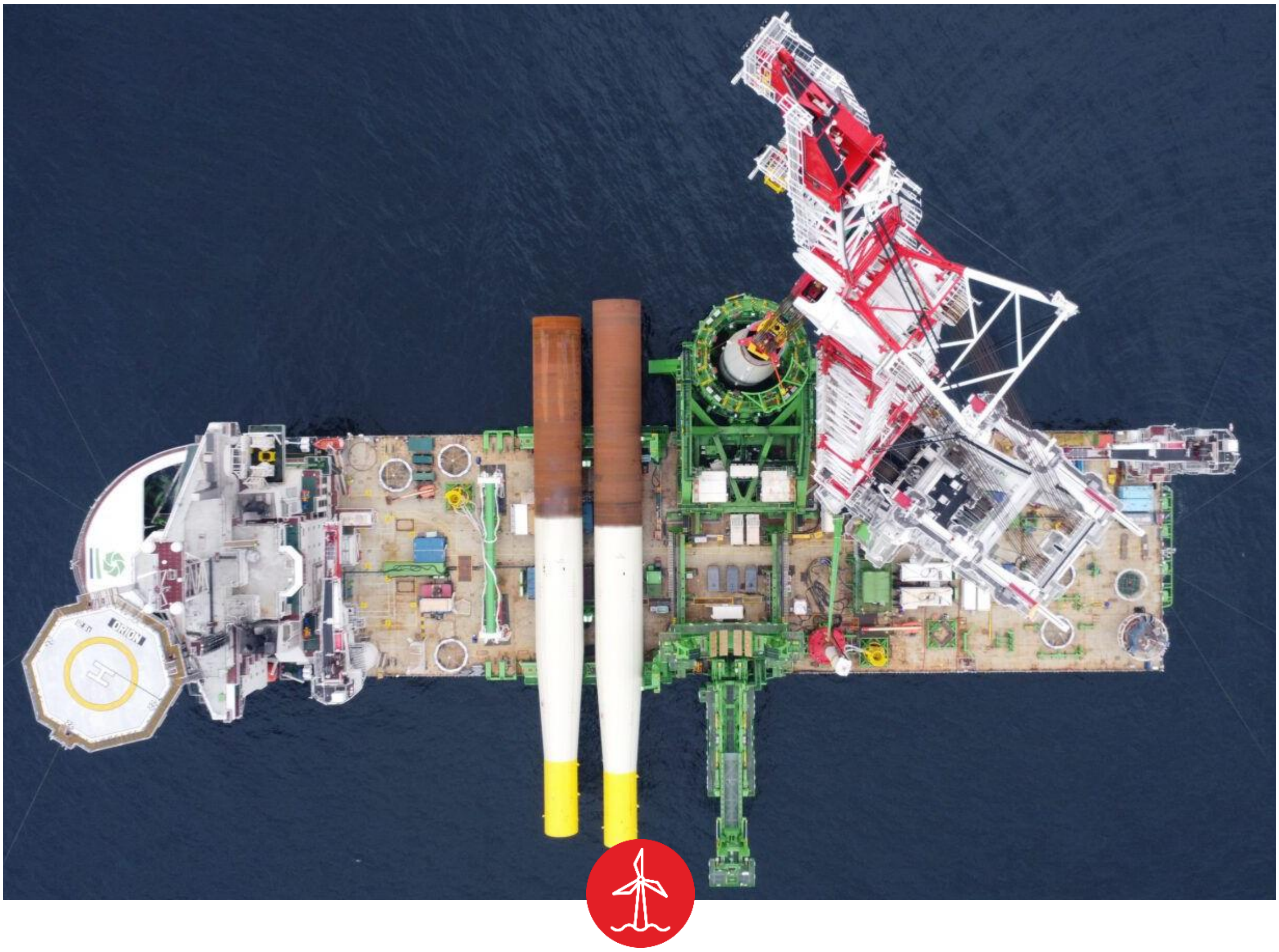

Motion compensated pile gripper – Final public report – Hernieuwbare energie

Project

Motion compensated pile installation

Project No.

TEHE118010

Our Ref.

TWD-NL-2017-072-PM-15

Program Line

SDE + techniek, Support structure installation

Project Location

The Netherlands

1	21-02-2023	F	WGR	-	JJA	KVN
0	31-10-2022	F	WGR	JKO	JJA	KVN
rev#	**date**	**status**	**initials**	**initials**	**initials**	**initials**
Status code: P - Preliminary C - Concept F - Final			Prepared by:	Technical check:	TWD approval:	DO Approval:

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1. General information

Below, the general data of the Motion compensated pile installation project are listed:

- Reference number: TEHE118010
- Project title: Motion compensated pile installation
- Contact person: Wesley de Groot (TWD)
  Kenneth Vannieuwenhuyse (DO)
- Consortium: Temporary Works Design & Barge Master
  DEME Offshore
- Start date of project: 15-08-2018
- End date of project: 31-07-2022

The project was performed with a subsidy from the Ministry of Economic Affairs and Climate and the Ministry of Agriculture, Nature and Food Quality, National schemes for EZK and LNV subsidies, Topsector Energy carried out by the Netherlands Enterprise Agency.

2. Summary

2.1. Introduction

Currently the majority of monopile foundations is installed by Jack-Up Vessels (JUVs), however most of the existing JUVs have insufficient crane and jacking capacity to efficiently install the XL-monopiles of future wind farms. Deployment of JUV's is also depending on soil conditions and water depth. Floating monopile installation vessels with higher crane capacities exist, however due to increasing tightness of verticality tolerances for monopiles, the workability of these solutions is limited.

2.2. Goal

The goal of the project is to design and construct the Motion Compensated Pile Gripper (MCPG) prototype for a more cost-effective floating MP installation. This will be achieved by compensating the disturbing vessel motions and herewith significantly increase the workability for floating installations. The MCPG (i) allows the use of a lower cost main installation vessel, (ii) allows the use of a vessel with significantly higher payload, (iii) reduces the required installation time.

2.3. Activities

The project consortium consists of two parties: Temporary Works Design & Barge Master (TWD - BM) and DEME Offshore (DO). TWD has extensive experience with the design of pile handling tools and motion compensated systems and were therefore responsible for the structural and mechanical design of the gripper and upend tool.

The development of the gripper's drive & control and safety / redundancy strategy was BM's responsibility. As they have a proven track record with the development of a motion compensated platform (BM T700), a motion compensated knuckle boom crane (BM T40) and a motion compensated gangway (BM MCG). The consortium has extensively interfaced with the dynamic positioning (DP) supplier Wärtsilä Dynamic Positioning (WDP) to integrate the MCPG with the DP system.

DEME Offshore has provided the essential operational input (installation, piling and DP experience) into the design and has effectively built the tools subcontracting to a steel fabricator and drive & control (D&C) supplier Huisman and has demonstrated the MCPG method with their new vessel the ORION on Arcadis Ost offshore wind farm.

2.4. Results

A motion compensated pile gripper was designed, tested and successfully taking into operation with the offshore wind installation vessel (OWIV) Orion at the Arcadis Ost 1 wind farm in Germany. On this first project:

- Extensive fabrication, harbor and offshore testing was performed
- A start-up plan was successfully completed transitioning from moored to DP installations in a safe manner
- Floating installation of XL monopiles on DP was proven feasible, reducing vessel and equipment costs
- Record monopile sizes were installed with a weight of 2100ton, a length of 110m and a 9.6m diameter
- Installation times of 10-12 hours per monopile were already achieved with still lots of optimization possibilities

The Orion equipped with MCPG, is designed for a workability between Hs 2,0 – 2,5 (depending on wave period), resulting in at least 73% workability year-round in the North Sea. Compared to the traditional JUV installation methodology this realizes a 34% reduction on the installation costs of foundations. A total cost reduction of 34% on the MP installation costs corresponds to LCOE reduction of €1.60/MWh, which is 2,60% reduction to the base case.

The vessel and gripper will be deployed on several upcoming projects until end of 2025. Meanwhile several other offshore wind installation contractors have also announced they are developing an MCPG following the successful offshore application and R&D that has been performed. And it is likely TWD – BM will be involved with new upcoming MCPGs.

3. Introduction

3.1. Project background

For optimal performance of an offshore wind turbine, very tight verticality tolerances for the MP-installation are specified by the turbine suppliers. In earlier offshore wind farms, where the TPs were grouted to the MP instead of bolted, the tolerance was set at 0.50 degrees. On the latest (and future) projects however, a maximum inclination of only 0.25 degrees is allowed. For 30m water depth, this corresponds to a maximum offset of the MP at water level of only ±130mm.

An MCPG on deck of the floating monopile installation vessel is used to (i) upend the monopile to vertical position, (ii) control the MP movements during lowering and (iii) hold the MP upright during piling. Alternatively, working from a JUV provides a stable platform, which makes it possible to manually adjust the pile inclination after touchdown. Discrete measurements of the pile inclination and manual adjustments with the pile gripper make sure the pile gets installed within tolerances.

For floating installations (either on DP or moored), the vessel is subjected to wave- and current induced motions. Depending on the vessel properties and the target sea-state, the motion envelope of a gripper on a floating vessel could be around ±2.0m. With this motion envelope, it is impossible to assure a pile verticality below 0.25 degrees. Therefore, continuous and real time inclination measurements are required, as input for an active compensation system which maintains the pile inclination within tolerances.

3.2. Results from basic engineering phase

The development of the MCPG covered three main areas of research having additional challenges compared to conventional installations with JUVs: (i) pile upending, (ii) pile lowering and (iii) pile driving (see Figure 3-1). These three stages are all affected by the motions and accelerations originating from a floating vessel. A list of all the technical research questions was setup before the start of the basic engineering phase. The research questions are derived from the HAZID analysis.

