PivotBuoy

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

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D3.5: Industrialization plan for serial production of large farms

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ACRONYMS

CAPEX	Capital Expenditures
DDR-2	Detailed Design Review 2
GBS	Gravity-based Structure
GPS	Global Positioning System
LCOE	Levelized Cost of Energy
OPEX	Operational Expenditures
PLOCAN	The Oceanic Platform of the Canary Islands
RNA	Rotor Nacelle Assembly
SPM	Single Point Mooring
SPMT	Self-Propelled Modular Transporters
TLP	Tension Leg Platform
TTA	Tower Top Adapter
WTG	Wind Turbine Generator

EXECUTIVE SUMMARY

This document presents a generic industrialization plan for the serial production of full-scale PivotBuoy systems for commercial scale offshore wind farms. The focus of industrialization, and thus of this deliverable, is the reduction of the time required to obtain materials and components, to fabricate the main structure, to assemble and launch the structure and to prepare the fully assembled floating offshore wind unit for installation offshore. The time required for these activities ('lead times') and the associated supply-chains currently present a barrier for full-scale floating systems compared to fixed foundation systems.

This industrialization plan begins by clearly defining the specifications of a full-scale PivotBuoy system, the definition of a commercial-sized wind farm and the criteria for successful industrialization. It is concluded that a successful industrialization plan manages to reduce the lead times from receipt of raw material to final commissioning checks for full-scale PivotBuoy systems by setting up an efficient industrialized supply chain.

To reduce the lead times, the production line shifts from a 'one-off' production to a production line including expanded group of suppliers, secondary fabrication sites and one or more primary assembly yards. The growing number of involved parties and associated material movements increase the logistical complexity of the overall production process. To identify critical points in the process, the criticalities of the following aspects are assessed: system components, fabrication & assembly sequence, and full-scale launch & installation.

In the system component assessment, the different components are rated on fabrication, transportation, and storage criteria to identify critical components. It is concluded that due to PivotBuoy's highly modular design, most components are not expected be critical to the industrialization when qualified fabricators are available. However, the handling and transportation of the pontoons becomes complex for full-scale systems due to their slenderness and long dimensions. Three methods for fabrication and transportation are discussed, where ultimately the final choice is a trade-off between complexity of transportation, required operations and available space at the primary assembly yard.

As a result of PivotBuoy's 'design for manufacturing' philosophy, few criticalities are observed at the supplier and secondary fabrication site level. Due to the high modularity and compact dimensions of the individual system components, each separate component can be fabricated by a broad range of secondary fabrication sites and transported to the primary assembly yard. This flexibility allows the utilization of long-term regional suppliers together with qualified local project-specific suppliers.

The increased dimensions of the full-scale PivotBuoy (vs. the X30 prototype) and number of units typically required for a commercial scale floating wind development will require large assembly and storage areas at the primary assembly yard. In the final industrialization plan, the selection of sites will be a trade-off of many factors such as budget, available local infrastructure, and local governmental rules. It is noted that the high modularity of the PivotBuoy concept gives it a significant advantage in terms of industrialization with respect to most competitors. The supply chain can be easily spread out and tailored to different project sites, which is more difficult for other concepts that require specialized fabricators and fabrication sites due to their larger dimensions and associated handling requirements.

Regardless of the final primary assembly selection, several final steps are required to prepare the PivotBuoy for installation. When the floater is fully assembled, it will be launched and towed to the assembly anchorage. Two launch methods are assessed: by semi-submersible barge and by slipway. The final method selection will be a trade-off between CAPEX, OPEX and available infrastructure. To increase the flexibility of the production sequence, the assembled floaters are stored at the assembly anchorage prior to outfitting. After outfitting, the finalized systems are towed to the marshalling anchorage. Here a buffer of PivotBuoys ready for installation will be gathered, to be installed when anchoring systems are ready offshore and conditions at site allow.

It is desirable that all the final preparatory steps (assembly anchorage, outfitting and marshalling anchorage) can be located near each other and as close as possible to the project site. However, if the project conditions don't allow for this setup, these steps can also be spread over a wider geographical area. This will increase the required transportation distances but improves applicability for a wider range of project sites. Ultimately, the location selection will depend on whether there is availability of sheltered waters for anchorage nearby the primary assembly yard.

Concluding, the industrialization plan for a full-scale commercial windfarm development using PivotBuoy will not be governed by capacity of a single fabrication site, but rather will be an optimization of logistics. By taking measures to optimize the industrialized supply chain by clever use of the modularity of the PivotBuoy system, it is expected that the lead times can be reduced significantly, thus overcoming the barriers perceived for full-scale commercial implementation of floating offshore wind.

1 INTRODUCTION

1.1 Document Objective and Outline

This document presents an industrialization plan for the serial production of full-scale PivotBuoy systems for commercial scale offshore wind farms. The term ‘industrialization’ here refers to the process required to go from the fabrication and assembly of a single prototype floating offshore wind unit to the large-scale, efficient fabrication and assembly of multiple units for deployment in a commercial windfarm. The focus of industrialization, and thus of this deliverable, is the reduction of the time required to obtain materials and components, to fabricate the main structure, to assemble and launch the structure and to prepare the fully-assembled floating offshore wind unit for installation offshore. The time required for these activities (‘lead times’) and the associated supply-chains currently present a barrier for full-scale floating systems compared to fixed systems.

Note that this deliverable can only address the aspects of PivotBuoy industrialization from a generic perspective. The specific plans and processes will be different depending upon the details of the actual windfarm project such as overall size of the development (i.e. number of units), geographical location and market conditions (e.g. third-party concurrent projects that compete for the same industry resources). Nevertheless, the generic approach described herein is applicable for any project and forms the basis for the project-specific approaches.

To clearly define the problem statement and to propose a solution to attain the objective of reducing lead times, it is important to first define the following key terms comprehensively:

- What are the specifications of a **full-scale PivotBuoy system**?
- What is the definition of a **successful industrialization plan**?
- When is an offshore wind farm considered to be of **commercial scale**?
- What are the start and end point of the **lead times**?

In the current section (Section 1), the resulting definitions are adopted to formulate the problem statement and solution method. The subsequent sections (Section 2, 3 and 4) will elaborate on the different facets of the proposed solution method. As the optimal industrialization plan is expected to be governed by a set of critical production steps rather than the full production sequence, the solution method aims first at understanding these criticalities and, subsequently, on minimizing their impact. The criticalities are assessed separately for three topics:

1. Criticality of required system components,
2. Criticality of fabrication/assembly logistics and requirements,
3. Criticality of launch and installation logistics and requirements,

Finally, the solution method output will be used to formulate the industrialization plan in the concluding section (Section 5). The criticalities are summarized, and a comprehensive plan to minimize their impact on the lead times is incorporated in the overall industrialization plan. The plan serves as a blueprint to be used for individual projects. The concrete fabrication procedure will vary per project. A simplified overview of the document outline is given in Figure 1.

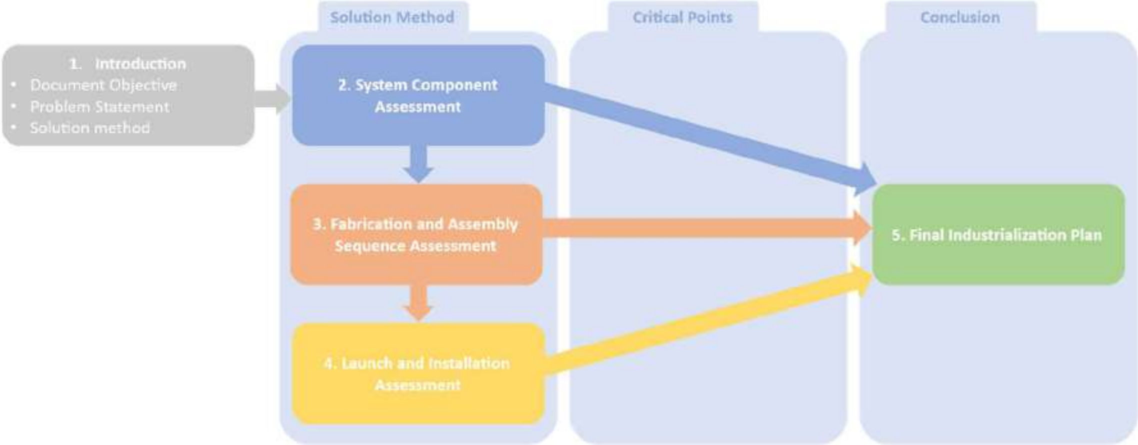

Figure 1 Document Outline Overview

1.2 Definition of a Full-scale PivotBuoy System

The PivotBuoy system is a novel floating wind concept that combines the advantages of Single Point Mooring (SPM) systems (easy installation) with those of TLP platforms (weight reduction and enhanced stability) in order to enable weight reduction compared to current established systems. The light structure allows for relatively simple assembly and installation with local infrastructure. The SPM system is integrated with a downwind wind turbine generator (WTG) that allows the platform to passively weathervane and self-orientate. The conventional turbine tower is redesigned, replacing the traditional tower with a pyramid-like structure resulting in more efficient load transmission and increased flexibility in avoiding resonance in the blade passing frequency range.

Figure 2 shows the “X30 platform”, a prototype project with a power rating of 225 kW at quayside in the port of Las Palmas, Gran Canaria. The prototype was launched at the Hidramar shipyard and will be towed and connected to the test site of the Oceanic Platform of the Canary Islands (PLOCAN) in 2022. Once installed offshore, the performance of the prototype will be monitored over an extended period to gather data for further design of larger scale units that will be implemented for commercial offshore wind developments.

Figure 2 X30 Platform Prototype in Las Palmas Port

Figure 3 shows a visualization of the most recent model of the PivotBuoy system as described in the Detailed Design Review (DDR-2) [1]. The terminology of the essential components of the system is shown and will be adopted throughout the report. The concept is based on a "design for manufacturing" philosophy, resulting in a highly modular design, aimed at reducing the overall costs and increasing fabrication flexibility. A more in-depth assessment of the different components is given in Section 2.

