must wait until its preceding processes are finished. From this basic and exemplary investigations, a serial production setup is recommended during the final assembly of floaters at this scale.

After the final assembly, the floaters are floated up in the dry docks and then towed to their respective sites, where the WTG is assembled. For Marseille, the assembly of the WTG takes place at the same site, whereas the completed floaters in Cadiz are towed to Marseille for further assembly of WTG. Once the WTG installation is completed, these floaters are ready to be towed to and installed at the wind farm site.

5.1.3 Recommendations for steel floater manufacturing

For large-scale manufacturing of steel floaters requiring shipbuilding techniques, the usage of newbuilding shipyards instead of repair shipyards is recommended as these kinds of shipyards usually have a full-fledged steel fabrication facility close by. In general, shipyards are located at shore or close to the open sea at large rivers which makes them a well-suited production facility in comparison to inland facilities, which increase the overall distance to the farm installation site. These characteristics make these yards well suited for the large-scale manufacturing of steel floaters. The employees of the yard are also well trained in operations related to steel structures (rolling, bending, cutting, blasting, welding, painting, etc.) due to their experience in dealing with ship building and other offshore O&G structures, maybe even related to wind energy projects such as jackets or monopiles.

Particularly, a manufacturing methodology is proposed that makes use of existing shipyard facilities. It must be ensured that the chosen facility complies with the dimensions of the floater. A detailed layout of the facility must be drawn considering additional space requirements which may be needed if an upgrade is necessary. Existing fabrication facilities generally have necessary equipment already available according to their ship building and steel fabrication needs. But if a large-scale production scenario needs to be initiated, the available capacity of these facilities in terms of the equipment, workspaces and manpower needs to be thoroughly evaluated and the capacity constraints must be identified. Trade-offs between outsourcing a part of the operations or capacity to other shipyards would then have to be considered and the most economically viable option must be chosen.

Pre-fabrication of sub-blocks during fabrication is highly recommended, for example refer to Figure 13. This means that the pre-fabrication may take place at separate sites dedicated to handling the production of steel modules for the floater. These modules would be then transferred to the coating area and, finally, to the assembly area where the entire floater gradually takes shape. It must be investigated whether the available workshops are designed to meet pre-fabrication. The design must also be subdivided accordingly into pre-fabrication modules while considering the facility, transportation and manpower constraints. It is highly recommended to involve the manufacturer during the planning of block subdivision to ensure the design breakdown takes every aspect of the manufacturing process into account. Manufacturers also are well informed about best practices and may recommend design changes which may have critical cost saving benefits.

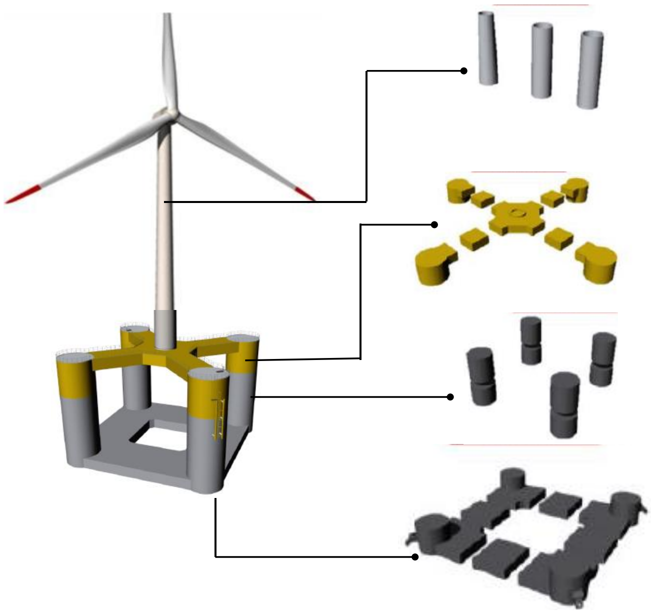


Figure 13. Basic design breakdown of the NAUTILUS floater using sub-blocks [modified from NAUTILUS].

The list of recommended upgrades needed in case of existing shipyards is as follows:

- Dry docks (if applied) need to be upgraded for final assembly of multiple floaters.
- Inclusion of an additional sea lock within the dry-dock to make more room for final assembly before float-up (depending on the production methodology), see Figure 22.
- Workshop automation by equipping high-tech rolling, bending and cutting machines
- Gantry cranes with magnetic grippers for easy material handling.
- Automatized submerged arc welding machines for better quality and efficient welding
- Storage areas with high tech (Radio Frequency Identification) RFID tracking system to track material flow is recommended
- Load bearing capacity must be checked for the accommodation of floater parts
- Workshops, coating sites and dry docks must be ideally located close to each other to minimize time spent in logistical operations
- An assembly sequence following a serial continuous production flow is found to perform faster than a parallel batch production flow in this exemplary, basic study

It shall be noted that in the market today also modular steel floater designs with different industrialisation approaches are proposed, relying on smaller supplied components to be assembled at port, not applying shipbuilding manufacturing techniques. Above results may not be fully applicable to such designs, as these have not been considered as part of LIFES50+.

5.1.4 Conceptual Production methodology for concrete floater

In contrast to the steel floater manufacturing, one dedicated manufacturing facility is proposed for the mass production of the OLAV OLSEN concrete floater. The nature of the concrete construction allows the portability of the equipment and raw materials allowing for a mobile plant setup. The location proposed for setting up such a production plant is Lundevågen in Farsund, Norway. This will act as the main construction site. Details regarding the site are provided by Figure 14 and Figure 15 below.

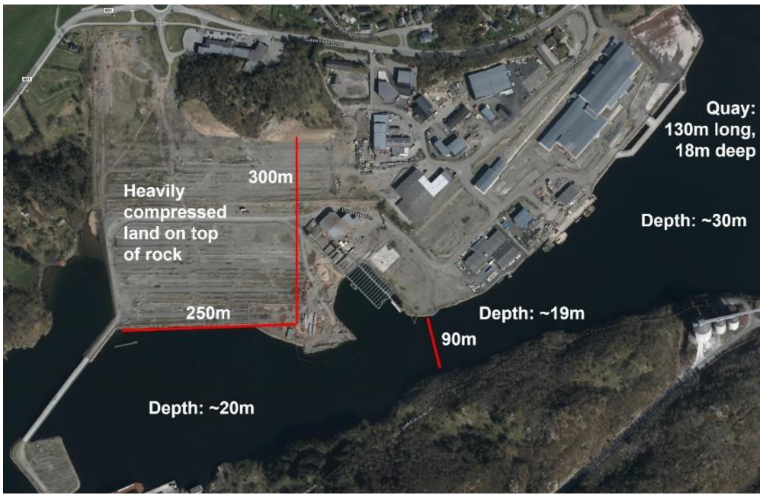


Figure 14: General specifications of the Lundevågen site (Farsund, concrete).

Figure 15: Proposed layout for fabrication and assembly (Farsund, concrete).