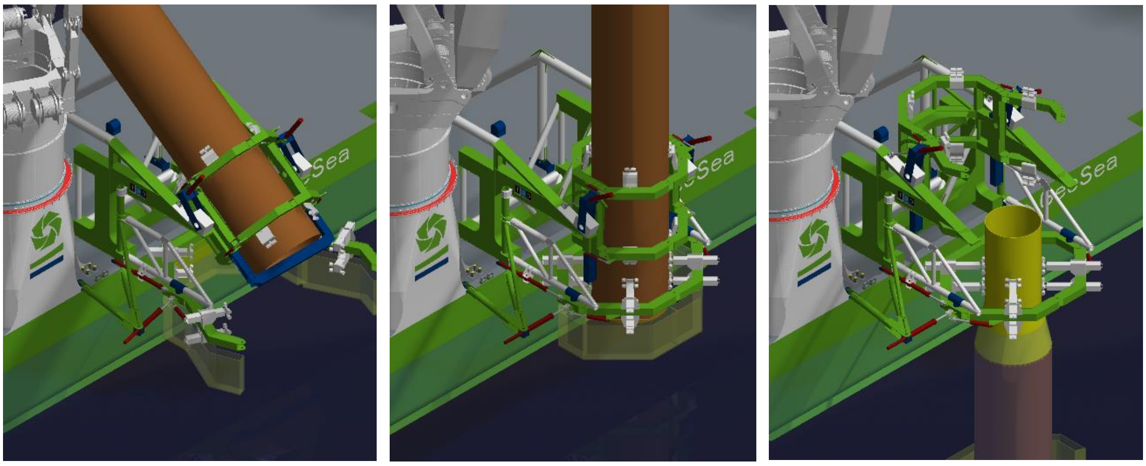

Figure 3-1, Three stages of installation; upending (left), lowering (middle) and driving (right)

In the basic engineering phase an integrated tool for the full operational sequence (upending, lowering and piling) was designed, which effectively mitigates the risks and downsides related to floating installations, see Figure 3-2. The installation method was demonstrated and validated with a scale model test campaign in a laboratory environment at MARIN. With these results all research questions were answered, and showstoppers were tackled.

The basic engineering phase of the MCPG project was finalized end 2017. This formed the starting point for the detailed design, production and testing.

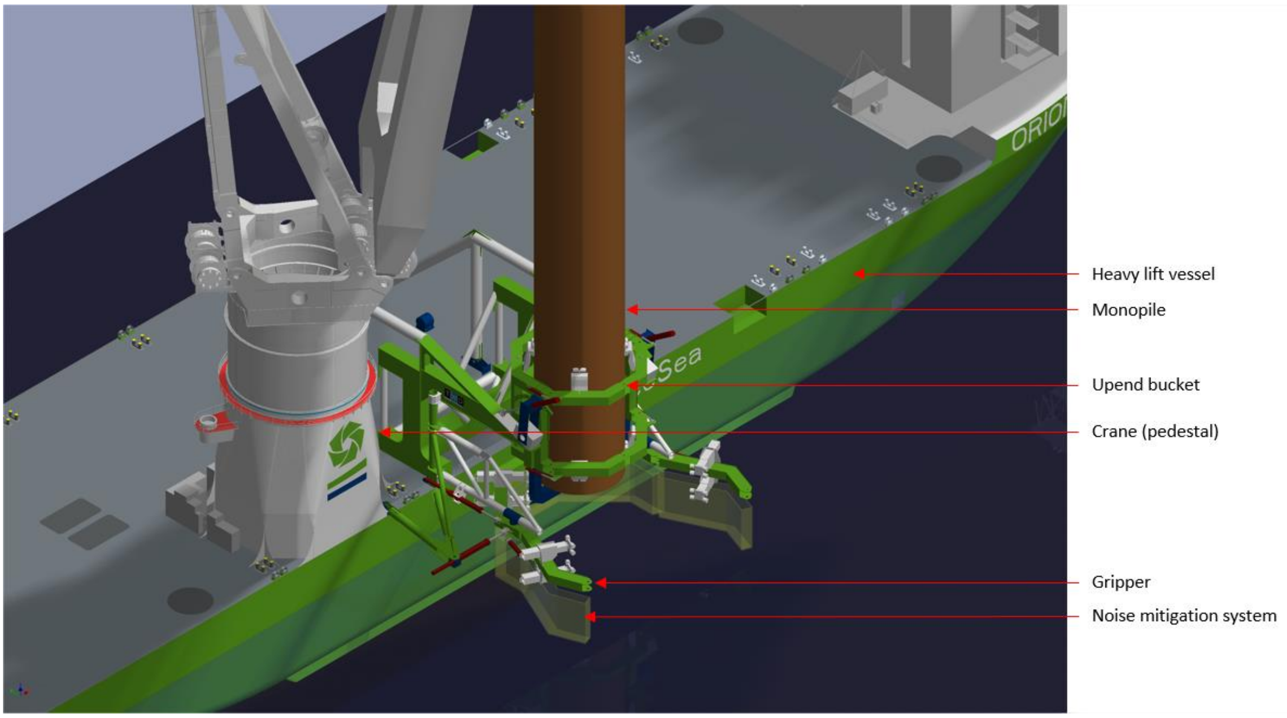

Figure 3-2, Render of the final concept of the basic design

Although all high-level research questions have been answered in the basic phase, a lot of innovative detailed design solutions had to be further developed. Required innovative detailed engineering includes the following:

- An actuated double upend ring of the upend bucket
- Upend bucket and gripper working together introducing complex roller boxes
- Upend bucket skid system and removable bottom beam for sufficient clearance for the gripper work envelope
- Complex upend frame to sustain high loads in a limited design space
- Complex gripper design with minimal friction in hinges to ensure controller stability
- High-capacity rollers to ensure structural integrity of the next generation monopiles
- DP system and MCPG interaction to ensure DP stability and overall system performance
- Motion compensation and rollerbox combination to prevent waste of hydraulic power
- Monopile yaw orientation during high loads
- Measurement and control systems to meet the high monopile vertically installation requirement
- Noise mitigation system integration in gripper

Therefore, all further performed detailed engineering for the upend bucket, gripper and NMS belongs to “Experimentele Ontwikkeling”, including the fabrication of the prototype.

4. Objectives

The goal of the project was to design the prototype (gripper and upend bucket) specifically required for efficient monopile installation with a floating vessel. The main goals are summarized in the overview below.

- Structural design of upending tool
- Structural design of motion compensated gripper
- Drive & control design of upending tool
- Drive & control design of motion compensated gripper (including DP controller design)
- Installation engineering (method statements, sequence drawings, lifting arrangements, etc.)
- Second campaign of laboratory testing
- Fabrication of the prototype
- Validation of principle by onshore and offshore testing of the prototype

As a result of the detailed engineering phase, a prototype was built to enable floating MP installation. The prototype was to be used as the first commercial product as the prototype is too expensive for demonstration purpose only. For DO (the end user), the MPCG prototype will allow to keep growing in the offshore installation market, broaden the field of application of their available assets and stay ahead of the market. For TWD – BM, the deliverables will be used to expand their market share in the field of monopile installation and motion compensation developments. An overview of the deliverables and results per work package is shown in Table 4-1.

Table 4-1, Overview of the objectives & results per working packages

Working packages		**Deliverables**	**Results**
2.1	Detailed design	Design report / Set of detailed drawings for construction / User's Manual	Detailed design ready for fabrication
2.2	Fabrication	All built components	All components ready to be assembled
2.3	Assembly	Built prototype	Working assemblies, built prototype
2.4	Onshore testing	Digital twin / Tested prototype / Report / Certifications	Digital commissioning, testing and training before offshore start of operations Tested prototype ready for installation on vessel
2.5	Offshore testing	Installed & tested prototype ready for use / Report / Certifications	Tested prototype ready for the final use

5. Approach

5.1. Project planning & scope

The overall project can be divided in the following three phases, per phase increasing the technical readiness level (TRL) of the design:

- Phase 0 – Feasibility studies, concept design and design base (TRL 1/2/3)
- Phase 1 – Basic design and laboratory testing (TRL 4/5/6)
- Phase 2 – Detailed design, fabrication, and testing (TRL 7/8/9)

A high-level planning including above mentioned phases is shown in Figure 5-1.

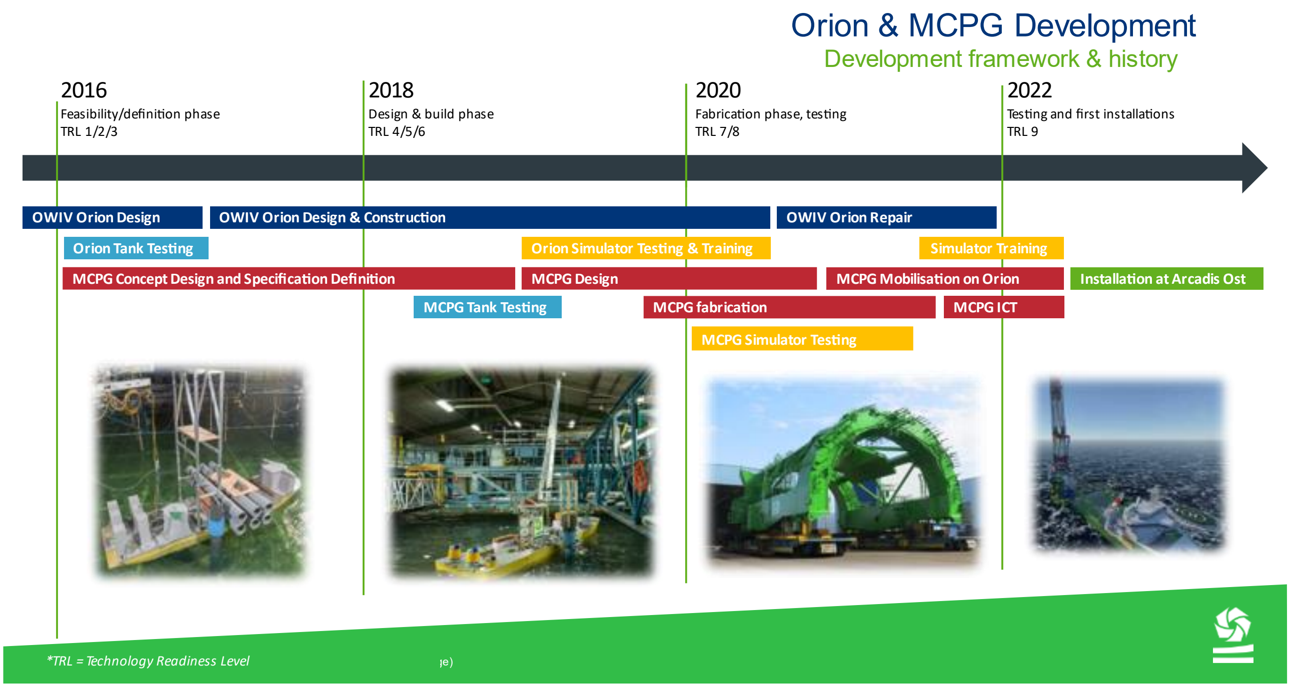

Figure 5-1, High-level project planning

Both Phase 0 and 1 were concluded. Part of this phase 0 includes the feasibility study, which was granted for a subsidy by the RVO. Basic design and laboratory testing are part of Phase 1, are also funded by the RVO and are partly finished in July 2018.