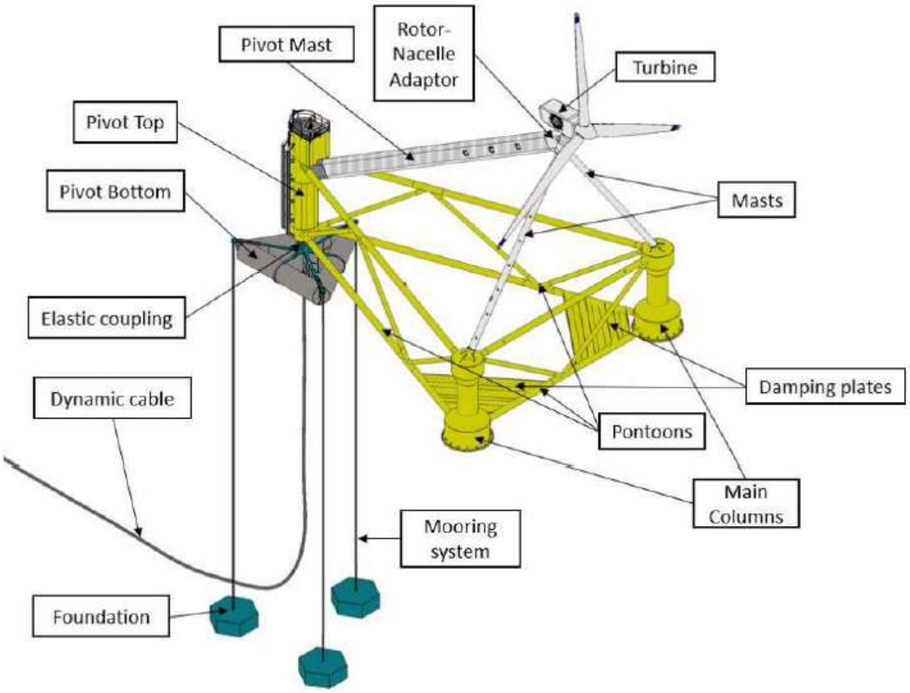

Figure 3 DDR-2 Model

To become commercially competitive, the prototype is scaled up to higher power ratings. A reference design for a **full-scale** 15 MW turbine configuration is made based on the X140 platform mentioned in the D2.5 report [2] and further scaling calculations. The (approximate) dimensions of the prototype and full-scale X140 platform are listed in Table 1 and will be adopted throughout this report. Note that the X140 platform is expected to undergo several additional design cycles, hence the final dimensions are subject to change. As the industrialization plan is based on the magnitude of size rather than exact dimensions, these changes will not impact on the overall conclusions in this document.

	X30	X140
Power Rating	225 kW	15 MW
Hub height	25 m	140 m
Length	40 m	±100 m
Width	30 m	±100 m

Table 1. General dimensions of the X30 and X140 Platforms

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To give a comprehensive description of the PivotBuoy system, a simplified installation sequence is presented in Figure 4. Firstly, the foundation is installed on the seabed. Hereafter, the tendons and pivot bottom are installed. Finally, the floater is connected to the pivot base via a quick connect system, which makes the installation a relatively time-efficient operation.

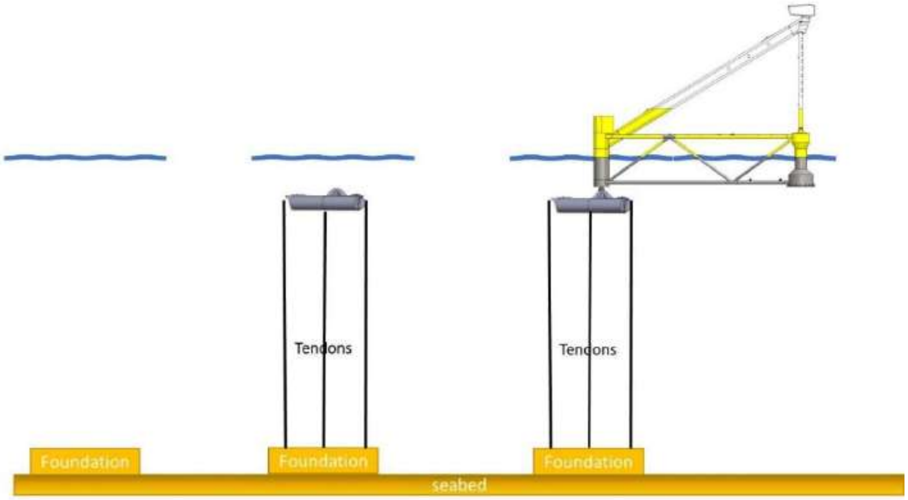

Figure 4 Installation sequence: 1) Foundation, 2) Tendons & Pivot Base, 3) Floater

The floater and the TLP system can be considered as two separate systems, which makes it possible to install all TLP systems prior to the tow-out and connection of the floaters. For both operations the most cost-effective vessel can be selected, reducing installation costs and required time offshore. Once a pivot bottom/foundation system is installed at site, the floater is brought into position, ballasted and connected to the foundation. Note that this installation sequence differs from the prototype installation, where the pivot base was attached to the pivot top prior to tow-out to the project site.

1.3 Definition of the Industrialization

The prototype demonstration results are of great value to validate various aspects of the PivotBuoy concept from a technical and logistical point of view. Lessons learned can be implemented in the subsequent phases of the concept development. However, in order to enter the commercial phase, the prototype must be scaled up to a higher power rating, and the scope expands from fabricating a single, smaller unit to fabrication and assembly of multiple units in accordance with a project schedule that will aim to achieve first power production as early as practicable. Both the upscaling of the prototype and the fabrication/installation of multiple units will come with challenges that will need to be addressed.

Due to the increased dimensions, larger yards with heavier lifting equipment and sufficient fabrication and storage area are required. Additionally, transport methods may shift from conventional transport (rail/road/small ships) to specialized vessels. As the process shifts from “one-of-a-kind” production to serial production, more on- and offshore acreage is required for assembly operations and storage. For commercial wind farms, this creates a complex logistical puzzle.

With the goal of being competitive in future energy markets, the industrialization plan in this document is based on fully **commercial sized** wind farms with power ratings exceeding 500 MW. Assuming a turbine rating of 15 MW, this translates to a total of more than 30 full-scale PivotBuoy systems within the windfarm. As shown in Table 1, larger turbines will require support structures of substantial dimensions. In order to facilitate the transportation, assembly and installation process of these support structures, top notch port facilities and significant on- and offshore storage space are required.

The novelty, complexity and required fabrication/assembly area of floating systems significantly increases the lead time compared to fixed systems such as monopiles. Throughout this document, the **lead time** of a production line is the time between receiving raw materials and the completion of final commissioning checks at the quayside. The increased lead times especially become problematic during the shift from ‘proof-of-concept’/small scale projects to full commercial farms due to the large number of required floater systems.

As an example, the three floaters of the WindFloat Atlantic project offshore Portugal were fabricated and assembled at three different locations. This quickly becomes an unmanageable approach when developing full scale wind farms due to the large number of intermediate equipment movements required during the process. A full-scale commercial project will benefit from an approach that streamlines the number and types of assembly locations to achieve an efficient ‘assembly line’ process. By reducing the lead time of the PivotBuoy floaters, the overall project flexibility significantly increases, allowing optimal use of offshore installation windows and assets and thereby driving down the overall costs. It is estimated that the minimum time required to deliver a single PivotBuoy system following the prototype’s ‘one-off’ production line is approximately three (3) months from initial receipt of raw materials to the completion final commissioning checks at the quayside. This duration already reflects a fabrication and assembly process that is not constrained by materials or equipment availability or by space limitations.

A target duration of 1 week per unit for final assembly and launching has been proposed in various offshore wind forums (e.g., 2nd annual floating wind Europe, Amsterdam 2022); however, the basis for this number is not well documented. In fact, it will be the offshore installation of the floating offshore wind units that drives the required fabrication rate. The offshore installation schedule typically will be dictated by equipment (vessel) availability and by the occurrence of suitable weather windows for safe operations. The fabrication process must therefore strive to ensure that sufficient units are available for installation as and when the offshore installation schedule requires them. In general, the fabrication process can aim for a ‘just in time’ approach where each unit is installed offshore almost immediately after completion of final assembly and (pre-) commissioning, or it can aim for an ‘off-line’ approach where the fabrication process creates a buffer of ready-for-installation units that are available to capture available offshore weather windows. The latter approach is considered more likely, especially for windfarms in areas with short installation seasons due to harsh weather conditions. In any case, the fabrication process will be influenced heavily by project-specific aspects such as the location of the windfarm, the availability of nearby ports infrastructure, the capabilities of local suppliers and global supply market conditions.

A **successful industrialization plan** manages to reduce the lead time from three months to a duration of several weeks by setting up an efficient industrialized supply chain where multiple critical steps can be conducted simultaneously (i.e. in parallel) at different locations. The reduction of the lead times brings down the overall expenditures of full-scale PivotBuoy wind farms and herewith reduces the LCOE, making it a more attractive concept.

1.4 Problem Statement

As mentioned in the definition of the industrialization plan, the prototype's 'one-off' production line approach will result in significant lead times for commercial-sized wind farms resulting in higher LCOE. So, to meet future renewable energy market demands, these lead times must be reduced.

Many parties from a variety of industries will be included in the full production sequence of the PivotBuoy system. Throughout this document, these parties are sub-divided into three groups: the primary assembly yard, secondary fabrication sites and suppliers. A short description of each group is given below:

- The **Suppliers** provide materials, components and/or equipment that can readily be used by both secondary fabrication sites and the primary assembly yard (e.g., raw materials, paint but also secondary steel like railing and ladders). Suppliers typically work from established manufacturing locations (e.g. factories, forges, steel mills, etc.) and transport their products from these locations to project sites globally.
- The **Secondary Fabrication Sites** fabricate both full system components (e.g., main columns, pivot top and masts) and partial system components such as steel tubulars and shells. Secondary fabrication sites typically will have established longer-term relationships for fabrication of PivotBuoy components. Due to the feasibility and cost of transportation, secondary fabrication sites typically will be selected in the same region as the primary assembly yard. Outfitting with in/external equipment such as electronic components, sensors, etc. and pre-assembly of fittings such as ballast systems, air conditioning systems, etc. is also done by the secondary fabrication sites.
- The components prepared at the secondary fabrication sites will be transported to the **Primary Assembly Yard** for the final preparatory steps for installation (e.g., final assembly steps, launch and outfitting with the turbine). The fully-assembled floating unit is not intended to be transported/towed over long distances[1], so the primary assembly yard should be selected as close as practicable to the offshore windfarm site

In an ideal world, it would be possible to cluster all three groups at the same location close to the project site. However, for all projects of this extent, the ideal scenario will never arise in the real world. For the X30 project almost all components were fabricated in a single secondary fabrication site (DEGIMA, Santander) and hereafter shipped to the primary assembly yard (Hidramar, Las Palmas). However, the suppliers were already scattered over various locations at different distances from the secondary fabrication site. The fabrication at a single location is a viable solution for a one-off prototype like the X30 platform. However, for commercial wind farms with several 10's of units, the supply chain will need to undergo further segmentation to reduce lead times through optimal use of expertise, area and availability. While the launch and final assembly will still be conducted at the primary assembly yard, preferably nearby the project site, the industrialized supply chain will be distributed over various secondary fabrication sites and many suppliers. Figure 5 visualizes the evolution of the supply chain from the single-location scenario to a realistic industrialized 'assembly

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[1] Note: this is not due to concerns about the integrity of the floating unit for transport / towing, but rather due to the practical aspects of minimizing the offshore time required for offshore installation; i.e. minimizing the required weather window.

line'. It shows that the group of involved parties expands, and the number of logistic steps, indicated by the arrows, will increase and become more complex. With the increasing complexity it is of paramount importance to manage the logistical interfaces. This includes early identification of (interface) risks and risk management throughout the project execution.