It is a green field ideal for the setup of a mobile batch plants since the construction plant can be assembled at the site using modular units and portable equipment. This is a common practice in the concrete construction industry. The main site itself is divided into two distinct areas indicated by phase 1 and phase 2 in Figure 15 below. The main idea here is to conduct the onshore assembly at phase 1 using a parallel production setup, where pre-fabricated blocks are cast together and assembled to form the pontoon and side columns only. The semi-finished structure is then launched onto a semisubmersible barge using skidding beams. The barge transports this structure to the second site marked with phase 2 where the floater is further completed. The production follows a batch parallel production setup (batch of 2 units at a time). The formworks are reused for both lines A and B. The use of pre-fabricated rebar units is recommended.

- **Phase 1** (onshore): bottom slab, outer and circular walls, internal walls
- **Launching** using standard barge and skidding beams
- **Phase 2** (inshore): top slab, roof corner tanks, mechanical outfitting

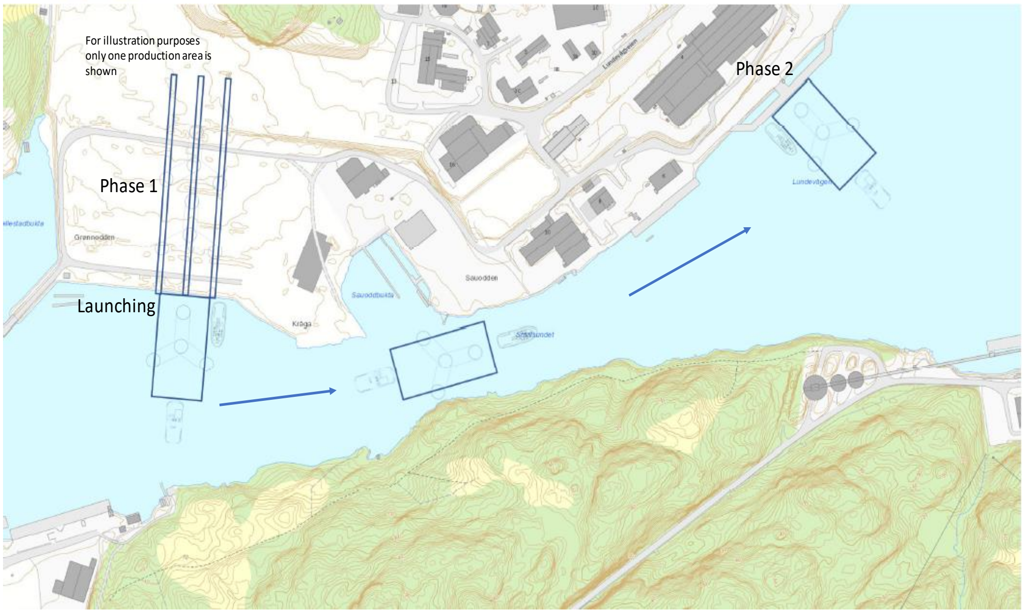


Figure 16. The two distinct phases in main production and the associated areas at Lundevågen, Farsund (concrete).

After the floaters are completed, the barge is submerged completely allowing the float-up of the sub-structure. The completed floating substructure is then towed to the WTG assembly site for further completion of the unit. For WTG installation, a separate shipyard—Kvina yard (Kvninesdal) is proposed, a couple of hours of towing away from Lundevågen. The shipyard is chosen as it satisfies the draft, dimensional requirements of the floater and wind turbine and required lifting capacity.

Figure 17. Details of the Kvina yard at Kvinesdal proposed for WTG installation (concrete).

The production schedule for the production of 50 concrete floaters in 2 years is as follows. The final assembly schedule at Farsund follows a batch parallel setup using two lines A and B each consisting of 2 bays. For assembling a batch of two floaters a span of 100 days is necessary, as shown in the Figure 18 below. To keep capital expenses low, the formwork is reused by line B after curing of line A which results in a waiting period of 10 days. In case the production rate needs to be increased further, an additional set of formwork needs to be purchased. Note that the usage of barges is assumed to carry out the launching and transportation between the onshore (phase 1) and inshore (phase 2) sites at Farsund. The shift system considers only work weeks (1 work week = 5 days) in the temporal estimation.

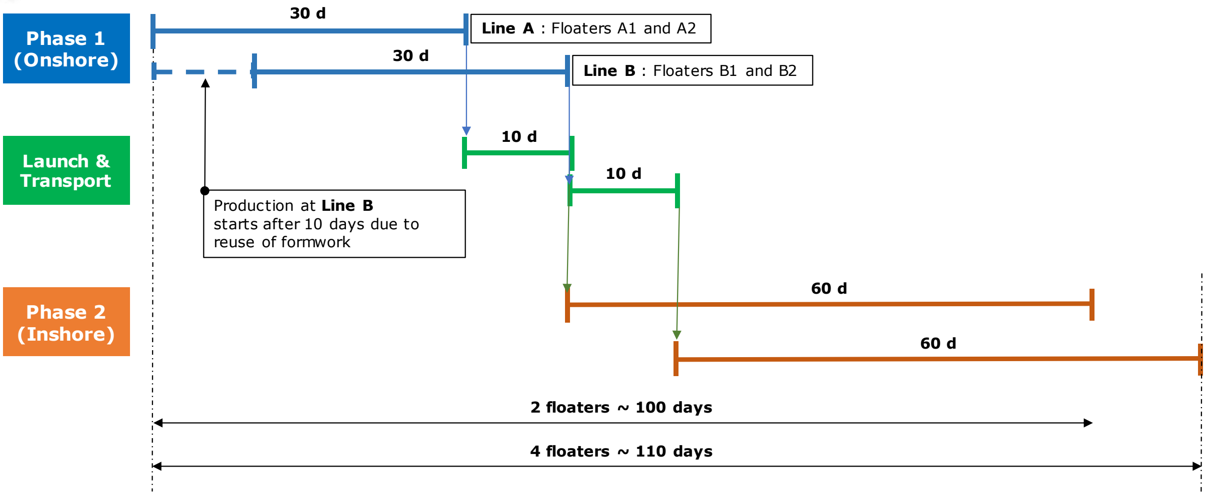


Figure 18. Final assembly schedule at Farsund (concrete).

5.1.5 Recommendations for concrete floater manufacturing

For the large-scale manufacturing of concrete floaters, a manufacturing study performed in the scope of this project proposes the setup of a dedicated manufacturing facility that concentrates solely on producing multiple floater units. Building such a manufacturing facility dedicated to the manufacturing of floating units will be an expensive undertaking involving large capital investments. But the nature of concrete construction allows its construction to take place anywhere given sufficient area is available. So, unlike the steel floater manufacturing, which is restricted to shipyards or alike infrastructure, the manufacturing methodology proposed for concrete floaters is more flexible when it comes to site selection. Inexpensive land can be selected rather than expensive locations.

Figure 19: Left: Mobile batch plant during transportation [12]; Right: Examples of quick assembly plant modules [12].