In the following sections the main planned activities are indicated per phase. The planning as shown is in line with the latest “Change in project execution” as communicated on 31-07-2020 to the RVO.

5.1.1. Phase 2.1 – Detailed design and engineering

TWD – BM and DO have worked together on the detailed design of Structural / Mechanical and Drive & Control aspects of the MCPG. DO provided comments related to the operational aspects. The collaboration resulted into a final detailed design of the MCPG and technical specification for the integration of DP and MCPG systems. Additionally, a technical specification for procurement of an MCPG was drafted.

Description	Cat.	Involved	Result	Start / End date
Upend bucket Detailed calculations & drafting	EO	DO / Huisman / TWD – BM	Detailed design report 2d detailed drawings	Dec 2019 - Dec 2020
Gripper (Rails, X-skid, Y-skid) Detailed calculations & drafting	EO	DO / Huisman / TWD – BM	Detailed design report 2d detailed drawings	Dec 2019 - Dec 2020
NMS Detailed calculations & drafting	EO	DO / Huisman / TWD – BM	Detailed design report 2d detailed drawings	Sept 2020 - Dec 2020

5.1.2. Phase 2.2 – Fabrication and assistance

Due to complexity of the integration of high accuracy steel structures with a complex drive and control system, Huisman was contracted to supply the MCPG in line with the drafted technical specifications. The NMS system was contracted separately and integrated by DO into the MCPG. Collaboration between all parties was essential and required to understand the complexity of the prototype components and interfaces.

Description	Cat.	Involved	Result	Start / End date
Upend bucket + Y-skid	EO	DO / Huisman / TWD – BM	Production of steel components, mainly at Huisman China	13 Jan 2020 - Q1 2021
Deck rails and X-skid	EO	DO / Huisman / TWD – BM	Production of steel components, mainly at Huisman Czechia	14 Feb 2020 - Q1 2021
NMS	EO	DO / TWD – BM	Production of steel components	Q3-Q4 2021
Hydraulic and electrical actuation	EO	DO / Huisman / TWD – BM	Production of HPU, Cylinders, Accumulators, E-motors, Control cabinets, E-drive cabinets	6 Feb 2020

5.1.3. Phase 2.3 – Assembly and assistance

Huisman fabricated and assembled the MCPG in parts and shipped these to Orion where DO and Huisman assembled the final structure. Tests were performed at different stages of assembly. This is explained further in this report.

Description	Cat.	Involved	Result	Start / End date
Steel Assembly	EO	DO / Huisman	Steel components assembled together	Feb 2020 - Apr 2021
D&C Assembly & Test	EO	DO / Huisman	D&C components assembled together and tested at fabricator	Nov 2020 - June 2021
Transport	EO	DO / Huisman	Rails and X-skid from Huisman The Netherlands to ORION	Apr 2021
Transport	EO	DO / Huisman	Y-skid and upend bucket from Huisman China to ORION	Jul - Aug 2021

5.1.4. Phase 2.4 – Onshore testing

DO constructed a digital twin of the Orion to test the vessel and its prototype and train the operators in a digital environment. Extensive testing was performed on the MCPG software, HMI and MCPG-DP interaction allowing troubleshooting before the prototype was installed onto Orion. As the installation methodology is new and involves significant risks, also the operators were trained prior to the actual offshore operation.

Global Maritime was appointed as third party to witness onshore, digital twin and offshore testing. Factory acceptance tests took place at all different fabrication facilities after which all parts were transported to the quayside and the mobilization and assembly onto the vessel began. This was done in different phases with onshore testing and offshore testing in between.

Description	Cat.	Involved	Result	Start / End date
Factory acceptance test	EO	DO / Huisman	At the Huisman yards	Q1 - Q2 2021
Mobilization & assembly	EO	DO / Huisman / TWD – BM	Prototype on vessel	Q3 - Q4 2021
Onshore testing	EO	DO / Huisman	Digital commissioning, testing and training before offshore start of operations Certification of prototype	Q3 - Q4 2021

5.1.5. Phase 2.5 – Offshore testing

Several sea trials were performed to verify vessel DP footprint and MCPG X motion compensation systems before attempting to install a monopile. After these tests were completed, sea trials with monopiles were done resulting in a successful start-up and indicating the project has reached the TRL 9. Global Maritime witnessed the offshore testing. DO, TWD – BM designed and attended the testing and discussed the results together with steel fabricator and D&C suppliers.

Description	Cat.	Involved	Result	Start / End date
Mooring Commissioning	EO	DO / WDP / TWD – BM / Huisman	Verify MCPG and survey system while using 8-point mooring system	Q2 2022
DP Commissioning	EO	DO / WDP / TWD – BM / Huisman	Working with MCPG on DP	Q2 2022
Close-out Sea Trials	EO	DO / WDP / TWD – BM / Huisman	Working prototype ready for use	Q2 2022

6. Results

6.1. Detailed design

TWD – BM & DO have worked together on the detailed design of Structural / Mechanical and Drive & Control aspects of MCPG. In the final design all Structural / Mechanical and Drive & Control challenges were overcome resulting in the MCPG as shown in Figure 6-1. This design is ready for fabrication.

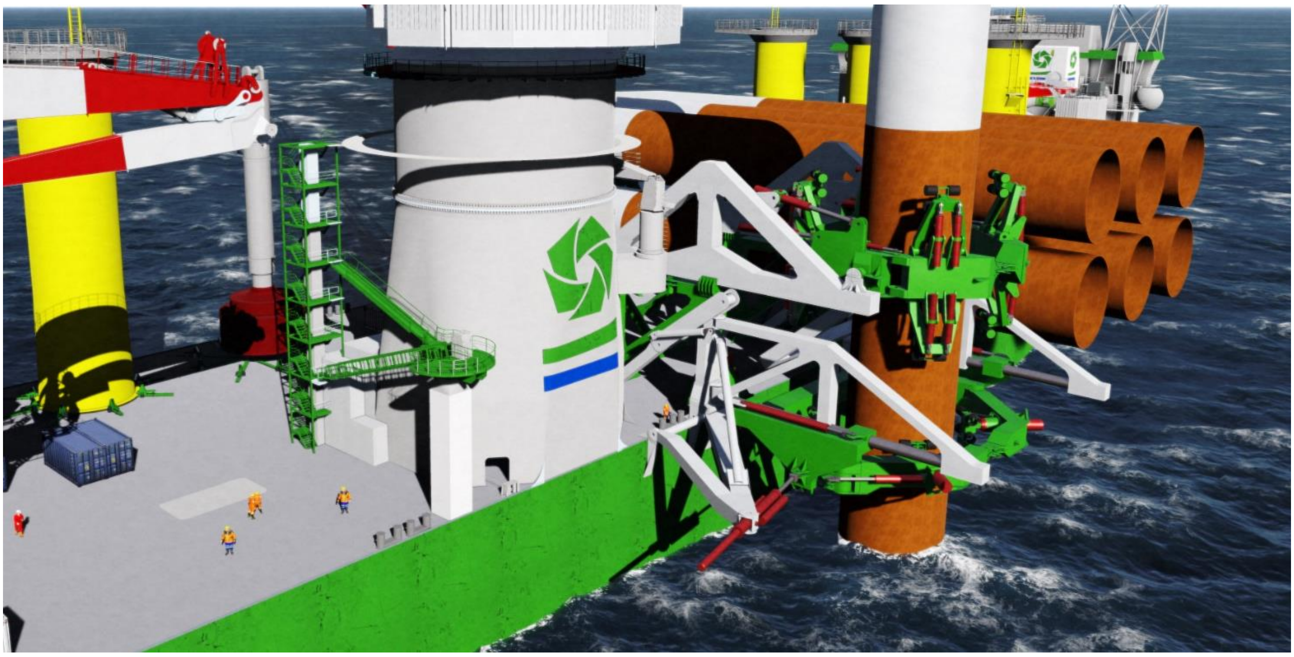

Figure 6-1: TWD – BM detailed design of MCPG

For commercial and technical reasons, further explained in chapter "Project execution", it was decided to translate the knowledge gained by TWD – BM & DO into a technical specification for an MCPG and to contract Huisman for detailed design and fabrication of the MCPG as shown in Figure 6-2.