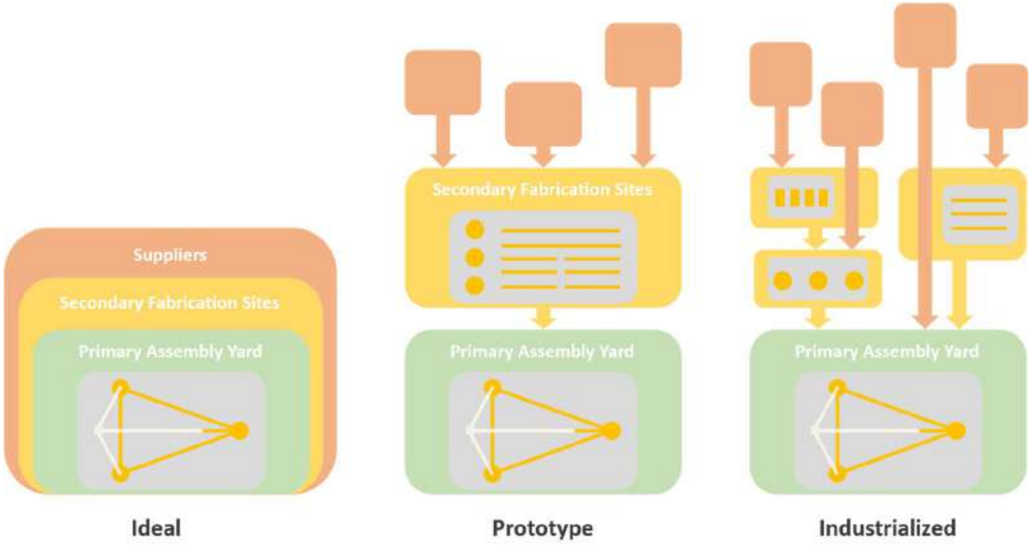

Figure 5 Evolution of Supply Chain

1.5 Solution Method

This document focuses on the optimalization of the industrialized supply chain as illustrated on the right in Figure 5. As shown in the flowchart in Figure 1**,** it aims to extract the criticalities in the production sequence and address them adequately in the final industrialization plan. The criticalities will be assessed separately for three topics:

1. Criticality of required system components,
2. Criticality of logistic manufacture/assembly sequence and yard requirements,
3. Criticality of launch and installation requirements,

The resulting criticalities per topic will both be input to the final industrialization plan, but also to other topics' criticality assessments. The following sections will elaborate on the method per topic and list the final findings.

2 SYSTEM COMPONENTS ASSESSMENT

In this section the different required system components as shown in Figure 3 will be described in detail. As stated, the adopted philosophy for this concept is “design for manufacturing”. The modularity of the PivotBuoy design allows for final assembly at a central primary assembly yard, while the required system components can be produced at various secondary fabrication sites. This increases the flexibility of fabrication process and hereby reduces the overall lead times.

An important aspect of the industrialization plan is the logistics behind the fabrication of the different components. This includes complexity of fabrication, difficulty of transportation and storage requirements in both area and bearing capacity. In this section each component will be rated on a scale from 1 to 5 on these three criteria to identify possible “bottle neck components”, which will likely be critical to the setup of the final industrialization plan. A score of 5 indicates that the component can be readily fabricated, transported or stored using conventional methods, established supply chains and/or commonly available facilities. A score of 1 indicates that the component requires special measures for fabrication, transportation and/or installation, and thus requires particular attention when developing the industrialization plan.

The components of the PivotBuoy system are subdivided in several sub-units, which are defined in Table 2. The description and criteria rating of the different components will be discussed per sub-unit. As the focus of this report lies on the industrialization of the PivotBuoy, only the full scale X140 model is assessed.

Sub-Unit	Component
Wind Turbine Generator	Rotor Nacelle Assembly
Floater	Main Columns
	Pontoons
	Damping plates
	(Pivot) Masts
	Pivot top
	Tower Top Adapter
TLP System	Pivot Bottom
	Tethers
	Anchor

Table 2. Sub-units’ description of the PivotBuoy system

2.1 Wind Turbine Generator (WTG)

The WTG sub-unit comprises every component typically attached on top of a conventional turbine tower. This unit is often called a Rotor Nacelle Assembly (RNA). The rotor consists of the blades and the hub. The nacelle is the ‘box’ where the power generation occurs. The interior of a nacelle strongly varies per turbine type. Usually, the RNA comes with a corresponding turbine tower. However, due to the novel pyramidical masts geometry of the PivotBuoy, the tower is redundant. The so-called (pivot) masts that form the pyramid are included in the floater sub-unit.

There is very little flexibility in the selection of a fabrication yard for the WTG sub-unit. In Europe approximately 68% of the cumulative installed offshore wind capacity connected at the end of 2019 was produced by Siemens turbines and 24% by MHI Vestas, which underlines the lack of variability in this field (Wind Europe, 2019). As the turbines are manufactured at each supplier's specialized manufacturing facility, the manufacturing location is governed by the desired turbine type rather than a logistically convenient location. Europe does, however, have a relatively high density of potential suppliers. It is note that the above-mentioned OEMs do not (yet) provide downwind turbines with power ratings required for full-scale systems. Various research underlines the high potential of downwind turbines by, for example, using 2-bladed turbine, rather than the conventional 3-bladed configuration (2-B Energy). At least one European manufacturer is focusing on the development of a downwind, 2-bladed turbine. Ultimately, the fabrication of the WTG will be done at a centralized location regardless of the final selection in turbine or support structure type. The WTG sub-unit scores **3/5** on the fabrication criterium.

The X30 prototype platform adopted a Vestas V29 225 kW turbine, which is a very small turbine compared to modern day standards. For instance, the 15 MW turbine used in the X140 design will have an approximate rotor diameter of 240 m compared to the 29 m of the prototype turbine. The small turbine used during the prototype phase is relatively easily transportable. However, commercial offshore wind turbines require specialized transport due to their significant dimensions. This especially holds for the turbine blades, which are made in one piece (100 m+ long) and are very flexible and vulnerable. Even though these are major operations and require specialized transport, the industry is experienced with the transport of all components. This results in a transportation score of **4/5**. Like the transportation process, the storage process is a well-known procedure, and it is rated with a **4/5** score too.

Due to the lack of freedom in selection of manufacturing location, this report will not research this sub-unit in more detail. In fact, the manufacturing process of this unit will not differ from any other floating wind concept with the same power rating. The manufacture location of the three major manufacturers in Europe capable of providing 15 MW turbines are listed in Table 3.

Supplier	Type	Location
General Electric	Generator	Saint Nazaire, France
	Blades	Cherbourg, France
Siemens Gamesa Renewables	Generator	Cuxhaven, Germany
	Blades	Aalborg, Denmark
Vestas	Generator	Lindø, Denmark
	Blades	Isle of Wight, UK

Table 3 Manufacturing Location

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2.2 Floater

The floater sub-unit is visualized in Figure 3 and comprises the following components:

1. Main Columns
2. Pivot Top
3. Pontoons
4. Damping Plates
5. (Pivot) Masts
6. Tower Top Adapter

Each component will be discussed and rated on the criteria separately in this subsection. Throughout this subsection, the approximate dimensions as given in Table 1 are adopted for the assessment. As the discussion and rating will be conducted based on the order of magnitude in size, small changes in the final design cycles will not affect the overall conclusions.

Main Columns

The main columns are the two columns located underneath the WTG that provide the overall buoyancy of the system (along with the pivot top and bottom) and provide rotational stability. As the volume of a cylindrical column geometry increases quadratically with an increasing diameter, expanding the column diameter can significantly increase the floating capacity and stability of the system.

Figure 6 Main Column Render

As shown in Figure 6 the main columns consist of simple geometries (mainly cylinder-like), resulting in a relatively straight forward manufacturing process. The industrialization challenges would therefore be limited for a prototype scaled PivotBuoy. In general, the fabrication process becomes increasingly difficult for larger diameters in terms of manufacturing, storage and transport. The main column diameter of the full-scale platform is expected to be approximately 10 m, which is within the capacity of current industry standards in the field of fabrication. The fabrication of large cylindrical geometries is considered a specialized industry, typically located in large fabrication yards with direct access to ports and sea-going transport vessels. An example would be a yard specialized in fabrication of large monopiles such as Sif Group at the Maasvlakte in the Netherlands. Due to the scarcity of yards with this experience and production capacity, the main columns are rated **3/5** on the fabrication criterion.

The yards are typically well connected to open seas, allowing for transportation by barge. The main columns are rated **4/5** on transportability. The final product has a small footprint with a geometry that lends itself to efficient used of storage area, therefore the main columns score a **5/5** on storage.

A photo of the prototype column is shown in Figure 7. For larger scale PivotBuoys, the general geometry will remain identical, but obviously the size will increase. The figure also shows the connection pieces for the pontoons.

Figure 7 Main Column of Prototype during Assembly

Pivot Top

The pivot top is comparable to the main columns in terms of its overall manufacturing process and dimensions. However, the additional connection component (for connection with the pivot bottom), boat landing and platform with corresponding secondary steel increases its complexity. The secondary steel (platform rails, ladders, boat landing etc.) is usually easily available from local suppliers. All secondary steel can be shipped to the secondary fabrication yards by rail, road, or water transport. For the fabrication of the connection component, an experienced supplier will be required. The complexity level of fabrication/transport and availability of this component depends strongly on the design of the PivotBuoy. A render of the pivot top layout is shown in Figure 8.