The nature of concrete construction enables the production to be conducted anywhere. The concrete industry has lately adapted its industrial practices to benefit from the flexibility offered by site selection. Mobile construction sites have recently gained popularity due to their numerous cost and time saving benefits (Figure 19). These sites are characterized by their quick installation times and ability to be adjusted or upgraded economically. Mobile construction sites use modular units for setting up the plant. The equipment needed for the operations can all be easily transported by normal transport vehicles. The modules also offer ample variations in setting up the facility thereby easing the site constraints when designing the floater. Nevertheless, there is a requirement of setting up a separate facility for pre-fabrication of rebars close to the final assembly site. If this is not possible due to limited space, then the option of outsourcing pre-fabricated rebars must be considered.

The large size and weight of the concrete floater makes it dependent on suitable cranes and lifts. Therefore, the proposed methodology recommends the manufacturing to take place in two distinct phases. The first phase involves onshore construction involving the partial production of the floater. A potential cost-effective alternative for minimizing the investments in heavy cranes to lift the concrete blocks that make up the floater is to use pre-fabricated rebars (Figure 20) instead of pre-cast concrete subblocks. This would enable easy transport of these pre-fabricated rebar modules and also will not require large cranes. These rebars can be transported to the site and assembled to the final shape, following which formwork and casting operations can take place. Considerable planning might be needed during the subdivision of rebar design to enable optimal assembly conditions without affecting structural integrity of the structure during its launching and transport operations. State of the art designing software are available to provide optimal rebar and formwork design solutions.

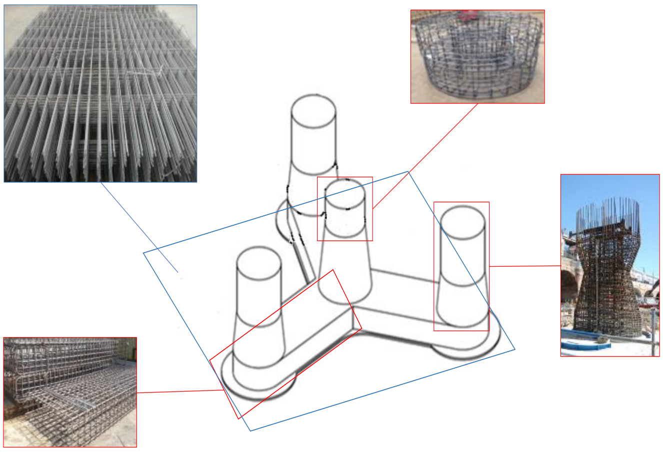


Figure 20. Exemplary subdivision of the floater design into prefabricated steel rebar elements [modified from OLAV OLSEN].

The onshore assembly ends with launching the structure onto a barge that would transport it to a nearby inshore facility where the remaining construction and assembly takes place. During launching the semi-finished structure is skid onto the barge using skid lanes which is a common practice in this industry. It must be ensured that the barge and the onshore cranes offer sufficient load carrying capacity. Moreover, the number of cranes and barges must be adjusted according to the required capacity to meet the demand of the required number of units. Further investigation might be necessary to check whether the structural integrity of the semi-finished structure is maintained during its launch and internal transportation.

The wind turbine assembly on the floater is proposed to be carried out at a separate location/facility with a sufficient draft. Once again, the site must be selected according to the available area for storage of the wind turbine parts and with sufficient number of cranes having sufficient load carrying capacity and additionally sufficient lifting height, particularly for large WTGs. The dimensions of the shipyard docks must be able to accommodate the floater of the desired size and weight. For the storage of the completed floating wind turbine systems, towing them to a separate, sheltered layup site where they are temporarily stored with adequate mooring is proposed. These sites are well regulated and are often used for the storage of container vessels offshore. These storage areas are located offshore, and they usually have very low layup charges in comparison to ports.

5.2 Comparison of manufacturing methodologies

Similarities and differences between the proposed manufacturing methodologies for steel and concrete and included in this section.

5.2.1 Similarities

Similarities between the steel and concrete manufacturing methodologies are:

1. **Similar Basic methodology**: The proposed methodologies for both steel and concrete floater concepts consist of analogous basic operations.
2. **Common bottlenecks:** Both methodologies are affected by common bottlenecks such as limited storage and barge capacity, limited lifting capacity, limited load bearing capacity, draft restrictions, storage capacity (pre-fabrication, WT parts, floating units), size of dry-dock, automation of machinery etc.
3. **MRL level:** Manufacturing maturity is still in its early stages for both production concepts and the manufacturing methodologies still need to be validated for reaching a commercial stage as discussed in the previous deliverable D5.3 [13].
4. **Industrial maturity:** Industries with vast expertise and maturity already exist for developing a full-scale production for both concepts. Industrial best practices from such industries can be adapted to be used for FOWT manufacturing.
5. **Improvement potential:** Well established quality control and lean management techniques can help improve quality and optimize the utilization of resources for both manufacturing methodologies concerning steel and concrete floaters.
6. **Cost reduction potential:** Benefits due to economies of scale can be expected for both methodologies as they reach higher levels of maturity.
7. **Parallel operations:** Both methodologies have operations that are scheduled in parallel resulting in minimized overall project duration. This reduces lead time and leads to an optimum utilization of resources.

5.2.2 Differences

Differences between the steel and concrete manufacturing methodologies are:

1. **Property of the material:** Concrete generally resulting in heavier structures demands a higher load bearing capacity and crane capacity in comparison to steel. This induces major constraints during the planning of transport and lifting operations. But innovation solutions such as of skid lines and pre-fabrication offer potential workarounds to overcome the challenges imposed due to the heavier objects.
2. **Sensitivity to weather conditions:** Since concrete is a robust material, it is less susceptible to external weather elements. The latter excludes the need for covered storage or sheltered production sites, which is not the case during steel floater manufacturing as it is susceptible to corrosion. However, a variety of primers and coating materials, in addition to proven technologies such as cathodic protection are available and already being used in analogous offshore manufacturing steel industries.
3. **Mobility and setup time:** Due to the in-situ characteristic offered by the concrete, its production can be carried out at any site. Investments in setting up a large production plant are lower in comparison to that needed for steel due to this characteristic. The use of pre-fabricated steel sub-blocks and mobile plant modules, pre-fabricated rebarring or precast blocks, reduces the setup time and costs related to it.
4. **Speed:** The steel floater has a speed advantage in terms of its world-wide supply chain maturity. An already mature supply chain that is well suited for mass production already exists speeding

up the overall lead time of the production of steel floaters. Additionally, the production of steel units can be performed faster than for concrete due to curing times and the potential for pre-fabrication. In contrast, the concrete floater can benefit from mobile sites and modular plants greatly decreasing site preparation times compared to steel. However, it must be noted that it is too early to draw definite conclusions at this point of manufacturing maturity. More studies must be conducted for measuring the effects of automation and economies of scale on both floater types.