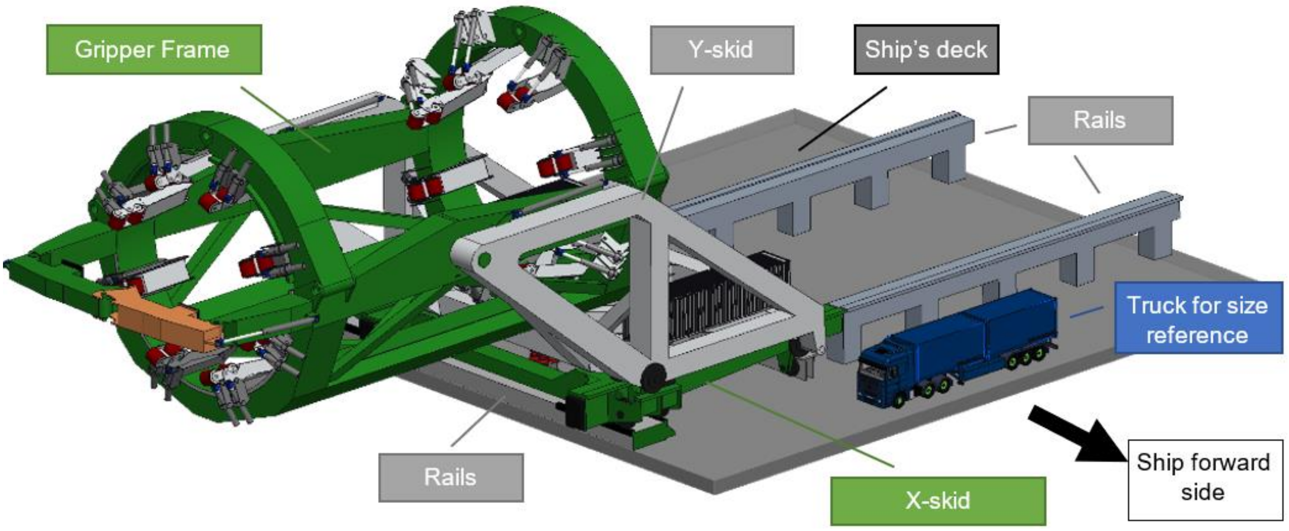

Figure 6-2: Huisman design of MCPG

6.1.1. Work sequence

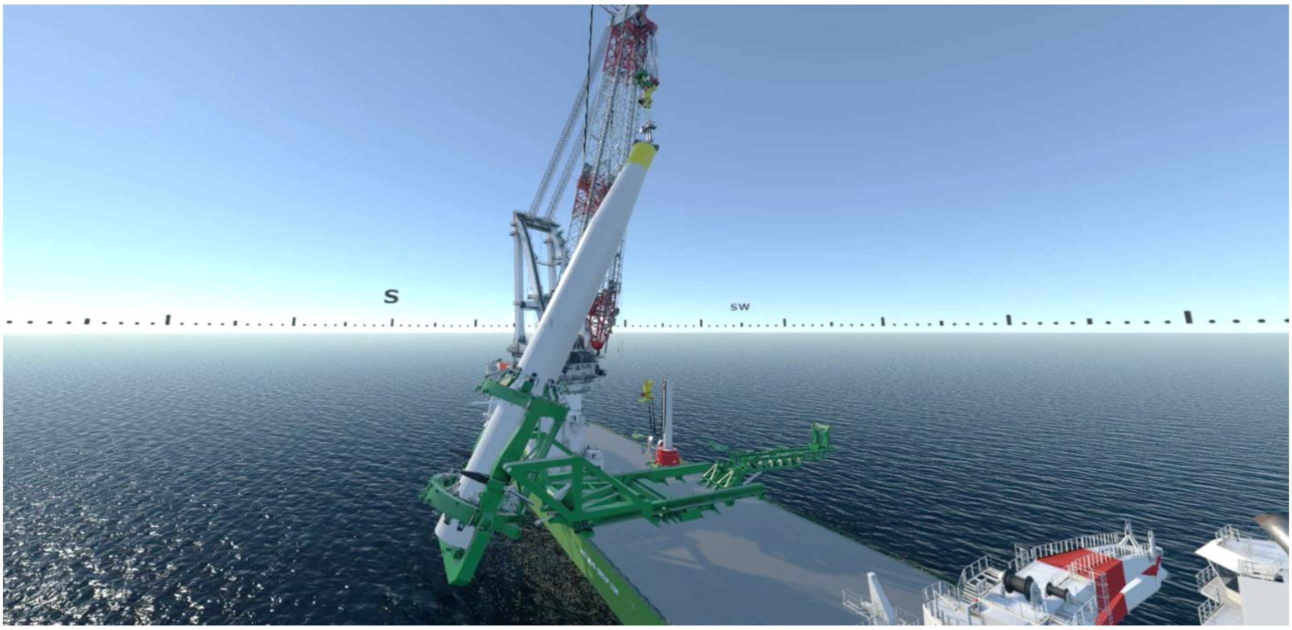

Figure 6-3: Step 2: MP upending

The MP is upended (Figure 6-3) using the main crane while the MCPG guides the upending motion and prevents the pile from creating harmful motions for the crane. Once the MP is fully vertical the upper rollerbox ring of the MCPG is opened, and the MP is lowered through the splash zone and on to the seabed.

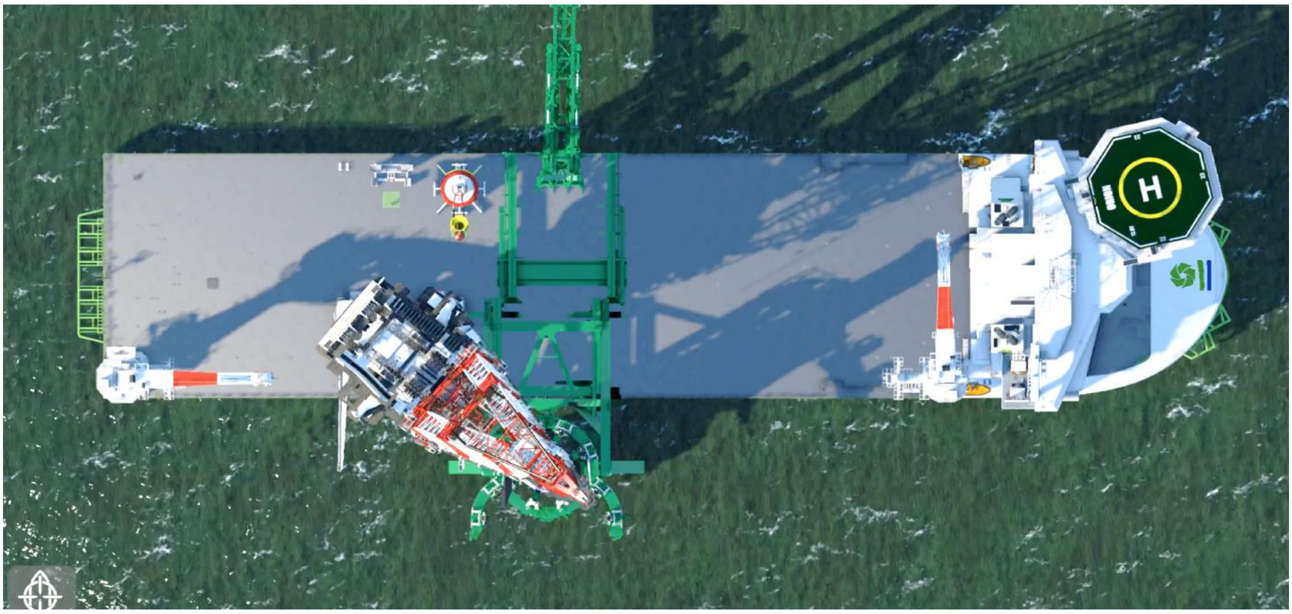

Figure 6-4: Step 3: motion compensated piling phase

After touchdown of the monopile when the weight of the MP is no longer carried by the crane, the piling phase starts (Figure 6-4). The MCPG compensates the verticality of the pile while it’s driven to depth with the impact hammer. Once at depth, the MCPG opens and disengages from the MP.

6.1.2. MCPG and DP interaction

Apart from MCPG equipment specification, DO, TWD – BM and Wartsila worked together on the integration of the MCPG with the vessel. Focusing on DP control systems and MCPG interaction to ensure DP stability and overall system performance.

Starting after the basic design phase two more advanced numerical models were constructed in which TWD – BM and DO were able to analyse the performance of the system for all different parameters (sea state, monopile type, vessel loading condition, incoming wave direction, etc). The first simplified linear model (left in Figure 6-5) was used to understand the complex dynamic behaviour of the system and the differences between the 3 operational phases and to retune the DP system controller. The second model (right in Figure 6-5) is a more detailed and more accurate non-linear model used to validate the retuned DP controller. This model was also used to calculate the operability of the operation. With this model the system settings and behaviour were evaluated. And workability plots were generated, giving insights into the capabilities of the system.

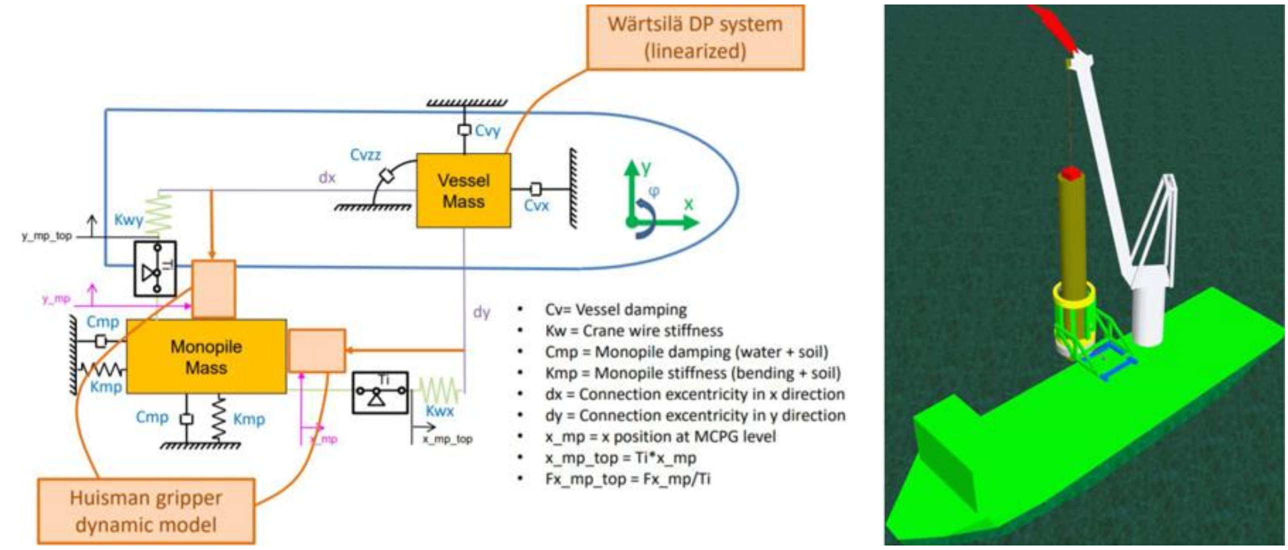

Figure 6-5: Left: Linear simplified model & Right: non-linear detailed model

The following points were concluded while analysing the system with the model:

- Controller strategies of the DP were changed and implemented
- Governing system limits are lower ring load, MCPG footprint and upper roller box displacement and velocity
- The ballasting system and resulting vessel heel angle are critical for successful operation
- The system remains stable and within limits (within reasonable sea-states) after a DP failure (losing up to 3 thrusters)
- Mitigation strategies after an MCPG failure

6.2. Fabrication

The company Huisman was subcontracted to prepare their detailed design for fabrication of the MCPG in line with the technical specifications of DO and TWD - BM. Huisman was selected due to their experience in design, fabrication in high accuracy steel structures and integration of drive and control components. Essential to ensure a working prototype. Due to the size of the equipment and the limited time available to make the gripper ready for operation, the fabrication, assembly, and factory testing (FAT) took place on 3 different locations:

- Huisman Czech Republic: Fabrications of main steel parts of X-skid and rails (Figure 6-6)
- Huisman The Netherlands: Assembly and testing of the X-skid and rails (Figure 6-6)
- Huisman China: Fabrication, assembly and testing of the Y-skid, gripper frame (Figure 6-7)

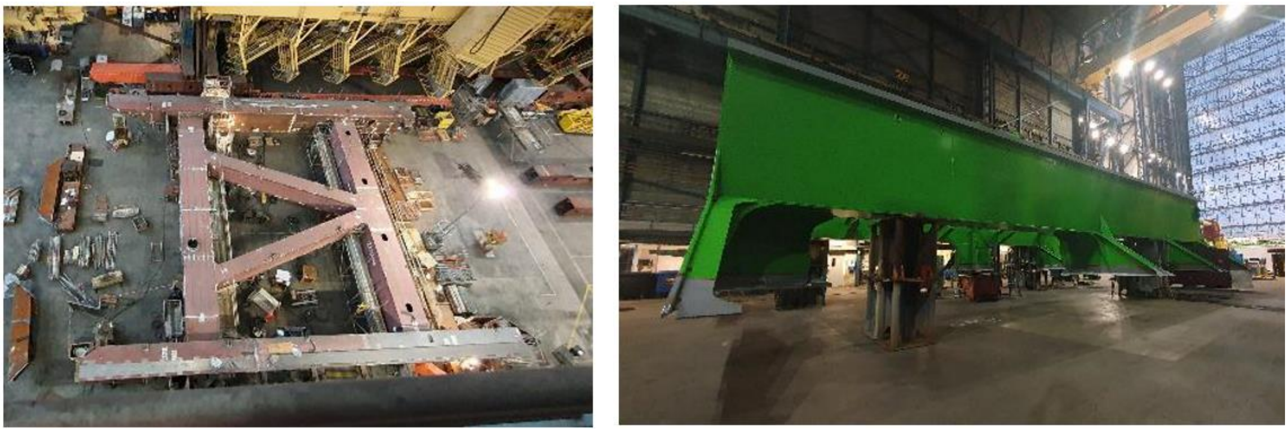

Figure 6-6: Left: Huisman Czech Republic: Fabrications of X-skid and Right: Huisman The Netherlands: Assembly and testing of the rails

On each location, DO stationed own personnel on site to follow up closely the fabrication and testing process. Despites travel restrictions due to COVID, DO managed (through remote video connections and involving local colleagues) to follow up the fabrication of the equipment at the fabricator's premises. Fabrication starts with steel cutting and welding all main steel sections together. Next, secondary steel like ladders, platforms, cable trays and small foundations are added. Once paint works after welding were finished, installation started of electrical cabling and hydraulic piping, followed by mounting various components, sensors and actuators. Finally, all components are energized and extensively tested for as far as possible withing the 3 factories.

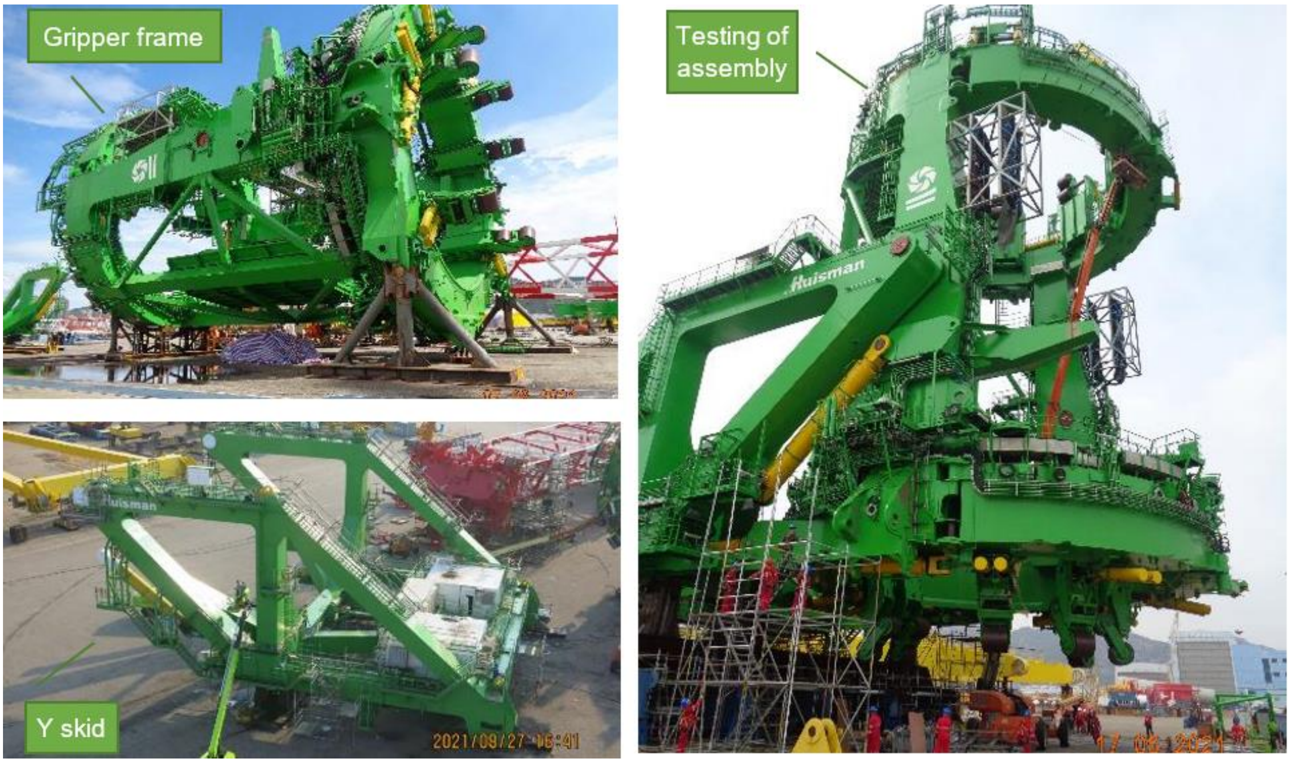

Figure 6-7: Huisman China: Fabrication, assembly and testing of the Y-skid, gripper frame

In The Netherlands, the focus was put on the testing of the motion compensation system. The X-skid comprises of sets of electromotors that will later move the entire gripper fore/aft, portside/starboard in a horizontal plane to compensate for ship's motions. In China the gripper frame (Figure 6-7) was tested with a focus on the cage tilting mechanism and the roller box system that guide a monopile by means of rollers towards and into the seabed.

As soon as assembled parts were successfully tested, these were shipped, via road and sea transport (Figure 6-8), towards the Orion in the port of Gdansk, Poland and later to port of Rostock, Germany, for installation and assembly on board.

Figure 6-8: Shipment of gripper frame & Y-skid

6.3. Assembly on board of Orion

The entire MCPG was delivered in 4 different large parts (Rails, X-skid, Y-skid and gripper frame) see Figure 6-2. All parts arrived in installation order, which allowed for sequential installation, assembly and testing of the entire gripper onto the deck of Orion.

Figure 6-9: Assembly of X-skid and storage rails on ORION in Rostock

The storage rails (Figure 6-9) were the first parts to be delivered. These were welded onto the ship's deck. Crucial during this process was the alignment and various construction tolerances that had to be achieved.

The second part delivered was the X-skid (Figure 6-9). This part was lifted by means of a 1500 Ton capacity shore crane on top of the rails. After installation, electrical power was connected, interfacing was set up with a control desk at the bridge, and checks could be conducted to test the motion compensation system. The X-skid allows for a longitudinal motion (fore/aft, or in X-direction of the ship) of the gripper by means of several large wheels onto the deck rails, and a transversal motion (portside/starboard, or in Y-direction of the ship) of the Y-skid which will be installed on top of it. This was tested during a sea trial offshore before the next part was installed.