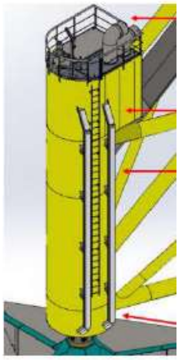

Figure 8 Pivot Top Layout

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Due to novelty of this component and its required 'sub-components' (connection piece, shaft, rotational bearings etc.) fabricated elsewhere, the pivot top scores **2/5** on the fabrication criterium. It is expected that the same vessels can be used for the main columns and pivot top. However, due to the increased complexity/vulnerability of the pivot top compared to the main columns, this is a new operation to the industry and temporary bracing might be required to ensure structural integrity during transportation. Similarly, the storage might require additional temporary bracings to mitigate the risk of damage to the connection piece. The pivot top scores **3/5** on transportation and **4/5** on storage.

<u>Pontoons</u>

The pontoons form the connecting frame between the main columns and the pivot top. They consist of an upper and a lower cylindrical member with diagonal cross bracing as shown in Figure 9. The frame comprises universally available simple tubular sections of existing commercial dimensions, improving the overall supply chain. The k-joints will be fabricated by specialized secondary fabrication sites. Although (sub)components of these dimensions require experienced secondary fabrication sites, they are not expected to be logistically critical.

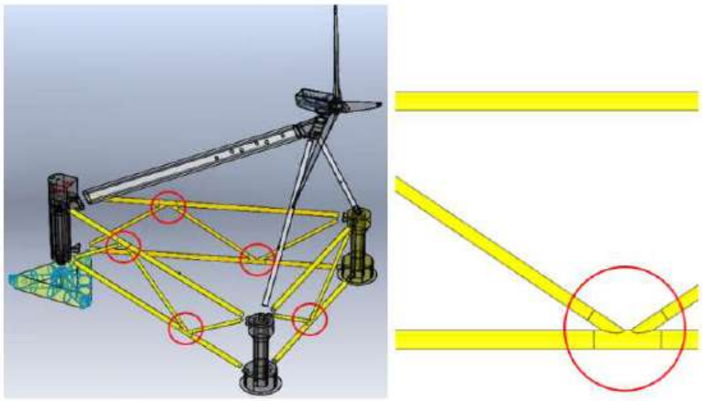

Figure 9 Pontoons with Encircled "K-joints"

The bracings of the X140 platform are longer and have smaller diameters than reference concepts of the same power rating. The slenderness of the pontoons makes the system relatively light, but also makes the fabrication and assembly a more delicate process. It will be necessary to construct the pontoons in a horizontal position and up-end the pontoon when finished. This lifting operation might require temporary support/bracing in the pontoons, as they cannot rely on the extra stability provided by the column connection and buoyancy from the water which they are designed for.

Due to the significant dimensions of the platform, sufficient area for assembly and storage of the pontoons is required. The industrialization logistics of the assembly will depend on the capacity of the envisaged primary assembly yard and will thus be project dependent. To increase applicability, three fabrication approaches are assessed:

1. Minimal prefabrication,
2. Partial prefabrication,
3. Full prefabrication

The minimal prefab method assumes that the primary assembly yard has sufficient area and capacity to conduct the full assembly. The partial prefab method fabricates each pontoon in two or three large sections at a secondary fabrication site, with final weld-up at the primary assembly yard. In the full prefab method, the entire pontoon will be fabricated in a secondary fabrication site and transported to the primary assembly yard. Key differences in terms of fabrication, transportation and storage will be discussed and the pros and cons of the three methods are summarized in Table 4.

As all components will ultimately come together at the primary assembly yard, this will be a critical location and minimizing the required time at this location is desirable. With increasing prefabrication, less fabrication steps will need to happen at the primary assembly yard. Due to the truss-like shape of the pontoon, many crucial welds must be made, which will need to be coated afterwards. It is important that the welding and coating process is conducted at a covered and dry location to ensure the highest quality. If no covered fabrication hall with sufficient space is available, setting up covers and finishing the welding and coating process can take a significant amount of time (and expertise).

Naturally, more compact components are easier to transport. Hence, with increasing prefabrication, the transportation becomes more difficult and temporary bracing might be required during handling and transport. With the minimal prefabrication method, the suppliers can directly distribute the members and k-joint to the primary assembly yard with conventional transportation methods (rail/road/barge). Whereas, with the full prefabrication method, specialized craneage and fleet is required to lift and transport the pontoons, making this a very difficult and costly operation. The partial fabricated sections will be easier to transport than fully assembled pontoons but will possibly still require temporary bracing, specialized craneage and fleet.

After (partially) finalizing the pontoons, they need to be stored temporarily prior to assembly or transportation. Due to the dimensions of the component the required area will be relatively large, which is an important factor during the primary assembly yard and secondary fabrication site selection. The use of secondary fabrication sites will increase the flexibility in time management as the storage can be divided over multiple locations. However, the difficulty of transportation significantly increases.

Table 4 gives an overview of the pros and cons of the different fabrication methods.

Method	Pros	Cons
No Prefab	• Allows use of conventional transportation methods	• Increase of required assembly operations and storage area in primary assembly yard
Partial Prefab	• Reduced required assembly operations at the primary assembly yard • Increased flexibility in logistics and time management	• Complex transportation and handling, which requires specialized fleet and temporary bracing
Full Prefab	• No required assembly operations at the primary assembly yard • Increased flexibility in logistics and time management	• Highly complex transportation and handling, which requires specialized fleet and temporary bracing

Table 4 Pros and Cons of Fabrication Methods

The table shows that the methods have their own advantages and disadvantages. In general, if the primary assembly yard has the capacity for the no prefab method, this is the preferred option due to the ease of transportation and handling of the components. If there is not enough fabrication capacity available, the partial prefabrication method would be the preferred method as the segments are still relatively easily transportable. Hence, a detailed assessment per individual project is required to select the optimal method. The pontoons score a **3/5** on the fabrication criterium and a **2/5** on both transportation and storage criteria. Since the benefits of minimal required operations at the primary assembly yard do not outweigh the highly complex transport of fully prefabricated pontoons, this method is considered unrealistic and will not be considered.

Damping Plates

The damping plates of the PivotBuoy reduce the dynamic response in the heave direction, mitigating risk of excessive displacement resulting in damage. Although they are an essential component in many floating concepts, the fabrication of these steel plates will be easily available, and transportation will be possible by most means of transport, with relatively easy storage. If required, the damping plates can also be shipped in pieces. Hence, this component scores a **5/5** on fabrication, transportation and storage criteria. Figure 10 shows a render of the damping plates.

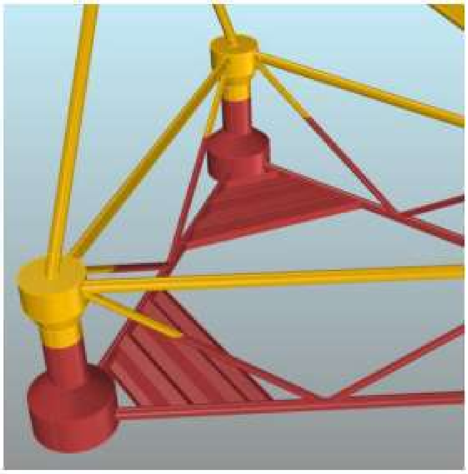

Figure 10 Damping Plates

(Pivot) Masts

The two front masts of the pyramidical turbine frame consist of tubular columns in the current design. These columns will have a diameter that is readily manufacturable and hence there will be a broad offer of secondary fabrication sites for these components.

The pivot mast of the X30 platform consists of oval cross-sectional shaped components as shown in Figure 11. This oval shape was required to allow for secure transit to the turbine by locating the stairway inside of the mast. To increase the manufacturing flexibility, the pivot mast is divided into several section of formed steel plate, resulting in “J” shapes that will be welded together. To increase manufacturability the X140 pivot mast will comprise commercially available tubular segments. Due to the increased dimensions, the sections will have enough space for secure transit.

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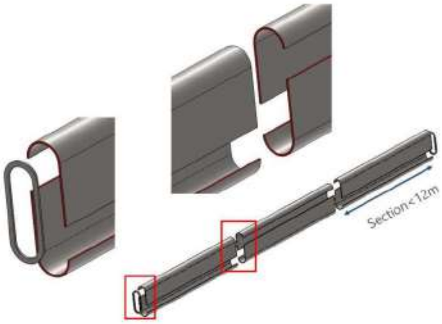

Figure 11 Pivot Mast Sections for Manufacturing

The conventional tubular shape allows for the use of 'conventional' automatic welding systems, resulting in relatively easy fabrication of both types of by specialized secondary fabrication sites. As the component can be divided into several segments (ultimately connected by bolt flanges) it is also easily transported, and stored. Therefore, this component scores **5/5** on all criteria. Even though the fabrication and transportation of the individual segments is relatively easy, lifting the fully assembled pivot masts with its internal jewellery into place during final assembly can result into governing load cases for this component. A full-scale lifting analysis must be conducted to ensure a safe operation.

Tower Top Adapter

The Tower Top Adapter forms the connection between the masts and the WTG as shown in Figure 12. This component is designed to be conveniently manufactured and assembled. However, as this component forms a critical connection between different components, high level dimensional control is crucial. The component has a complex shape with 4 flanges in different planes, which require repositioning without losing the reference between different flanges. Any small deviation of the design (angle between flanges/sizing) can cause a lot of complications during assembly. Therefore, this component scores **3/5** on the fabrication criterium. Due to the relatively small size of this component, the transportation and storage are not expected to result in complications and therefore it scores a **4/5** on all three criteria.