5. **Availability:** The costs associated with the procurement of the raw materials for the concrete mix have mostly remained constant. This is not the case with steel as prices tend to fluctuate. But since steel reinforcement materials are used in the concrete floater manufacturing in the proposed concrete floater design, the effect of fluctuation of steel process may also have an effect in this case. By means of pre-fabrication of steel sub-blocks potential cost benefits originate from the availability of a world-wide supply chain and high competition.
6. **Variable costs:** Normal concrete is much cheaper compared to steel per ton of unit in general. Moreover, procurement of steel and raw materials for concrete in bulk further reduces their costs.
7. **Fixed costs:** Potential costs associated with setting up a mobile manufacturing facility for concrete is found to be lower in comparison to investments required in upgrading an existing facility like a shipyard.
8. **Carbon footprint:** Steel manufacturing has been found to have a 32% larger carbon footprint in comparison to concrete production for an analogous case study [14]. However, more research in this area may be required to confirm this claim in terms of floater manufacturing.

5.3 Logistics at production site

Logistics and infrastructure at the production site are an important influencing factor for the large-scale manufacturing of floaters. The floater design must be taken into consideration to make these logistical processes more efficient. Floater design should enable easy transport operations. Existing transport systems must be analysed based on their dimensions, load carrying capacity and fastening systems and the design of the floater must be adjusted accordingly. E.g. floater design can be adapted for easy loading and offloading on SPMTs by integrating an additional transport pallet to the original design. Submersible Barges can be modified to speed up loading processes of floater sub modules by introducing ramps or sliding mechanisms.

Automatization of the workshop to maintain a constant production flow can drastically impact production times. Gantry cranes having magnetic grippers or similar features can be installed in workshops to minimize time for setup in turn easing the transport of steel sheets during prefabrication. Lifting and height capacities of the cranes must match the maximum weight and dimensions of the prefabricated modules. Sufficient space must be provided in workshops for rework and repair works to be carried out without stoppage of the production line.

SPMTs are recommended for transportation of large blocks within the shipyard. These modular transportation systems allow the transportation of very large structures with high mass, see Figure 21. More modules can be added to the system in order to increase its load carrying capacity.

Figure 21: Left: Transfers of vessel onto barge using SPMT [15]; Right: Shipyard transporters by KAMAG with pay-loads of up to 1300 tonnes [16].

An upgrade of crane capacities on dry docks is likely required. Not only is it important to ensure that the cranes possess sufficient lifting capacity to carry the different floater components while lifting it to the dry docks, it also needs to be ensured that there are sufficient number of cranes to satisfy the required large-scale production output. Additional cranes may be needed to be setup at the dry blocks to minimize waiting times and quicken the transfer of blocks within the final assembly line, see Figure 22.

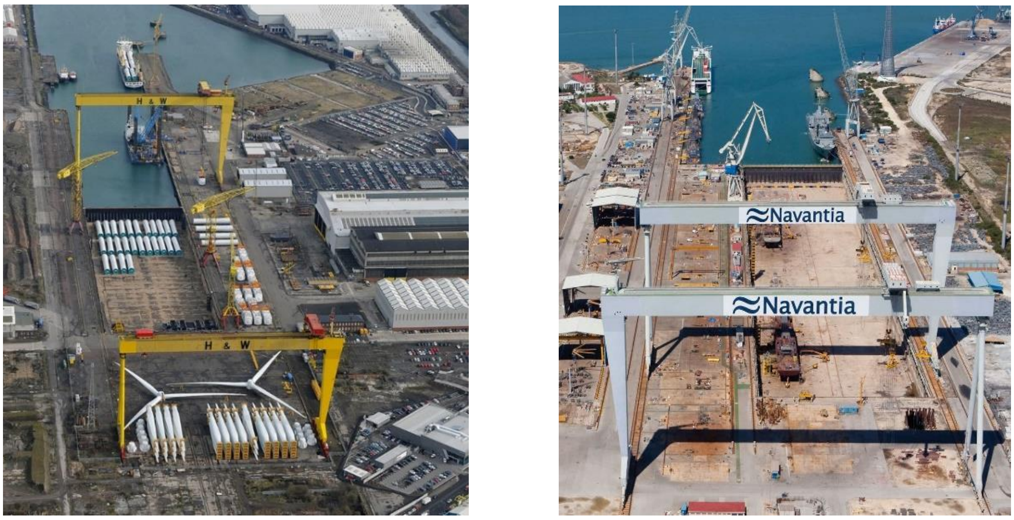


Figure 22: Left: Inner lock gate at Harland & Wolff [17]; Right: Navantia Puerto Real Shipyard view of the gantry and construction cranes [18].

It is highly recommended to carry out the wind turbine assembly operations at or near the same facility where the floater manufacturing takes place (Figure 23). This way, the need for offshore operations for wind turbine installation will be eliminated considerably reducing the development time. Investing in a crawler crane of sufficient height, lifting capacity and span specifications must be setup for this onshore operation. The area must be prepared for the storage of wind turbine parts and the unrestricted movement of the crane to increase efficiency.

In general, it must be ensured that only the optimum logistical pathways and areas are selected so that the travel time is kept at a minimum level. A thorough investigation of these transport lanes must always precede the FEED stage so that the floater logistics can be mapped in an efficient manner. State-of-the-art 3D mapping services are available to accurately map these pathways which can be later used for simulating logistical runs with enhanced precision.

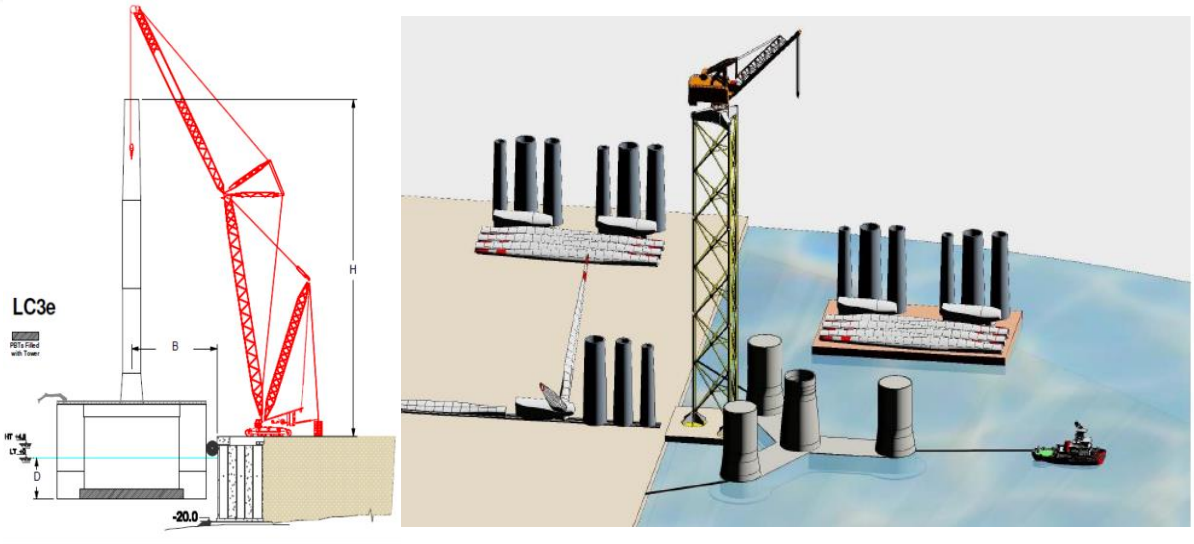


Figure 23: Left: Schematic assembly of wind turbine tower [NAUTILUS]; Right: Illustration of exemplary wind turbine assembly at quay side [OLAV OLSEN].