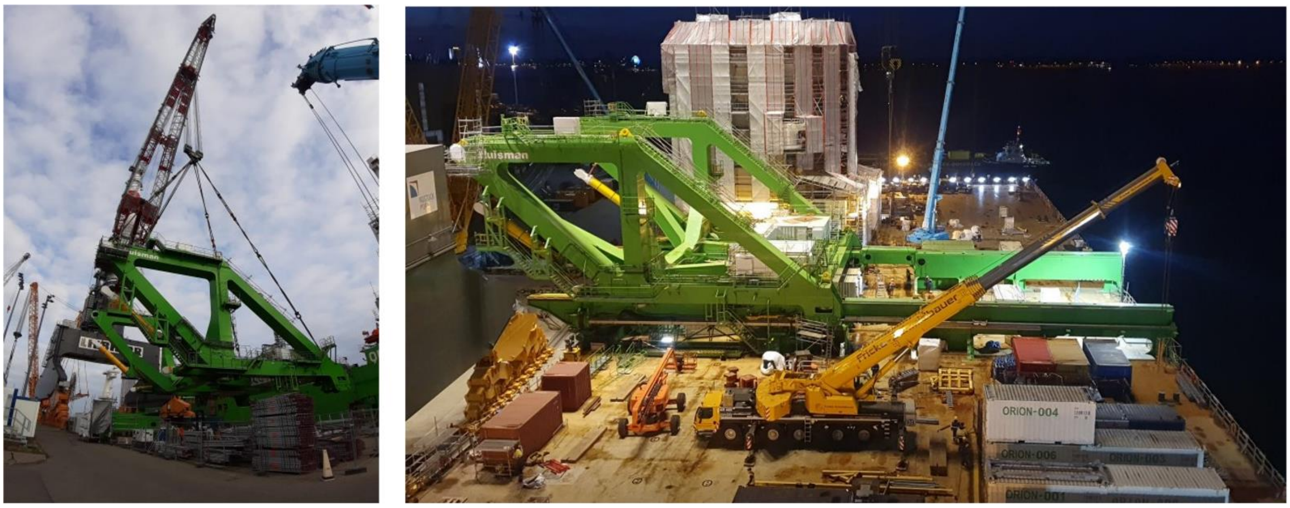

Figure 6-10: Assembly if Y-skid on the ORION in Rostock

The third part which was installed, was the Y-skid (Figure 6-10), mounted by the same shore crane on top of the X-skid. The Y-skid contains the main upending hinge point and holds the hydraulic cylinders which control the tilting of the gripper frame during upending of a monopile. A locking mechanism ensures that the gripper frame is safely secured once tilted vertical.

The fourth and heaviest part which was installed, is the gripper frame. After installation, various electrical and hydraulic completion works took place to connect all MCPG parts together. Right after the last cables were electrically cold wire checked and the last hydraulic lines were pressure tested, the final testing phase on board in the harbour could take place.

6.4. Onshore & offshore testing

Simulation and testing of the MCPG has been performed throughout the entire fabrication, installation, and commissioning works to ensure the quality and performance of the MCPG and floating installation operation.

6.4.1. Simulation

At DO head office engineered simulations were performed. In these environments the real-time virtual offshore installation operation could be performed (Figure 6-11). Using as much as possible vessel specific hardware and software. This allowed DO to:

- Early identify key challenges & opportunities
- Act out contingency scenarios
- Train operators in a true-to-life environment
- Realistic communication between key operators (for example via radio)
- Reduce the offshore learning curve
- Prototype the MCPG and all other equipment onboard the ORION

Using the simulator allowed a safe and swift transition from moored to DP installation and resulted in significant time savings for commissioning, testing & training.

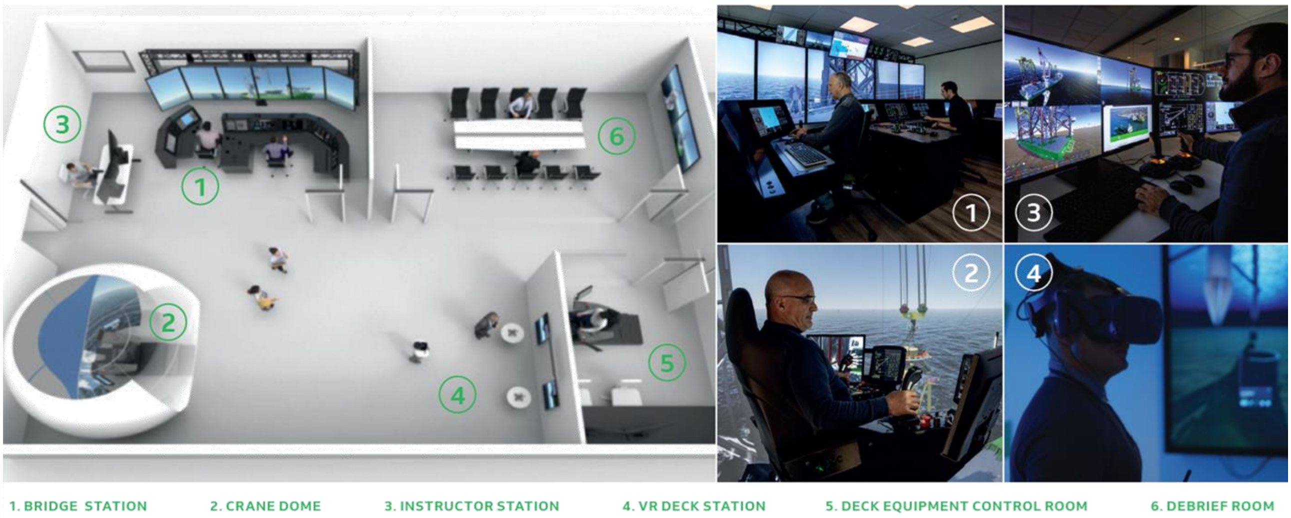

Figure 6-11: ORION Digital twin simulator

6.4.2. Testing

All acceptance tests (MC, EC, HC, FAT, HAT, SAT) have been prepared in test protocols during engineering stage. These specify what is to be checked and tested to assure the proper functioning and performance of the components/subassemblies and complete MCPG. The test results have been documented in reports and discussed in meetings between DO, TWD – BM, Wartsila and Huisman to define follow up actions (repairs, improvements, etc.).

The testing that was performed on the MCPG can be subdivided in following phases:

- Mechanical, electrical and hydraulic completion checks (MC, EC, HC)
- Factory acceptance tests (FAT)
- Harbor acceptance tests (HAT)
- Sea acceptance tests (SAT)
- Startup on first offshore wind farm project

<u>Mechanical, electrical and hydraulic completion checks</u>

Mechanical, electrical and hydraulic completion (MC, EC, HC) checks have all been completed during the fabrication at Huisman premises and are required before energizing the system (electrical power, hydraulic pressure).

<u>Factory acceptance tests</u>

For factory acceptance tests (FATs), DO had commissioning engineers present at Huisman yard (in The Netherlands and in China) and cooperated closely with them during their internal testing and preparations for the sea transport. As such during the final acceptance testing phase DO was well aware of the capability of the tested systems.

<u>Harbor acceptance tests</u>

The MCPG was fabricated in three different parts in the world and was for the first time joined together onboard of Orion. Largest part of the commissioning works took place in the harbor where step by step gripper subassemblies were installed. During this period, the functionality (operational modes, but also redundancy and safety systems in case of failure) of the gripper as one device were tested while the ship stayed along the quayside. Also interfacing with ship's systems (dynamic positioning, power management system, survey equipment, etc.) were tested.

Figure 6-12: ORION during the sea acceptance tests

<u>Sea acceptance tests</u>

Offshore sea acceptance tests were conducted in December 2021 and April 2022 (Figure 6-12). These were prepared in close cooperation with all parties and involved:

- Verification and tuning of motion compensation capabilities MCPG
- Verification and tuning of DP control strategies
- Verification and tuning of vessel survey and positioning systems

<u>Startup on first offshore wind farm project</u>

To allow for safe and efficient monopile installations fully on DP, a test program was developed wherein DO started the monopile installation on anchors and gradually stepped up to installations fully on DP.

On this first offshore wind project, the MCPG was able to:

- Enable floating installation of monopiles
- Successfully complete transitioning from moored to DP installations in a safe manner
- Install monopiles with a record weight of 2100ton, a length of 110m and a 9.6m diameter
- Achieve installation times of 10-12 hours per monopile, with still lots of optimization possibilities

The Orion equipped with MCPG, is designed and engineered for a workability between Hs2,0 – 2,5 (depending on wave period), resulting in at least 73% workability year-round in the North Sea (see Appendix B2).

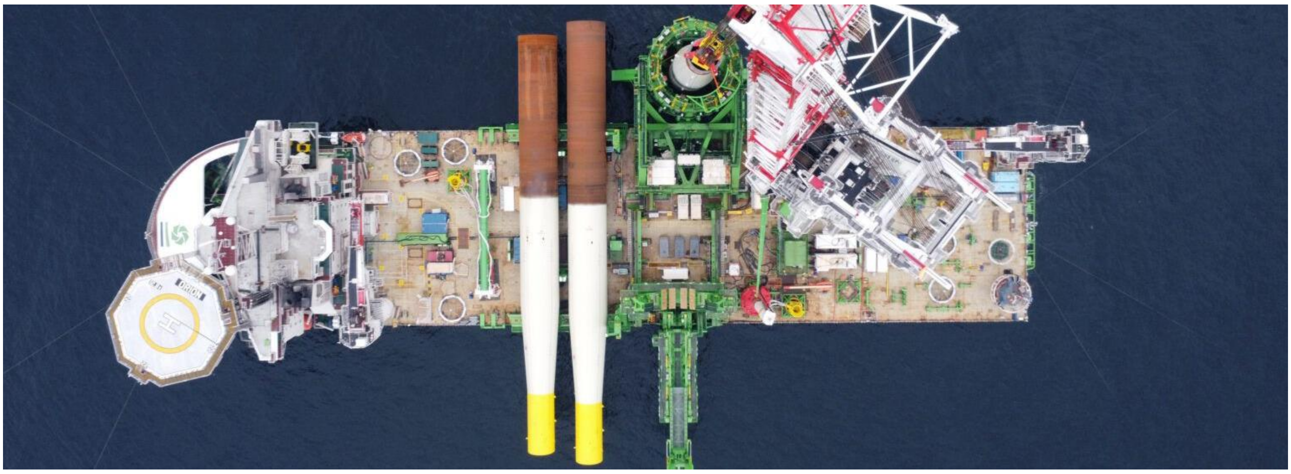

Figure 6-13: ORION during seatrials of MCPG using 8-point mooring spread for position keeping

6.5. Cost reduction

6.5.1. Foundation installation scenarios

A comparison was made of 3 scenarios back in 2017 when applying for the subsidy. This comparison was updated incorporating the new state of the industry (see appendix B2).