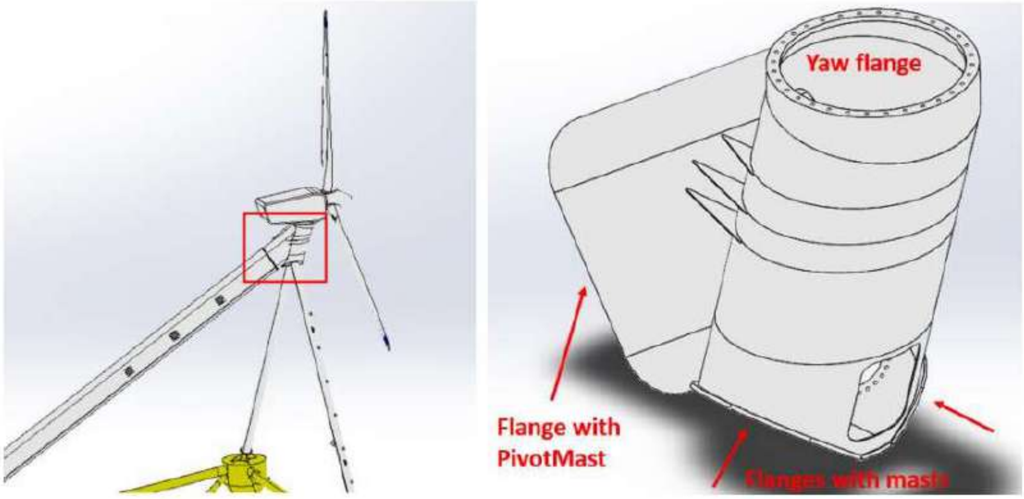

Figure 12 Tower Top Adapter

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2.3 TLP System

Tethers

A TLP-type mooring system is adopted for the PivotBuoy concept. These mooring systems consist of vertically tensioned tendons or tethers. The applicaton of tendons and tethers for TLP type structures is a well-known industrialized technique in the offshore industry, often applied in oil and gas projects.

For a full-scale mooring system each mooring tendon will likely come on its own spool with significant dimensions. When considering a commercial size wind farm including more than 30 PivotBuoy systems, this will result in more than a hundred spools. As mentioned earlier, the production line of the floater and the mooring system (including the pivot bottom) can be considered seperately. The fabrication, transportation and storage of the mooring system will be mobilized directly from the manufacturers location prior to the installation time frame. Due to the high level of experience in this field by various manufacturers, this is not expected to be a critical point and thus the mooring system scores **5/5** on all three criteria.

Pivot Bottom

The Pivot bottom forms the connection and load transfer between the mooring system and the pivot top. It consists of a triangular three-tank shape with internal stiffeners for stability and is equipped with connection components with the pivot top and mooring system as shown in Figure 13.

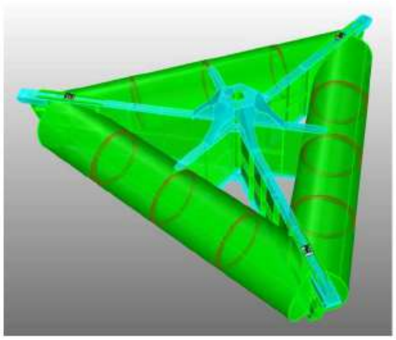

Figure 13 Pivot Bottom with Inner Stiffeners

The main structure (buoyancy tanks and inner stiffeners) of the pivot bottom consists of simple geometries and can therefore be relatively easily fabricated by a broad range of secondary fabrication sites. The elastic coupling component with the pivot bottom, however, will need to be fabricated (manufactured) by a specialized company. The component includes a machined plate where the flexible coupling is installed. Also, the tolerance between the mooring line connection and the flexible coupling connection is demanding, which increases the complexity of fabrication. Therefore, this component scores **3/5** on the fabrication criterium. As this component is relatively compact, transportation and storage will not be a showstopper and the exact fabrication location(s) is not limiting to the industrialization plan. Based on the project specifications one or various (regional) secondary fabrication sites can be selected to ensure a smooth logistic sequence. The pivot bottom scores a **4/5** on all three criteria.

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Anchors

The foundation of the PivotBuoy system ensures that displacement of the floating system is restricted. In the offshore and naval industry there are many different foundation types available, each with their own (dis)advantages. The latest proposed anchoring system consists of three concrete blocks (one per tension leg) with pad eyes and an internal steel structure. Figure 14 shows a render of the current foundation concept (as proposed in DDR-2). Another GBS-based alternative would be the use a single large concrete anchor.

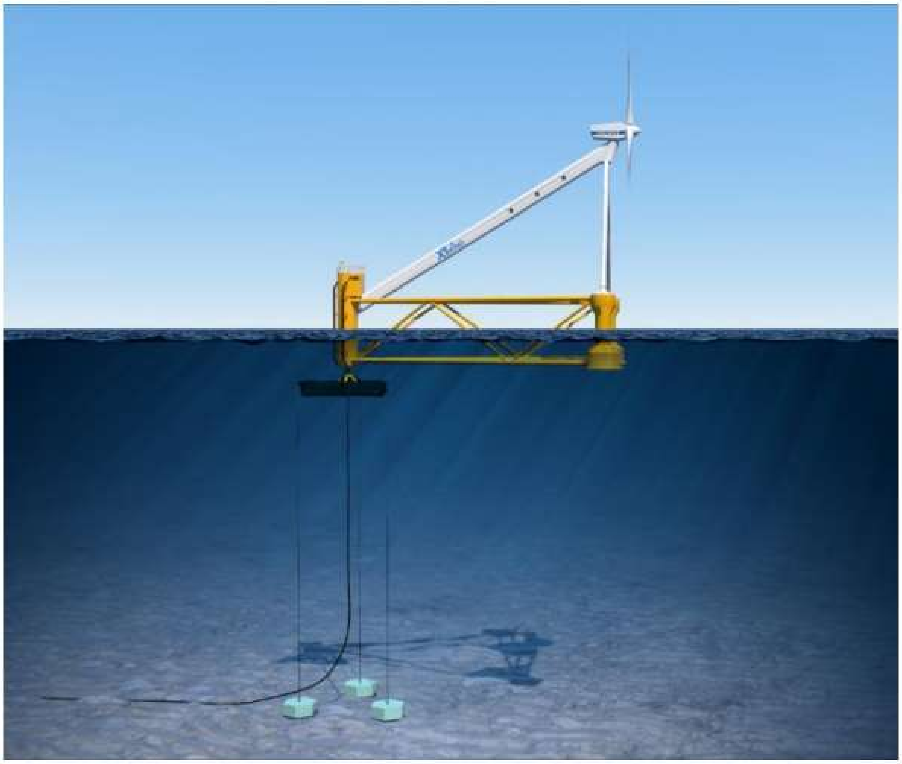

Figure 14 Render DDR-2 Foundation

Gravity bases consist of a steel frame with space for placement of large concrete ballasting blocks. The steel frames are easily fabricated by local secondary fabrication sites and transported to the quayside where the vessels for the anchor placement will embark. As concrete is relatively cheap and easily available from many suppliers, it is beneficial to select a convenient location for pick-up and mobilization to the offshore installation site. As the benefits of low-cost concrete quickly diminish if the concrete is transported over long distances, it is desirable to find a local supplier. As concrete is a widely available material, this will be possible for practically every global region.

Like the pivot base and the tendons of the mooring system, the foundation sub-unit is considered a fully decoupled production line. For optimal lead times, the logistics of these three sub-units that comprise the ‘bottom’ of the PivotBuoy system must be attuned to each other. Due to the relative ease of fabrication and selection of suppliers and secondary fabrication sites, the foundation scores a **5/5** on all criteria.

2.4 Summary

Table 5 shows a summarizing table of all the component ratings per criteria and their overall score.

Sub-Unit	Component	Fabrication	Transportation	Storage	Overall
WTG	Rotor Nacelle Assembly	3	4	4	3.7
Floater	Main Columns	3	4	5	4.0
	Pontoons	3	2	2	2.3
	Damping plates	5	5	5	5.0
	(Pivot) Masts	5	5	5	5.0
	Pivot top	2	3	4	3.0
	Tower Top Adapter	3	4	4	3.7
TLP System	Tethers	5	5	5	5.0
	Pivot bottom	3	4	4	3.7
	Anchors	5	5	5	5.0

Table 5 Component Rating Sheet

Following the resulting overall ratings, the crucial components in terms of fabrication, transportation and storage show to be the pontoons and pivot top. As the main risks of the pivot top results from its novelty, it is expected that the overall score can improve through gained experience with the maturing of the concept. Hence, the fabrication, transportation and storage of the pontoons are expected to be the most critical factors in determining the final industrialization plan. Due to its slenderness and dimensions, the handling and transportation becomes complex for full-scale systems. Three methods for fabrication and transportation were discussed, where ultimately the final choice is a trade-off between complexity of transportation, required operations and available space at the primary assembly yard.

3 FABRICATION AND ASSEMBLY SEQUENCE

As discussed in Section 1.4, not all components will be fabricated and/or assembled at the same location. This section will elaborate on the fabrication and assembly sequence logistics and will list the required equipment and criticalities during the processes. A general overview of the sequence is given, and the different stages are discussed in more detail in the subsequent subsections.

3.1 General Overview

In the fabrication and assembly sequence we distinguish three levels of yards/partners: suppliers, secondary fabrication yards and primary assembly yards. The suppliers generally provide materials, components and/or equipment that can readily be used. They will supply to both the secondary fabrication sites and the primary assembly yard. The finished components of the secondary fabrication sites will be transported to the primary assembly yard. A schematic overview is given in Figure 15.

The following sub-sections will list what type of components are manufactured at which site and mention the required equipment. These requirements can be used in later stadia to select appropriate sites per project.

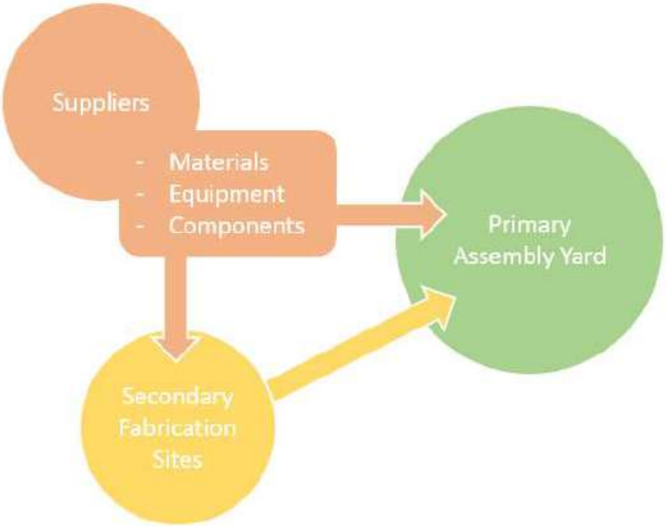

Figure 15 General Overview Fabrication and Assembly

3.2 Suppliers

As shown in Figure 15 the suppliers can provide (but are not limited to) products like materials, equipment, and ready-made components. Usually, a supplier is specialized in the fabrication of a small number of products and therefore many different suppliers will be included in the fabrication sequence. Due to the relatively small dimensions and low mass of these products, transport and storage is not considered to be a problem during industrialization. As mentioned, the products can vary from materials (such as paint, steel plates, welding materials etc.) to ready-made components (secondary steel structures such as ladders and rails, but also the more specialized elastic joint unit).