Adequate number of sea transport vessels such as tug boats, sea cranes (if relevant) and barges must be made available based on the required production output. The logistical pathways must also be planned accordingly by taking into account the influencing weather conditions. The distance to the port and the weather in particular have a major influence on planning installation and O&M operations. Since the manufacturing strategy will be draw on existing infrastructure and shipyards, the influence of other traffic and reserved capacity for other projects must also be assessed. Ideally, shipyards which are relatively less busy must be chosen in order to minimize interferences during the floater manufacturing.

5.4 Quality control recommendations

Typical shipyards maintain a quality control system according to recognized standards. Although, such systems are more oriented towards the production of steel floaters, few of these procedures may also be beneficial during the production of concrete floaters. Using such quality control measures (Table 4) not only ensures the longevity of floaters but more importantly reduces the number of defects and wastages that commonly occur in a manufacturing process, thereby making the process leaner and sustainable.

Table 4: Recommendations for quality control.

Methods	Details
Qualifications	Hiring of skilled personnel only. If required by class, all personnel should have valid certifications for their respective tasks (e.g. welder's performance certificates).
Usage of approved standards	In this study Ship building standards from the 12 IACS member associations are proposed [19]. Others: ISO, EN, IEEE, DNVGL, ABS, RAI, Class NK.
Application of tolerances	Tolerances should be applied following IACS recommendations. Selection of tolerance classes must consider technical requirements with respect to design and life cycle and optimal manufacturing conditions as recommended by the fabricator i.e. tolerances should be only as tight as necessary to avoid unnecessary high production costs.
Load cells	As an additional measure of quality control, the weight of each block/great block should be weighed. A high accuracy can be achieved using calibrated

	load cells. A suitable number of load cells should be placed between the support(jigs) of a completed block and the block itself. The number depends on the capacity and the required supporting points below the structure.
Procedures and Methods	Procedures and methods utilized in the floater construction should be based on approved procedures. E.g. The companies own internal procedures, procedures approved by an external supervision e.g. by class. Welding procedure specifications must be approved by class, coating procedures according to ISO standards.
Incoming goods inspection	All delivered materials are subject to an incoming goods inspection. Properties and certificates should be checked upon arrival.
Weld seams	Weld seams should be prepared and produced based on approved welding procedure specifications. Weld seams should be checked according to class requirements with respect to number of tests, test positions, test methods, requirements to documentation, etc.
Dimensional checks	Dimensional checks should be performed as required in the rules and regulations e.g. misalignment, distortion between stiffeners. Special consideration has to be paid to the interface sections of the blocks and sub blocks. Interface sections should meet the "global" tolerances as well as local tolerances (e.g. gap width of a weld seam).
Coating	Coating should be applied according to e.g. ISO 12944 ff. Quality control is performed acc. to part 7.
Other tests	For other components and equipment (e.g. tanks, pumps, piping, electrical installations) rules and regulations for quality control as well as proven methods are available too and should be applied accordingly.

5.5 Performance monitoring

Once the process is active, it is important to constantly monitor the process in order to maintain its overall efficiency and keep a check on defects or any other emerging bottlenecks. This is typically conducted using a pre-defined set of Key Performance Indicators (KPIs). These key statistics help measure the performance of the process. Recommended KPIs for the assessment of the production performance of floaters are listed in Table 5. Since the design of the floater is new, we expect a slow start which will increase later due to the learning curve effect predominantly observed during the beginning of most production runs. In the beginning the KPIs show the speed on which the fabrication gets on the scheduled track and performance. KPIs should be established for relevant processes indicated as bottlenecks (e.g. specific welding processes) as well as for the overall assessment of the production performance (e.g. output per year) as indicated below.

Table 5: KPIs used for performance monitoring.

KPIs	Description
Floaters per year	Represents the total output of floaters per year. Can also be used to measure for the total capacity of the yard. Higher value indicates better performance.
Fault rate	Identify rate of specific faults at every production step (e.g. weld seam defects, defects in the coating). Typical and accepted fault rates are well known in each areas of industry. A lower value is indicative of better performance.
Production hours per block	Hours / block is a measure for the effectiveness of the work performance and measured against the scheduled hours. Can be used for every stage of production and a lower value indicates a better performance.
Total time per block	It is a measure for the speed of fabrication for one block. It includes working hours and the number of workers, transport times, waiting times and time lost due to disturbances e.g. occurred by heavy weather conditions. A lower value indicates better performance.
Overall Effectiveness of Equipment	The overall effectiveness of equipment includes availability, quality and performance of equipment. Higher down times of equipment require a higher number of units, e.g. more welding machines without large impact to the production itself. A lower value here indicates better performance.
Weather Down Times	Final assembly is performed outside in a dry dock near the coast. All lifting operations are time critical but depend on the local climate and weather conditions, mainly wind speed. A lower value indicates better performance.
Use of auxiliary Materials	In all production steps auxiliary materials like welding wires, shot (blasting), thinner (coating), etc. is necessary. Increased use of these materials is related to higher costs and increased production hours. A lower value indicates better performance.

6 Considerations during offshore operations

6.1 Floating wind farm installation

This chapter covers the influence of the process of the floating wind farm installation on economic and environmental issues. The installation procedure of a floater consists of different steps and is launched after all shoreside work is finished. Generally, shoreside work implies the fabrication of the floater and the assembly and mounting of the wind turbine onto the floating substructure. It is further assumed that both dynamic cable and mooring system are pre-laid and not part of the herein considered installation process focussing on the substructure.

The float out – as the first part of the installation procedure – of the floater is port specific. For example, in the case of a dry-dock, the dock is flooded, and the floater is towed out, while in the case of a construction barge, the barge is submerged in order to initiate the installation. After the floater is prepared for the transit to the offshore wind farm site, typically involving temporary changes of the ballast, it is moved by appropriate towing vessels. Simple tug boats might be sufficient for self-stabilizing floaters and appropriate proximity from port to site, while projects in regions with more severe weather conditions or larger distances from port to site might require more resistant and specialized vessels. This does not apply for TLPs or other floater types, which are not self-stable. For these floater types, individual transport strategies are developed, usually. After the arrival at the wind farm site, the actual installation is initiated. The mooring lines are picked up by suitable vessels, depending on both mooring and site characteristics. Conditional upon the chosen technology, the hook-up is made. After the floater is connected to the mooring system, its ballast is adjusted in order to reach stable and safe operating conditions. Afterwards it is connected to the grid by attaching the pre-laid dynamic cable. Finally, the installation is terminated by testing and confirming the floating wind turbine functionality and operation.