A comparison is made of foundation installation with (1) jack-up vessel, (2) moored vessel with static gripper and (3) the Orion with MCPG. For all 3 scenarios it is assumed that the installation will be performed by comparable vessels, either equipped with jack-up legs, a traditional static gripper or a motion compensated gripper. The compared vessels are assumed to have the same size, same crane, same sailing speed and the same accommodation facilities. The difference in day-rate is based on the contribution of the jacking system, legs and hull reinforcement required to jack-up compared to the new-price of the Orion, derived from DO's experience. This way, only the impact of the MCPG on the LCOE is considered.

The final cost reduction comparison was made between the JUV with static gripper versus the DP vessel with MCPG. As we see these are the base cases in the North Sea.

6.5.2. Input information and assumptions

Following assumptions were made for the analysis (see appendix B2):

- The Orion is able to transport 6 XL foundations per trip, while the JUV is restricted to a maximum of 4 XL piles. The payload of the JUV is limited by the jacking capacity and the weight of the jacking system and a floating vessel has more deck-space, as jack-up legs are obstructing the flexibility of a deck-lay-out.
- The new JUVs that enter the market have a dayrate of around €350.000. The day-rate of the heavy lift vessels is €250.000. For which in case of the moored vessel additionally 2 anchor handling tugs need to be considered at a rate of €20.000 per tug per day.
- Mooring anchors for the first piles at Arcadis Ost offshore windfarm took 1,25 hour per anchor for deployment and retrieval, resulting in 10 hours per MP. Jacking up and down is 4 hours per MP.
- The costs for the mission equipment required for installations of the XL MPs with either a JUV or a floating vessel are provided in Appendix B2. It is assumed that this equipment will be used on equal number of projects. We see that the deck equipment has developed to become more future proof than previous years.
- For a moored vessel with static gripper a workability is achieved (Hs = 1.0m) to position MPs accurately.
- The wind farm, Hollandse Kust Zuid, is considered as reference case. Assumed data is provided in Table 6-1.

Table 6-1, Wind farm data - Hollandse Kust Zuid

Parameter	Value
Wind farm location	North Sea
Number of turbines	70
Total wind farm capacity	700 MW
Distance to mobilization port	50nm

Table 6-2, Vessel specific input

Parameter	JUV	Moored vessel*	Orion w. MCPG
Vessel (spread*) day-rate** / ***	€ 350.000	€ 290.000	€ 250.000
Maximum MP on board	4	6	6
Positioning / Jacking / Mooring per MP in field	4.5hr	8.5hr	0.5hr
MP installation	9hr	9hr	9hr

** For moored vessels, 2 anchor handling tugs are included.*

*** Excludes equipment spread*

**** Dayrates are indicative*

6.5.3. Results

For the reference wind farm, the contribution of the different installation steps to the total installation time is summarized in Figure 6-14. The effective cycle time for the ORION with MCPG is significantly shortened compared to the moored vessel with static gripper. This is mainly affected by the difference in weather down time (Figure 6-14) and mooring or positioning time (Figure 6-15).

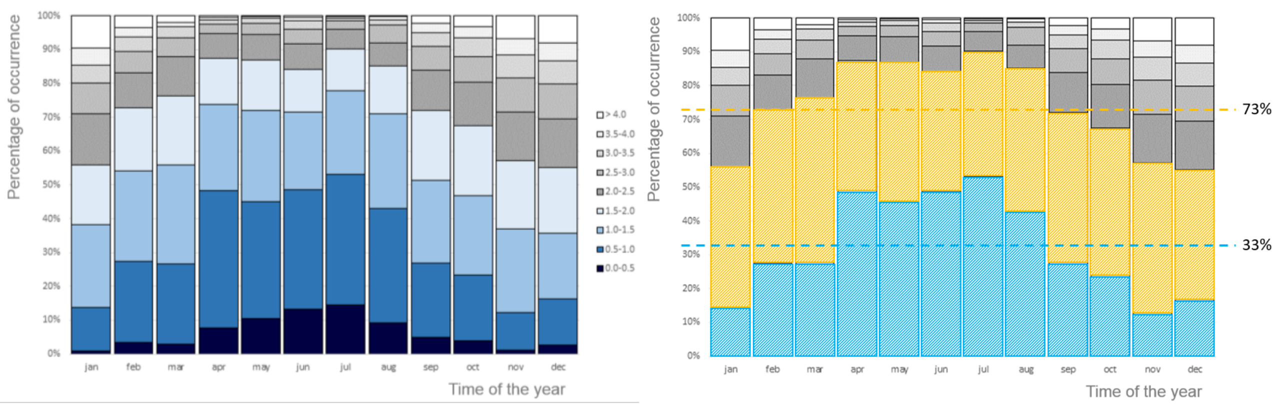

Figure 6-14: Occurrence of significant wave heights in the North Sea (Hs, in [m]) and workability for Hs 1m vs Hs 2.0m

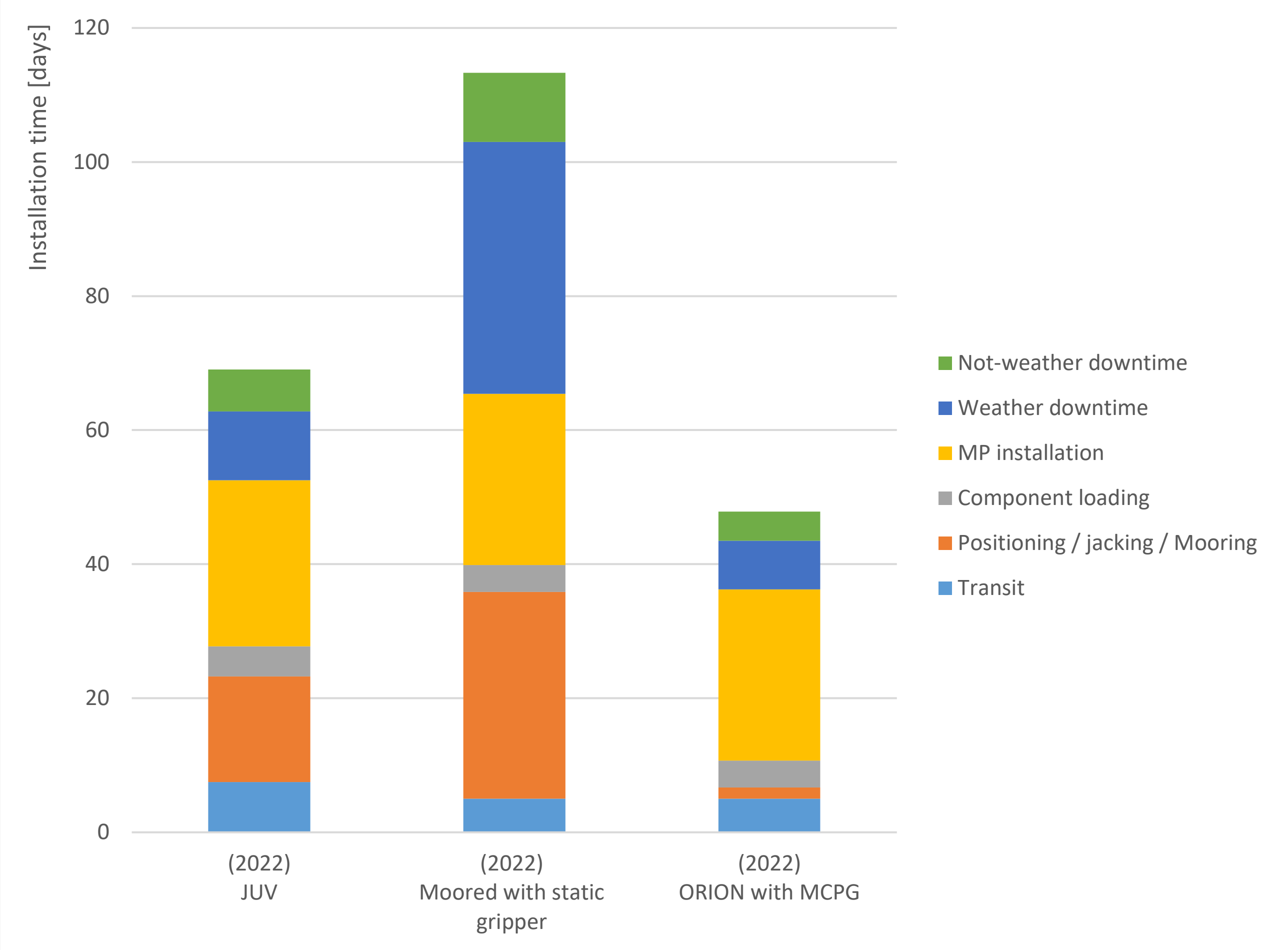

Figure 6-15: Total installation time of a JUV compared with traditional floating and motion compensated installation

The total project costs are provided in Appendix B2 and summarized in Table 6-3, The project costs are defined by the day-rate vessel costs, day-rate equipment costs and length of project. Altogether this results in a total cost reduction estimate of 34% of the ORION with MCPG compared to the JUV and even 52% reduction compared to a moored vessel with static gripper.

Table 6-3, Results, total installation costs for one project (see for calculation Appendix B2)

	JUV	**Moored**	**MCPG**
Time for one project	69 days	113 days	48 days
Total cost for one project	€ 28.000.000	€ 38.500.000	€ 18.500.000

6.6. Effect on Levelised Cost of Energy

The impact on the Levelised Cost of Energy (LCOE) is achieved by reducing the foundation installation project costs, mainly due to reduced installation time. A total cost reduction of 34% on the MP installation costs corresponds to LCOE reduction of €1.60/MWh (see Appendix B3). The results of the cost reduction are summarized in Table 6-4.

Table 6-4, Quantitative estimate of cost reduction

Cost Element	**X**	**% reduction**
1. CAPEX e. Support structure installation	X	2.60 %

6.7. Saving on costs of SDE+

The reduction in LCOE will result in saving on costs of SDE+, calculated with appendix B3*. The reduction of €1.60/MWh causes total saving of €39million (Appendix B4). This calculation was based on the following assumptions:

- In period 2023 - 2030 a total of almost 20GW will be installed in the Dutch North Sea spread over 8 sites (Offshore Wind Energy roadmap RVO 2022), simplified to 2500MW of installed capacity per year.
- The offshore windfarms (OWFs) in the Dutch North Sea will gradually be installed in deeper waters, the foundations for these OWFs will therefore increase in size an require an Orion like vessel for installation. It is assumed that after 2025 this will be the case.
- In period 2026 – 2030 DO will win 25% of the installed capacity, thus 625MW per year.
- TWD – BM will assist in the development of at least 1 other MCPG that will be ready for MP installation after 2025. Doubling the installed capacity by MCPGs from 2026 onwards to 1250MW per year.