3.3 Secondary Fabrication Sites

To allow for simultaneous fabrication of multiple PivotBuoy systems and support the ‘design for manufacturing’ philosophy, the fabrication of the components is divided over several secondary fabrication sites. These sites can be close to or remote from the primary assembly yard and will vary from small to medium capacity. The smaller capacity fabrication sites will provide sub-components such as steel shells and tubing, which are either transported to a medium capacity secondary fabrication site for further fabrication or shipped directly to the primary assembly yard.

Generally, all the system components mentioned in Section 2 will be fabricated in medium capacity secondary fabrication sites. An exception could be the fabrication of the pontoon frames, if it is decided that the assembly of this component is done at the primary assembly yard (no prefabrication method in Table 4). As all components are made from structural steel, no significant differences in material handling are required. The secondary fabrication sites will need to be able to perform the following operations:

- Plate cutting/bending,
- (Certified) welding,
- Non-destructive testing,
- Coating and painting,
- Large storage capacity,
- Access to sea/river transport

Due to the large dimensions of the full scale PivotBuoy unit, components like columns and pontoons become significant ‘structures’ on their own. The fabrication yards require heavy lifting equipment (both in terms of lifting capacity and in terms of lifting height or boom-out) to transport finished products to the storage area and onto transportation barges. If it is decided to assemble the pontoons partially in the secondary fabrication site and transport in segments (partial prefabrication method in Table 4), lifting equipment with multiple lifting points are required. The slenderness of the pontoons means that integrity under self-weight (i.e. gravity load) is a key consideration, a risk that can be mitigated by proper lifting technique and adding bracing for stability. The secondary fabrication sites will ultimately deliver the following components:

- Main columns
- Pivot top
- Partial pontoons (If option partial prefabrication method is selected)
- Damping plates
- (Pivot) masts
- Pivot Bottom

3.4 Primary Assembly Yard

The finalized components are transported to the primary assembly yard and stored onshore. Logically, these yards will require equivalent or higher lifting capacity than the secondary fabrication sites to do so. When all components are available at the yard, the assembly process can begin.

A desirable feature for each support structure type is to be as widely applicable as possible, but not all envisaged floating wind project sites will have access to ports and yards with equal capacities. In this document we distinguish two types of primary assembly yards. The first option is a so-called 'greenfield' primary assembly yard. This is a site that will be specially built to the needs of the project in terms of area and equipment. The second option concerns the use of existing infrastructure. The first option will typically drive up the cost for fabrication and assembly, but significantly reduces the difficulty of logistics and operations, which will reduce the lead times and thus drive down the installation cost. The second option should drive down the fabrication and assembly cost, but may have a much higher difficulty of logistics and operations due to the limitations imposed by existing facilities. This latter aspect may also drive up the installation cost if the overall offshore program is extended. As no drydocks with suitable dimensions for full scale PivotBuoys are available, the full assembly of the floater will occur onshore. This might require temporary bracing and complex lifting operations to ensure structural integrity during the assembly phase.

3.4.1 Option 1: Greenfield

As mentioned, the first option is the so-called greenfield site, with no limitations in space and availability of equipment. With sufficient storage and fabrication acreage, multiple assembly lines can be established. Naturally, by doubling the number of assembly lines the lead time approximately halves. Figure 16 shows a visualization of a primary assembly yard where the pontoons are assembled on site in fabrication halls. It shows multiple streamlined assembly sequences that lead to the launch at the quayside. The launch of the assembled floaters will be discussed in Section 4.1.

Figure 16 Preliminary Render of Greenfield Primary Assembly Yard

3.4.2 Option 2: Use of Existing Infrastructure

It must be noted that due to the large dimensions of the PivotBuoy, typical existing yards will only have room for a limited number of PivotBuoys at the same time. Figure 17 gives a sense of the difference in scale between the X30 and the X140 platform and the required storage acreage.

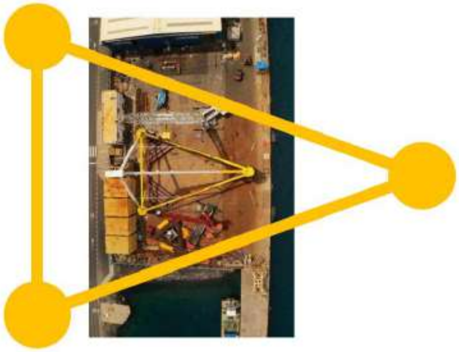

Figure 17 Size Comparison X30 and X140 Platform

Figure 18 shows the Navantia fabrication yard (located along the Ría de Ferrol in Galicia) used to fabricate one of the WindFloat Atlantic floaters (8.4 MW) and a visualization of a X140 platform for comparison. It shows that this specific location would have room for at most one full scale system, which underlines the earlier statement that existing yards will generally not have the spatial capacity for many simultaneous full-scale PivotBuoy production lines.

Figure 18 Size Comparison WindFloat Atlantic (8.4 MW) and PivotBuoy X140 (15 MW)

If the project specifications (available area, budget etc.) do not allow for establishing a greenfield primary assembly yard, assessment of available existing infrastructure can provide a solution. As the local infrastructure typically has less onshore area, the logistics for a smooth constant supply chain become more complex. Use of multiple yards in a region remains an option; however, the additional logistics will result in a less efficient and, therefore, more expensive operation. As an alternative to utilizing multiple onshore sites, Section 4 elaborates on including temporary offshore anchorage into the supply chain to increase flexibility and reduce lead times.

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3.5 Assembly Sequence

An overview of the assembly sequence is given in Figure 19. Firstly, jig frames will be laid out to correctly position the columns and pontoons. These frames make sure that the columns are levelled, and that the connection piece of the pivot top is safely located from the ground to mitigate the risk of damage. The alignment is an important step, as misalignments can be very difficult to fix in later stadia. To achieve high precision, laser trackers and GPS can be used to ensure the right position in horizontal and vertical plane. The jig frame layout will be followed to fix the main columns and the pivot top in the exact correct positions. The lifting operation of the main columns and pivot top is expected to be possible with conventional mobile cranes, slings, and a spreader. Using lifting equipment with multiple lifting points, the pontoons are carefully upended, lifted to their final position, welded to the columns and the welds are coated securely. Modelling of lifting procedures is required to assess whether temporary bracing and/or support points are required as onshore conditions can result in large stresses (especially in slender structures). Finally, the two masts and the pivot mast are connected to the floater. Note that the lifting operation of a full-scale pivot masts with its internal equipment is a complex lifting operation, which requires detailed planning and might add to the requirements of the primary assembly yard selection.

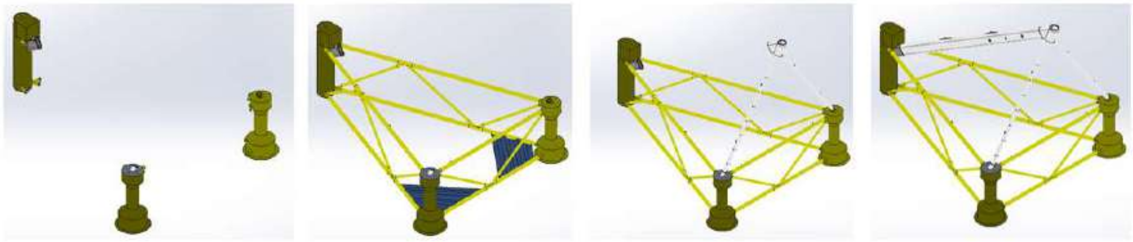

Figure 19 Overview Assembly Sequence

Since the mooring system including the pivot bottom are installed offshore prior to the connection with the floater, they are not incorporated in the assembly sequence. The WTG will be attached to the pyramidical towers in a later stage as will be discussed in Section 4.

3.6 Summary

As a result of the design for manufacturing philosophy, few criticalities are observed on the supplier and secondary fabrication site level. Due to the high modularity and compact dimensions of the separated system components, the different component can be fabricated by a broad range of secondary fabrication sites and the (local) suppliers can be selected accordingly.

The increased dimensions and number of required systems, however, will significantly increase the required assembly and storage area at the primary assembly yard. Two options for this primary assembly yard are assessed: a greenfield option and the use of existing infrastructure. In the final industrialization plan, the selection will be a trade-off of many factors such as budget, available local infrastructure, and local governmental rules.

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It must be noted that most of the complications do not only apply to the PivotBuoy concept. Other semi-submersible/TLP concepts will have dimensions of comparable magnitude in size and will thus have to overcome the similar logistical barriers. The high modularity of the PivotBuoy concept gives it a significant advantage in terms of industrialization with respect to most competitors. The supply chain can be easily spread out and tailored to different project sites, which is more difficult for other concepts that require better specialized fabrication sites due to larger dimensions.

4 FULL SCALE LAUNCH AND INSTALLATION

The floater sub-unit, now fully assembled, is ready to proceed to the next phase, launch and installation. Due to the increased dimensions of a full-scale PivotBuoy system, the floater cannot be simply lifted into the water by cranes, and different launch techniques therefore are required. Since launching the floater with the WTG attached is more challenging than without (e.g. due to higher weight and higher center of gravity), the outfitting of the floater with the WTG occurs when the floater is afloat (*outfitting*). Primary assembly yards will not have spatial capacity for onshore storage of all finished PivotBuoy floaters simultaneously. However, since the installation of the systems typically require specialized fleet and suitable weather conditions, it is cost- and time-inefficient to separately install each system directly after assembly. The assembled floater sub-structures typically cannot be stored on land due to the space required, and they are also not yet ready for installation offshore at the project site. Use of temporary offshore anchorages is therefore envisaged to manage this. Two anchorages are required: before outfitting with the RNA (*assembly anchorage*) and before tow out to the project site (*marshalling anchorage*). In practice, these may be the same physical location.

Figure 20 shows an overview of the mentioned operations, which will be discussed in detail in the subsequent subsections.