In the following sections main influences and mutual effects of this installation process on other project phases are described. These are summarised as economic considerations. Additionally, main stakeholder considerations are taken into account.

6.1.1 Economic considerations

The choices, which are made within the installation procedures, also affect other phases of the project or are influenced by them. In order to facilitate the installation process and minimize its costs, three main aspects have to be considered: Firstly, the required vessel types, secondly, the distance from port to site and, thirdly, the weather impact. While less specialized vessels are both better available and also less cost intensive due to lower charter rates, they can only be utilized, if the boundary conditions are suitable. This directly relates to the other two main aspects, mentioned above.

The weather majorly impacts the installation procedure primarily by governing the timeframes when installation vessels can operate, and necessary marine operations are performed, such as the connection of the floater to the mooring lines. This impact increases if larger distances have to be covered and therefore require more time. This leads to increased risk regarding the accuracy of weather forecasts and higher contingency considerations. Smaller distances between port and site therefore reduce the weather impact and reduce risk and cost. The influence of the weather and the resulting increased stand-by times are illustrated exemplary in Figure 24 for the LIFES50+ site B (Gulf of Maine, medium weather conditions) and site C (West of Barra, severe weather conditions) (see definitions in [11]). Differences arise in terms of the installation times and costs.

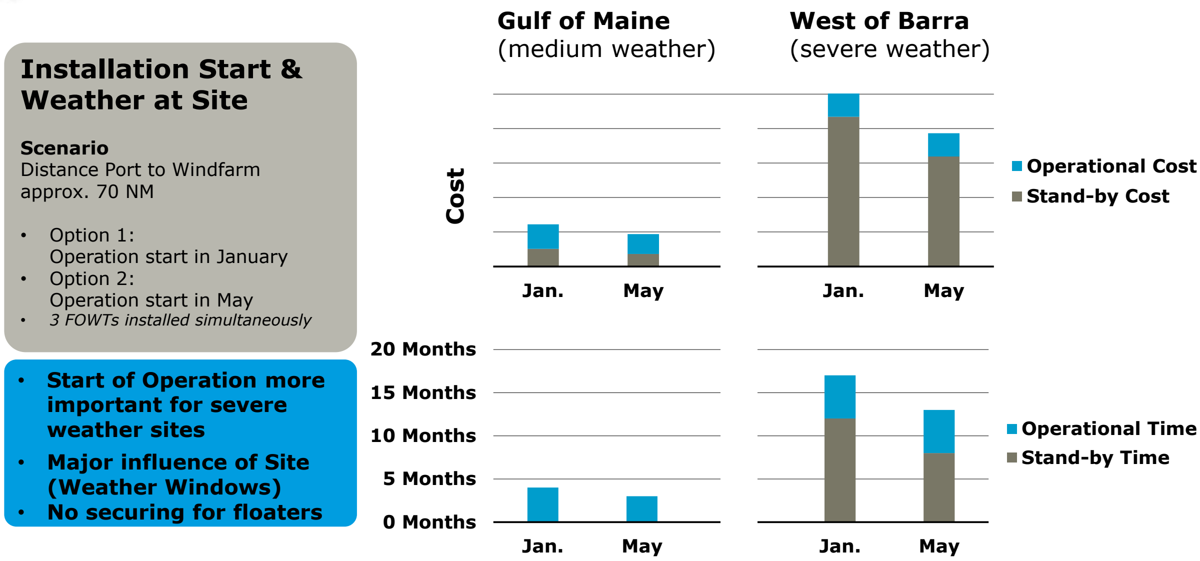


Figure 24: Influence of environmental conditions and installation start.

Regarding the port choice, economic factors become crucial. The optimal port meets the high infrastructure requirements of floating wind and is located in the direct proximity of the intended wind farm site. If this is available, the effect of the other mentioned factors is minimized. As for LIFES50+ site C (West of Barra) [11], deep-water sites, which can be exploited by floating wind, are often distant from suitable ports. It can then be considered to invest in a closer port and upgrade its infrastructure for the requirements of the project. The likely high investments must be compared to the alternatives including higher risks regarding weather forecast and higher vessel costs. A comparison of those two options of either a close port which requires certain upgrades and a more distant port are compared for LIFES50+ site C in Figure 25. As a result, additional costs and time for the different distances are found.

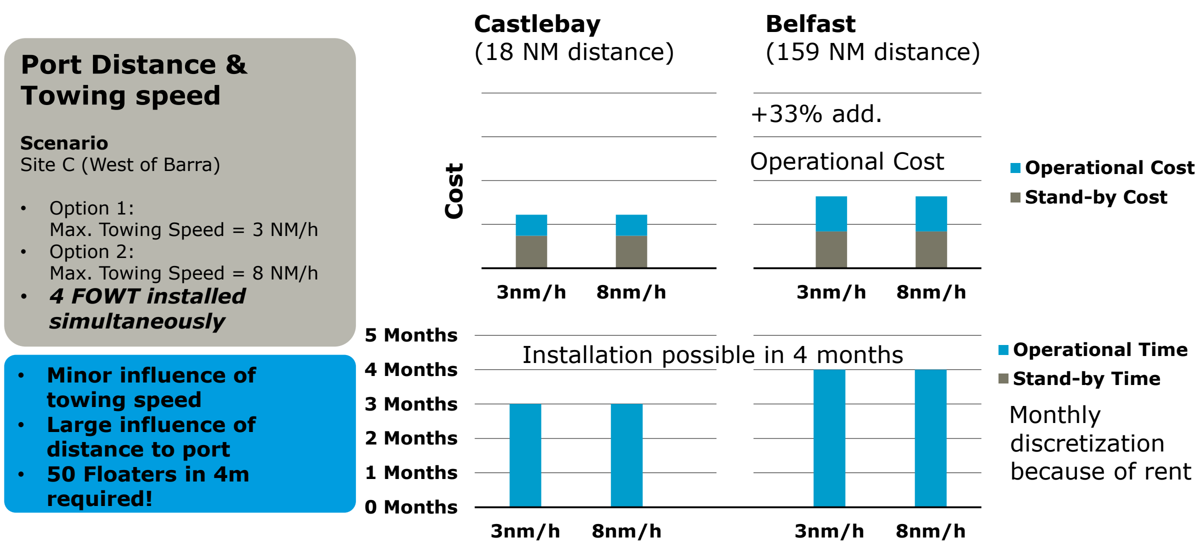


Figure 25: Influence of port distance and towing speed, 4 FOWTs installed in parallel.