*Note that the Excel sheet of 2017 is used, to be consistent with the calculation as performed in 2017 for the subsidy request.

6.8. Additional benefits (not quantified)

Besides the direct reduction on the LCOE and the saving on SDE+ subsidy as calculated above, floating foundation installations with respect to the traditional JUV provide additional benefits:

- Investing in a floating foundation installation vessel provides more flexibility to the installation contractor, as floating vessels have additional advantages for jacket installations. Furthermore, a floating vessel can be efficiently used for topside installations, transport and decommissioning projects
- Floating installations are more future proof. Scaling up floating vessels is much more cost efficient than scaling up JUVs, as increasing the jacking capacity is much more expensive than increasing the buoyancy
- Floating solutions are independent of soil conditions and water depth and therefore the only solution for particular wind farm locations with poor soil conditions
- The further offshore, the better the floating installation method will score compared to the jacked-up variant (as the floating vessel can transport more foundations per trip)
- Besides a reduction in installation project costs, the LCOE is further reduced because power can be generated at an earlier stage. This means that generation can begin sooner after the point at which capital has been borrowed.

Table 6-5, Concluding table

Question	Answer
Which specific SDE+ category is affected by the project?	Offshore Wind – Foundation installations
How is the base-amount lowered? How is the project reducing the base-amount?	The base-amount is lowered by reducing the cost of the foundation installation. This is achieved by reducing the foundation installation project costs, mainly due to reduced installation time.
What will be the expected cost reduction?	<u>€1.60/MWh</u>
How much will the energy producers profit from this cost reduction?	<u>€1.60/MWh</u>
Why is it probable that this reduction will directly affect the energy producers?	The reduced installation cost will be directly included in the foundation installation tender. This will increase DO's chances on winning the tender and will directly and for 100% influence the costs for the developer.
Provide a list of the assumptions made for the cost reduction calculation and reduction of the SDE+ expenses.	The assumptions are provided in section 4.2.2. Below, the most important assumptions are repeated: - Day-rate next generation JUV is €350.000. (The day-rate estimate of the heavy lift vessels is €250.000) - Without the MCPG, a floating vessel can accurately position MPs up to an Hs of 1m; - The heavy lift vessel of the same size as the JUV will be able to transport 6 foundations per trip - It is assumed that the equipment can be used on 10x700MW projects before replacement is required. - Mooring anchors will take approximately 1,5 hour per anchor, for deployment and retrieval resulting in 12 hours per MP. Jacking up and down is 4 hours per MP.

7. Conclusions and way forward

7.1. Conclusion

Piling with a vessel on dynamic positioning using a motion compensated pile gripper was successfully achieved utilizing DO's OWIV Orion and a Motion Compensated Pile Gripper designed and constructed by Huisman in line with DO and TWD – BM technical requirements. The interface between gripper and DP system was managed by an integrated DO and TWD – BM team interfacing Wartsila DP and Huisman MCPG systems.

After an extensive engineering phase including tank testing, several sea trials and a digital twin simulation platform to perform test and train the operators, the vessel and pile gripper were successfully taking into operation with OWIV Orion at the Arcadis Ost 1 wind farm in Germany. On this first project:

- Extensive fabrication, harbor and offshore testing was performed
- A start-up plan was successfully completed transitioning from moored to DP installations in a safe manner
- Record monopile sizes were installed with a weight of 2100ton, a length of 110m and a 9.6m diameter
- Installation times of 10-12 hours per monopile were already achieved with still lots of optimization possibilities

The Orion equipped with MCPG, is designed for a workability between Hs2,0 – 2,5 (depending on wave period), resulting in at least 73% workability year-round in the North Sea. Compared to the traditional JUV installation methodology this realizes a 34% reduction on the installation costs of foundations. A total cost reduction of 34% on the MP installation costs corresponds to LCOE reduction of €1.60/MWh, which is 2.60% reduction to the base case.

7.2. Way forward

The vessel and gripper will be deployed on several upcoming projects and is as good as fully booked until end of 2025. Currently the commissioning of the MCPG is being finalized and its being tuned for the upcoming projects in the USA. The environmental conditions in the USA are challenging due to the swell, this will lead to further insight in the performance of the MCPG.

8. Project execution

8.1. Technical challenges

As described in the previous chapters many technical challenges were overcome during the project. The main technical challenge being:

- Design, fabrication and on/offshore testing of a gripper able to install XXL monopiles

With technical sub challenges as:

- Design of a stable and robust gripper motion compensation algorithm with integration into the existing ships Dynamic Positioning system
- Develop simulation tools (Matlab / Orcaflex) to engineer a prototype. These tools have been validated by tank test and sea trial tests
- Develop a digital twin simulator
- Develop training sessions for MCPG operators by means of a Digital Twin simulator.
- Develop test protocols for shop testing and harbor testing, to ensure safe and reliable work performance. Develop a startup plan to safely allow offshore installation works
- Various optimizations to reduce installation time by means critical path analysis and simulator sessions

Many iterations between all the parties, both internal and external where required for this innovative design process. Gathering expertise from the consortium and outside. Next to that structured and elaborate quality control and testing was required to ensure a working system.

8.2. Organizational challenges

During the development of the MCPG many parties were involved, this required a good organizational structure which was managed mainly by DO. Two of the main challenges and solutions were:

- Fabricating and testing the equipment at Huisman and various subcontractors in 3 different countries around the world (The Netherlands, Czech Republic and China), during COVID times in 2020 - 2021. As traveling was restricted, this required strict coordination and video conferencing meetings between these locations by means of local site teams and management.
- From the second half of the project the of TWD-BM and DO teams had so many interfaces that it was decided to integrate the engineering teams of TWD-BM and DO into one office for more efficient collaboration.

8.3. Changes with respect to project plan

8.3.1. Delay

The original project plan, with start in September 2019, would take 16 months and finalize commissioning in January 2021, rendering the MCPG ready for operations in February 2021.
Due to COVID-19 (causing delays in procurement and transport), delayed readiness of the ship, the Orion, extra engineering review cycles, development of more extensive test protocols, the final commissioning date shifted to April 2022. The total design & build project duration was 31 months. Including the first offshore project and all debrief sessions, this took up to July 2022 or 34 months.

8.3.2. Role shift in the consortium

At the start of phase 2 (as described in chapter 5) of the MCPG development two parties were mainly involved: TWD – BM and DO. Next to the consortium other companies were involved:

- DNVGL/MWaves, for third party review
- Wartsila (WDP), the DP system supplier of the vessel
- HYCOM, one of the D&C parties involved for early engineering
- The steel fabricator was yet to be decided at that stage

In close cooperation with DO, TWD – BM further developed the Structural / Mechanical detailed design of the gripper, upend hinge, NMS and secondary steel. Along with the development of the Drive & Control according to the plan.

During the procurement process for the fabrication and delivery of the MCPG, DO decided to select Huisman for the delivery of the steel and drive & control components. From that point on the focus of TWD – BM shifted from Structural / Mechanical design and development of Drive & Control to only the latter.

For the rest of the phase 2 development the division of responsibilities shifted to:

- Detailed design and construction MCPG – Huisman
- Detailed design and supply of DP system – Wartsila DP
- Integration of MCPG and DP control systems – DO & TWD – BM
- Integration of MCPG into ORION – DO
- Operational procedures, training of operators – DO
- Third party marine warranty review of MCPG, MCPG-DP interaction and operations – Global Maritime
- Offshore testing – DO supported by all stakeholders

This means that the detailed Structural / Mechanical design of the DO & TWD – BM gripper and upend hinge, which was very far advanced as shown in Figure 6-1, was in the end not finished. Neither was the design of the NMS and secondary steel.

8.3.3. Second campaign of laboratory testing

It was decided that the second campaign of laboratory testing was no longer required for validation of the system and put more emphasis on the model validation utilizing the digital twin simulator and the harbour tests and sea trials.

8.4. Knowledge distribution

Internally the design decisions and concept trade-offs were monitored in a continuously updated design decision register. With this document, all team-members and stakeholders within the project team have access to the latest status of the project. This approach assures that no knowledge got lost within (changing) project teams and allows efficient repetitions of the design for subsequent clients.

Externally, TWD and BM actively promote the performance of the MCPG, such that the market gets convinced of this innovative foundation installation solution. Information has been distributed via press-releases (A1 & A2), direct client meetings, lectures at specialized conferences. DEME Offshore is actively marketing the MCPG method via their contacts with energy majors and wind farm developers. The successful installation of the XL monopiles of Arcadis Ost offshore windfarm is the perfect example for convincing the industry to change their way of working for the installation of the upcoming XL monopiles. Recent announcements from other installation contractors proof that the MCPG unlocks the potential for existing monohull vessels and semisubs to install XL monopiles afloat.

8.5. IPR agreements

IP-rights of the MCPG method as developed in phase 0 belong to TWD – BM. DEME Offshore has been licensed to use the design on their installation projects. The IP rights of all installation methods developed during phase 1 & 2, which don't lead back to common engineering practice but to an installation method as specifically developed by DEME Offshore, belong to DEME Offshore. However, TWD – BM is not limited to develop the MCPG method for other parties. The only specific limitation for TWD – BM is the patented in line gripper and upend system.

Appendix A, References

Ref. No.	Document name	Revision	Description
A1	Press release DEME	-	https://www.deme-group.com/news/monopile-installation-completed-arcadis-ost-1-offshore-wind-farm
A2	Press release TWD	-	https://www.linkedin.com/posts/temporary-works-design_offshorewind-engineering-activity-6988773453176659968-FmnQ?utm_source=share&utm_medium=member_desktop