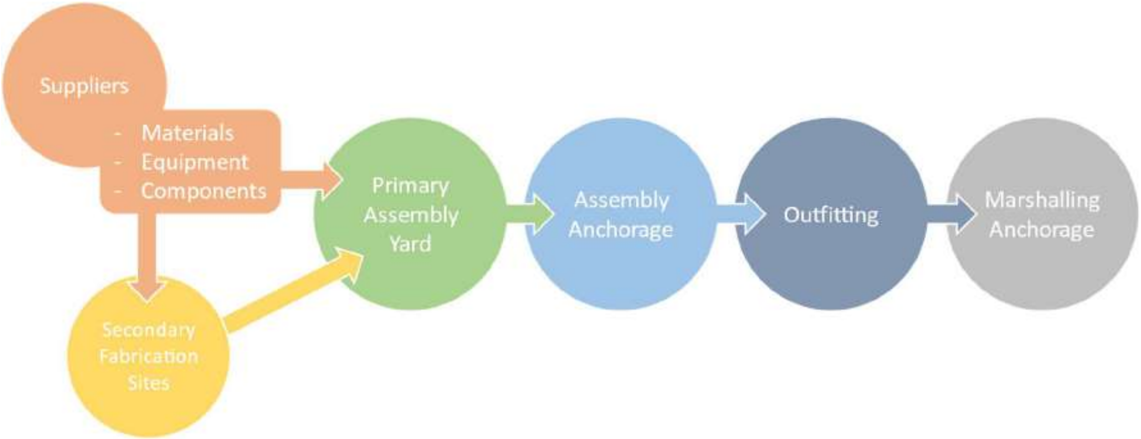

Figure 20 Overview of Launch Sequence

4.1 Launch

Due to the size of the X140 platforms, regular crane lifting from quayside into the water becomes difficult, if not impossible. Therefore, other launch techniques will be assessed for the PivotBuoy systems. The two considered launching techniques are the use of semi-submersible barges and the use of slipways.

4.1.1 Semi-Submersible Launch

The first method is a familiar technique to the naval and offshore industry and has already been used in the floating wind industry during the WindFloat Atlantic project. The fully assembled floater (excluding the WTG) is loaded onto Self-Propelled Modular Transporters (SPMT) onshore, designed to transport heavy loads. The floater is carefully transported from the quayside onto a submersible heavy lifting vessel(s). Due to the size of the PivotBuoys, large semi-submersibles will be required. Since the weight of the floater is low compared to its size, the lifting vessel(s) will not use its full capacity. As the costs of these vessels generally reflect the lifting capacity rather than the size, this can become very cost in-efficient. To save costs, an optimal combination of number of barges, individual lifting capacity and difficulty of operation must be obtained. If it is decided to use two or more barges, the required vessel dimensions will reduce, but the complexity of the launch operation will increase. A detailed technical analysis and cost assessment is required to select the optimal configuration of barges.

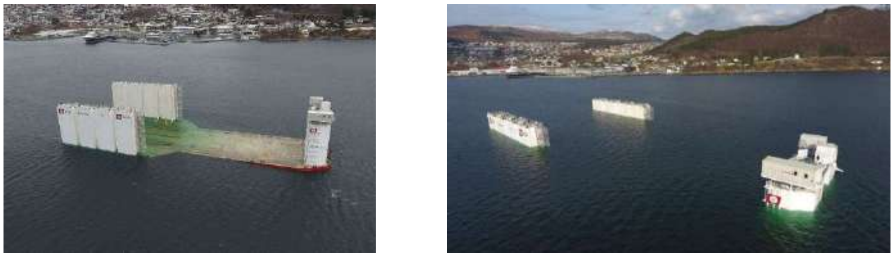

Figure 21 BOA Barge 33 in Floating (left) and Submerged (right) Position

When the floater is loaded onto the submersible heavy lifting vessel, the vessel moves to deeper water and is lowered by ballasting. Submersible barges can provide a draft above deck of approximately 8 m meters, with extremes of around 20 m. After lowering the vessel, towing tugs can be used to tow the floater to the temporary assembly anchorage. Figure 21 shows the BOA BARGE 33 in floating and submerged position. The full launch sequence is visualized in Figure 22 (note the visualization is for illustration purpose and actual scale will differ). Currently, multiple configurations for this launch method are assessed. The industrialization of the launch is process is a hurdle that the entire industry must overcome and is thus not solely related to the PivotBuoy concept.

As an alternative to a submersible lifting vessel, it may be feasible to use a jack-up platform in locations where the quayside draft is sufficient to allow lowering of the platform adjacent to the quayside. This alternative may result in cost saving versus the use of specialized vessels.

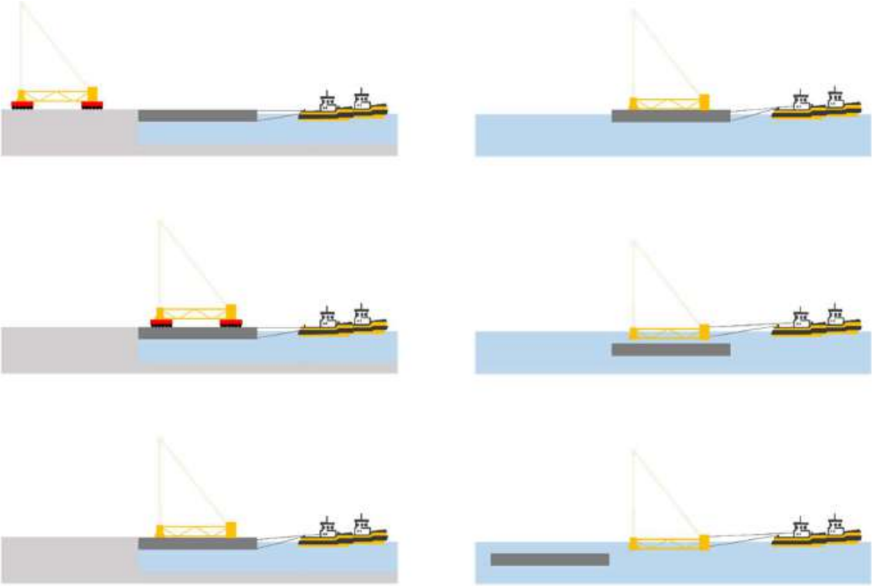

Figure 22 Submersible Barge Launch Sequence

4.1.2 Slipway Launch

The second launch option is the use of slipways. This launch method is widely used in the naval architecture sector but has yet to be assessed in the floating wind industry. Due to the relatively small scale of floating wind support structures to date, the use of drydocks or regular crane lifting generally sufficed. For the launch of a X140 platform a concrete slipway with sufficient dimensions to fit the full platform and an angle of approximately 10 degrees would be required. The global availability of this type of slipways is scarce and generally investments to modify the primary assembly yard will be required. However, for a large number of floaters this might become an attractive investment.

The general launch sequence will be as follows: The platforms are transported from the assembly site to the slipway using SPMTs and are loaded onto slipway karts with the main columns facing front. Hereafter, the platform is carefully slid into the water until the main columns become buoyant. Tugboats are used to position the floater and to transport it to the assembly anchorage. A simplified visualization of the process is given in Figure 23.

The development of a mobile slipway can be considered for use across multiple projects and at different sites.

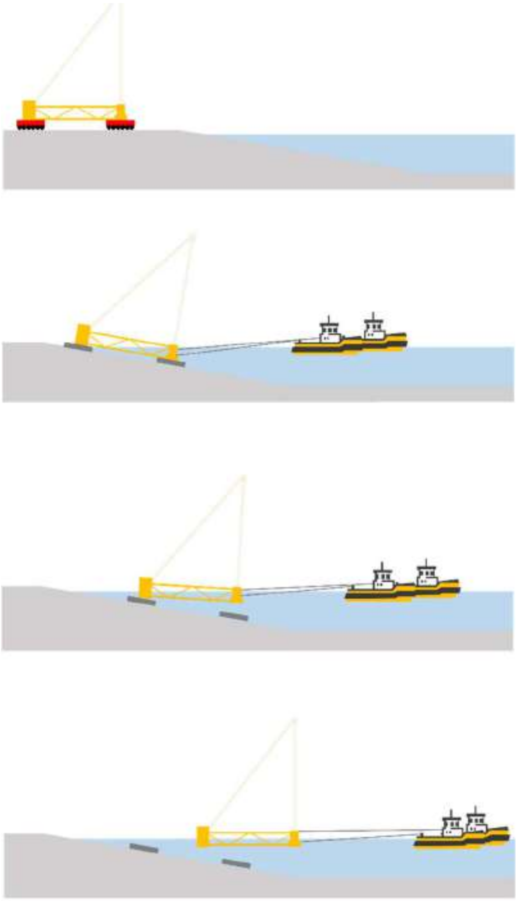

Figure 23 Slipway Launch Sequence

The final method selection will ultimately be done by cost comparison, which will be strongly driven by availability of local facilities and the project size. It is expected that the costs of the slipway launch are lower, but with higher CAPEX (if no suitable slipway is readily available). With an increasing number of units, the total costs per unit will thus decrease for this method. Additionally, when the primary assembly yard doesn't allow for multiple production lines, the use of barges becomes less appealing. The periods between launch of floaters will increase and since the costs of the barges are typically time-based, this would increase expenses for the overall launching procedure.

4.2 Assembly Anchorage

As stated, it is assumed that the primary assembly yards will not be able to store all PivotBuoy systems onshore, hence offshores storage will be required. The use of temporary anchorage will also increase flexibility of the production line and thus reduce the overall lead times. The temporary offshore storage before installation of the WTG is called the assembly anchorage. As this will be a temporary storage, a full mooring system is redundant at this point. The assembly anchorage should be in a sheltered location (to reduce environmental forcing) with room for many hulls and proper accessibility. The location can be close to the primary assembly yard or close to the outfitting quayside discussed in the next sub-section, depending on availability of suiting conditions.

Use of a work platform within the anchorage (e.g. a small jack-up or barge) can be considered to allow carry-over workscope from the primary assembly yard to be executed within the anchorage. This may include tasks like surface treatment of weld zones, assembly of secondary components and system pre-commissioning activities.

4.3 Outfitting and Quay-side Commissioning

The floaters will be transported by tugboats from the assembly anchorage to the outfitting and commissioning quayside for the final assembly steps. The assembly site must have craneage with sufficient capacity to perform quayside lifting operations with either the full WTG or separate lifting operations for the nacelle and the blades. The one-lift operation is the preferred method, as it saves time, however heavier lifting equipment is required. The anticipated use of the two bladed turbines will make a single lift operation easier. After outfitting, the floaters are transported to the marshalling anchorage by tugboats. Figure 24 visualizes the outfitting of a X140 floater with a 2 bladed turbine in a single lift.