These three main aspects, vessel types, port-site distance and weather impact, are also the factors which influence further operational processes in the life cycle of the wind farm. For all manufacturing processes, O&M, logistics and decommissioning, these factors are important. The infrastructure and accessibility of the port is especially important for logistics and manufacturing considerations. Regarding these two, existing ports with possible ship yard infrastructure would be favourable. For O&M and decommissioning phase, the proximity and the independency of weather are higher rated, which would favour closer ports instead. It can be summed up, that if no ideal port exists, often trade-off considerations are governing: Often, an advantage for one phase or aspect can result into disadvantages for another phase or aspect. The ideal solution is therefore very much dependent on the project characteristics, e.g. the chosen substructure concept.

The above discussion furthermore does not include floater design aspects such as the complexity of the required marine operations, which varies significantly amongst different concepts. TLP and spar designs are more challenging due to the tendon system installation being more complex and challenging, respectively the deep draft of the spar limiting port selection and possibly requiring large heavy lift vessels for near-shore WTG assembly.

6.1.2 Stakeholder considerations

Apart from the operational and technical aspects, external stakeholder interests may also be influenced by the installation process. Regarding environmental impact, floating wind has the potential, to decrease the ecological impact on the marine ecosystem in comparison to conventional offshore structures. For example, noisy hammering during the installation, as in the case of monopiles, is not required and the impact is eliminated for floating. The anchor systems are, in the case of drag embedded anchors, also fully recoverable. This further reduces the environmental impact.

The installation procedure itself does not influence other major stakeholders. For floating wind farms in general, military and cargo transport should be taken into account in order to ensure a safe and undisturbed operation of the wind farm.

The impact of the mooring line resting and moving on the seabed, particularly for large footprint catenary steel chain system may be a problem for marine life. Also reports suggest possible risks for whales and other larger species regarding entanglement and/or marine space blockage.

6.2 Decommissioning

O&G industry shows, that the neglection of the decommissioning strategy may lead to increase of efforts and costs [20]. To get an overview over the existing offshore decommissioning strategies, common methods of both floating O&G and conventional fixed-bottom offshore are reviewed. Afterwards challenges and opportunities for floating wind are stated. Existing decommissions strategies both for O&G and fixed-bottom wind are briefly discussed in the following with respect to their applicability to FOWT.

6.2.1 Oil and gas

Proserv Offshore shows in its “state-of-the-art” review of O&G decommissioning how different O&G devices would be decommissioned [21]. The application to floating wind is, however, difficult. The reason is that for O&G, the main attention is paid to the decommissioning of the pipelines in order to prevent oil leakages. For floating constructions, only limited information about the decommissioning process is available. Generally, it is simply stated, that floating devices are detached from the mooring lines and towed to the shore for further decommissioning. While floating wind often considers drag embedded anchors, which can be recovered, the Proserv Offshore study considers O&G pile anchors to remain in the sea bed and not being removed. The mooring lines are however recovered. Sea disposal of parts is generally often considered for certain parts of the structure. The application to floating wind is difficult also due to increasing awareness and considerations of environmental impact. The cost assumptions cannot be transferred easily, due to high risks and safety factors of O&G devices on the one site and high revenue per device on the other side. Furthermore, the size of O&G platforms and also the total amount of installed devices are much different to floating wind. While O&G floating substructures are large but singular installations, floating wind substructures are considerably smaller in size, however must be decommissioned in larger numbers for a larger scale wind farm. For the detailed decommissioning procedures, like the usage of ROVs to detach the mooring lines in larger water depths, the experience from the O&G industry might be useful. Regarding decommissioning strategies, floating wind can most probably not exclusively rely on the O&G experience.

6.2.2 Fixed-bottom offshore

Fixed-bottom offshore wind is less applicable to the requirements of decommissioning of floating wind. For conventional fixed-bottom offshore, the wind turbine has to be removed from the substructure on site. Afterwards, the substructure is often left on site or piles are cut (Figure 26). Both these steps differ from floating wind. The only comparable part of the decommissioning procedure is the decommissioning of the cables, both inter-array and export cables. Since the removal of these cables would "involve extreme costs" and also "cause substantial damage and disruption to the seabed given the extensive length of the cables" [22], the cables are often left buried and in situ and are not removed. It can be assumed, that similar choices will be made for floating wind farm applications.

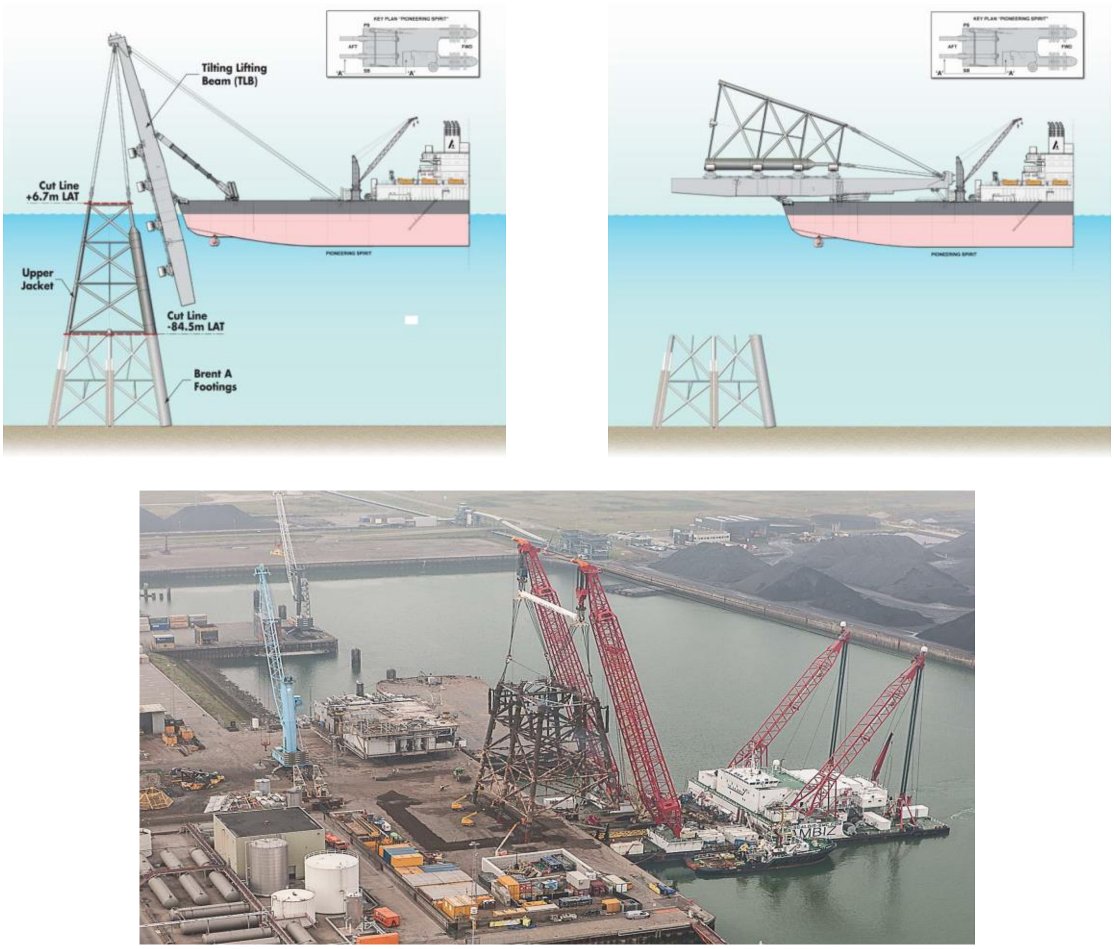


Figure 26: Top: Schematic illustration of the procedure for lifting of the upper part of a jacket using a specialised vessel [23]; Bottom: Jacket is unloaded at a disposal yard [24].