Figure 24 X140 Outfitting

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4.4 Marshalling Anchorage

With the WTG attached to the floater, the floater sub-unit of the PivotBuoy system is ready to be installed offshore. The offshore installation of the PivotBuoys will commence when sufficient TLP systems are installed, installation fleet is available, and the weather window allows for smooth operations. Due to the separated production lines, the TLP systems can be fabricated and installed separately of and simultaneously with the floater assembly. A quick connector system enables fast installation of the floater unit with a shorter weather window compared to conventional catenary mooring systems. Experience from the prototype project, however, showed that this time frame remans critical due to uncertainties in weather conditions. It is therefore key to prepare a buffer of PivotBuoys ready for installation to optimally use the timeframe with suitable installation conditions. The temporary storage of the fully commissioned PivotBuoys is referred to as the marshalling anchorage. This location can be the same as the assembly anchorage if space allows, or a sheltered location closer to the project site. Figure 25 shows a conceptual launch and installation sequence visualization of a full scale PivotBuoy wind farm. In the figure the use of existing infrastructure for the primary assembly yard was selected (space for limited number of PivotBuoy assembly lines). However, the marshalling anchorage will be required for both the 'greenfield' primary assembly yard and the use of existing infrastructure.

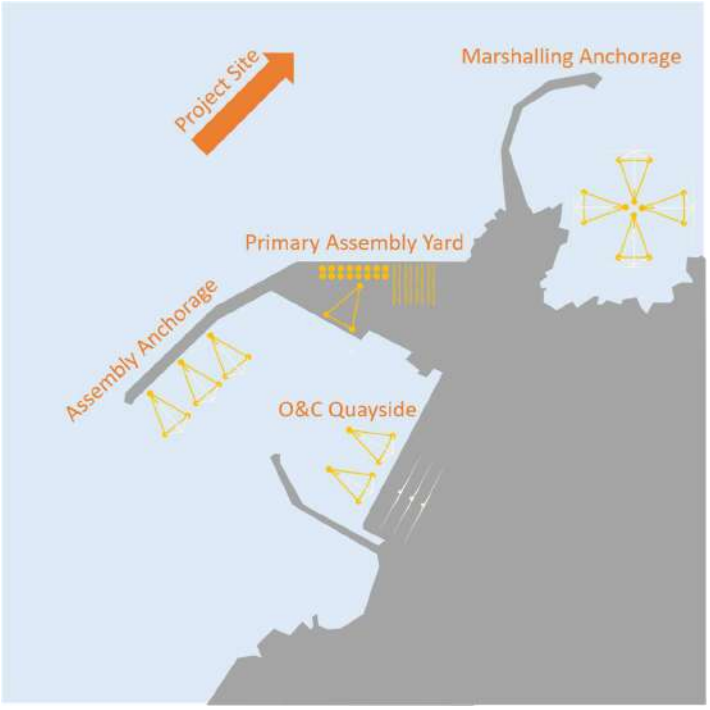

Figure 25 Conceptual Launch and Installation Sequence

For commercial size wind farms, it is possible that 2 or 3 'offshore seasons' will be required to complete all installation activities. These offshore seasons comprise the months when wind, wave and current conditions at the offshore site are better suited for construction activities based on historical observations; i.e. when the risk of downtime due to weather is most predictable and is acceptably low. As an example, the typical installation season in the North Sea extends from April 1 to September 30. Meanwhile, the assembly line should continue to refill the buffer of the marshalling anchorage.

4.5 Summary

Regardless of the final primary assembly selection, several final steps are required to prepare the PivotBuoy for installation. When the floater is fully assembled, it will be launched and towed to the assembly anchorage. Two launch methods are assessed: by semi-submersible barge and by slipway. The final method selection will be a trade-off between CAPEX, OPEX and available infrastructure. To increase the flexibility of the production sequence, the assembled floaters are stored at the assembly anchorage prior to outfitting. After outfitting the finalized systems are towed to the marshalling anchorage. Here a buffer of PivotBuoys ready for installation will be gathered, to be installed when conditions align, and a suitable timeframe opens.

It is desirable that all the final preparatory steps (assembly anchorage, outfitting and marshalling anchorage) can be located near each other and close to the project site. However, if the project conditions don't allow for this setup, these steps can also be split. While this will increase the required towing distances of the systems, it will also increase the applicability. Ultimately the location selection will depend on whether there is availability of sheltered waters for anchorage nearby the primary assembly yard.

5 CONCLUSIONS AND FINAL INDUSTRIALIZATION PLAN

This deliverable elaborates on the industrialization plan for serial production of commercial windfarms supported by full scale PivotBuoy systems. When shifting from the prototype to commercial phase, the dimensions and number of required systems of the PivotBuoy will increase. As the 'one-off' production approach adopted for the prototype platform will result in infeasible lead times for commercial wind farms, the supply chain will have to shift to an industrialized supply chain. The final industrialization plan aims at reducing the overall lead times from receipt of raw materials to final commissioning checks at the quayside from approximately 3 months to several weeks. The industrialization plan is expected to be governed by a set of critical points throughout this sequence. This document aims at extracting these criticalities and minimizing their impact on the overall lead times. The key critical factors are summarized in Table 6:

	Criticality
System Component Assessment	• Little industry experience in handling of pivot top and bottom, • Complex handling, transportation, and storage of pontoons
Fabrication and Assembly Sequence	• Available assembly and storage area at primary assembly yard
Launch and Installation Sequence	• Launch method selection, • Available temporary anchorage area

Table 6 Summary of Critical Factors

The list of criticalities indicates that the adopted 'design for manufacturing' philosophy successfully mitigates problems of fabrication. Due to the high modularity of the system, system components can be fabricated by a broad range of secondary fabrication sites with relative ease.

As a result, the industrialization plan is not governed by capacity of fabrication sites, but rather becomes an optimization of logistics. By taking measures to optimize the industrialized supply chain by clever use of the modularity of the system, it is expected that the lead times can be brought down to a couple of weeks or a month. Several proposed lead time reduction methods are listed below:

- The fabrication of the 5 sub-units (WTG, floater, mooring system, pivot bottom and foundation) should be considered as independent production lines as visualized in Figure 26.
    - The fabrication of the WTG, mooring system and foundation are readily industrialized production lines and will therefore require little optimization.
    - The pivot bottom is a compact component comprising relatively simple steel sub-components, which are easily transported and stored. By contracting qualified (local) secondary sites, this production line will not be critical to the lead times.
    - The optimization of the floater production line is ultimately governing for the overall lead times. The ratings found in Section 2 showed that the pontoons are the only critical system component. Two feasible fabrication methods are proposed (no prefab and partial prefab), of which the final selection depends on the primary assembly yard capacity.

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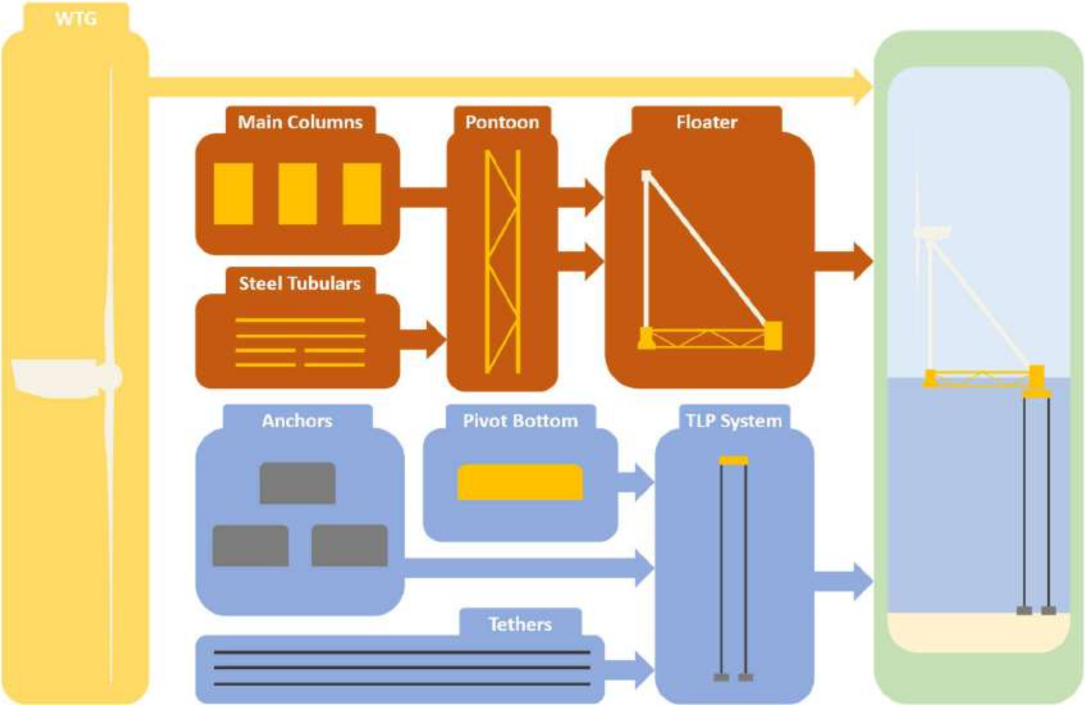

Figure 26 Independent Production Lines

- The primary assembly yard for the floater is critical to the production line of the floater sub-unit. It is desirable to establish as many assembly lines as possible to minimize the lead times. Two types of primary assembly yards are proposed, a green field option and the use of existing infrastructure. If the project specifications allow for the establishment of a greenfield assembly yard, this is the preferred option. Generally, the existing infrastructure will have limited assembly area and will thus result in longer lead times.
- To increase flexibility of logistics, temporary anchorage can be included in the assembly line, both prior to outfitting with the WTG (assembly anchorage) and installation (marshalling anchorage). The temporary anchorages should be located in sheltered, easily accessible waters. The assembly anchorage can be close to the primary assembly yard or the O&C quayside. The marshalling anchorage can be at the same location as the assembly anchorage or another sheltered location close to the project site.
- Since the suitable installation windows are limited, it is key to build a buffer of PivotBuoys ready for installation at the marshalling anchorage. This way maximal installation operations can be performed during these installation windows. Naturally this also means that the mooring systems must be in place at this time. Due to the quick connector systems between the pivot top and bottom this can be done relatively quickly and with a broad selection of fleet. It is expected that 2 or 3 offshore installation seasons will be required for commercial floating wind farms.

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