6.2.3 Challenges and opportunities

Due to the young age of floating wind industry, not many details have yet been published to definitely designate, how the decommissioning should be conducted. The main advantage of smaller floating devices in terms of decommissioning is their mobility. The decommissioning can be done, after the floaters are towed back to the port, which favours also the disposal. No obvious use of specialized vessels is required for this type of decommissioning. For the detachment of the mooring lines, experience from the O&G industry could be utilized. A challenge is the size of the floating substructures. Even though, they are much smaller than their O&G counterparts, feasible recycling or disposal options for the high number of substructures in large scale offshore wind farms have to be found. For mooring lines, the disposal seems more sustainable for steel, since they are more likely to be recycled. According to the American Iron and Steel Institute, “Steel is the most recycled material on the planet, more than all other materials combined.” And: “Steel retains an extremely high overall recycling rate, which in 2014, stood at 86 percent.” [25]. Theoretical, this can be also achieved for synthetic lines provided that recycling procedures are optimised. Concrete recycling is becoming more attractive because of increased environmental awareness, new legislative regulations and potential cost reductions. For example, after crushing and removing of rebar by means of magnets or sorting devices, recycled concrete can be used as aggregate for mixing new concrete.

7 References

[1] C. Morgan, P. Reynolds, E. Greig, J. Philips, P. Butler, R. Rawlinson-Smith, F. Jones and O. Fitch-Roy, “Offshore Wind - 10 years 10 lessons,” DNV GL - Garrad Hassan, 2013.

[2] R. James and M. Costa Ros, “Floating Offshore Wind: Market and Technology Review,” 2015.

[3] M. Borg and H. Bredmose, “Deliverable 4.4: Overview of the numerical models used in the consortium and their qualification,” LIFES50+ Deliverable, 2015.

[4] F. Borisade, J. Gruber, L. Hagemann, M. Kretschmer, F. Lemmer, K. Müller, N.-D. Nguyen and L. Vita, “Deliverable 7.4: State-of-the-art floating offshore wind turbine design practice and guidelines,” LIFES50+ Deliverable, 2016.

[5] L. Kraeckel, "Structural Design and Optimization of a Semi-Submersible Floating Substructure for a 10 MW Offshore Wind Turbine," Master Thesis, Technische Universität Hamburg-Harburg, Hamburg, 2017, (confidential).

[6] S. Tiedemann, "Conceptual Design of a Semi-Submersible Floating Substructure for a 10 MW Offshore Wind Turbine," Master Thesis, Technische Universität Hamburg-Harburg, Hamburg, 2016, (confidential).

[7] G. Boothroyd, Assembly automation and produt design, Estados Unidos: Taylor & Francis, 2005.

[8] S. David, “Introduction to Desifn for (Cost Effective) Assembly and Manufacturing,” [Online]. Available: http://me.gatech.edu/files/capstone/L071ME4182DFA. [Accessed 27 02 2019].

[9] United States Department of Defense, “MRL User Guide,” U.S. Governement Printing Office, Washington, DC, 2015.

[10] Austrailian Renewable Energy Agency, “Commercial Rediness Index for Renewable Energy Sectors,” Austrailian Government, Canberra, 2014.

[11] A. Krieger, G. K. V. Ramachandran, L. Vita, P. G. Alonso, G. G. Almería, J. Berque and G. Aguirre, “LIFES50+ D7.2: Design Basis,” 2015.

[12] Spanos group, “Mobispa 60,” [Online]. Available: http://www.spanos-group.com/product/mobispa-60/. [Accessed 18 03 2019].

[13] F. Borisade, J. Bhat, L. Kräckel, S. Tiedemann and D. Matha, “LIFES50+ D5.3: Design report - steel and/or concrete design,” 2019.

[14] B. A. N. M. S. M. Chilana Lalit, “Comparison of carbon footprints of steel versus concrete pipelines for water transmission,” *Journal of the air and waste management association,* vol. 66, no. 5, pp. 518 - 527, May 2016.

[15] Heger Dry Dock, Inc., “Transfer and Launch of JHSV,” [Online]. Available: http://www.hegerdrydock.com/projects/vessel7.html. [Accessed 28 03 2019].

[16] KAMAG, “Shipyard Transporter 1400,” [Online]. Available: https://www.kamag.com/products/shipyard-transporters/shipyard-transporter-1400.html. [Accessed 28 03 2019].

[17] Harland and Wolff, “Facilities,” [Online]. Available: http://www.harland-wolff.com/Facilities-(2).aspx. [Accessed 28 03 2019].

[18] CádizEconomic, “Shipbuilding,” [Online]. Available: http://www.cadizeconomic.com/en/sectores-productivos/industria/construccion-naval. [Accessed 28 03 2019].

[19] “IACS Rec 1996/rev. 6 2012, No. 47. Shipbuilding and Repair Quality standard,” 2012.

[20] Shell International Limited, “Brent Spar Dossier,” 2008.

[21] Proserv Offshore, “Review of the State of the Art for Removal of GOM US OCS Oil&Gas Facilities in greater than 400' water depth,” U.S. Department of the Interior, Houston, 2009.

[22] E. Topham and D. McMillan, “Sustainable decommissioning of an offshore wind farm,” *Renewable Energy,* vol. 102, pp. 470-480, 2016.

[23] Shell U.K. Limited, “Brent Alpha Jacket Decommissioning Technical Document, Shell Report Number BDE-A-JKT-BA-5801-00001,” 2017.

[24] T. Eley and P. Linjebygg, “Decommissioning in the North Sea: Market Overview, Challenges & Opportunities,” in *Scotland - Norway Technology Partnership Event 2015*, Aberdeen, 2015.

[25] American Iron and Steel Institute, “Steel is the World's Most Recycled Material,” American Iron and Steel Institute, [Online]. Available: https://www.steelsustainability.org/recycling. [Accessed 28 03 2019].

[26] F. Borisade, J. Bhat, R. Scheffler and D. Matha, “LIFES50+ D5.4: Design report - fabrication and installation,” 2019.

[27] K. Müller, D.-N. Nguyen, F. Borisade, M. Kretschmer, F. Lemmer, J. Gruber, L. Hagemann and L. Vita, “State-of-the-art floating offshore wind trubine design practice and guidelines,” LIFES50+ Deliverable D7.4, www.lifes50plus.eu, 2016.