Ref. Ares(2024)3886896 - 30/05/2024

Funded by the European Union

Horizon Europe programme, grant agreement No. 101096068

RETROFIT SOLUTIONS TO ACHIEVE 55% GHG REDUCTION BY 2030

WASP installation flowchart

WP 7 – Technology Demonstration
Task 7.1 – WAPS systems installation and see trial protocol
D7.1 – WASP installation flowchart
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Project details

Project Title	RETROFIT SOLUTIONS TO ACHIEVE 55% GHG REDUCTION BY 2030
Project Type	Innovation Action
Project Acronym	RETROFIT55
Grant Agreement No.	101096068
Duration	36 M
Project Start Date	01/01/2023

Deliverable information

Status (F: final; D: draft; RD: revised draft)	D 29/02/2024
Planned delivery date	31/12/2023
Actual delivery date	30/05/2024
• **Dissemination level:** PU – Public, fully open, e.g. web (Deliverables flagged as public will be automatically published in CORDIS project's page) • SEN – Sensitive, limited under the conditions of the Grant Agreement • Classified R-UE/EU-R – EU RESTRICTED under the Commission Decision No2015/444 • Classified C-UE/EU-C – EU CONFIDENTIAL under the Commission Decision No2015/444 Classified S-UE/EU-S – EU SECRET under the Commission Decision No2015/444	PU
Type: Report, Website, Other, Ethics	Report

Document history

Version	Date	Created/Amended by	Changes
01	29/11/2023	Anna Margenat (B4B)	First draft
01	22/02/2024	Laura Herrera (ATD)	Annex 1
02	28/02/2024	Sabino J. Chapero (B4B)	Update
03	29/02/2024	Anna Margenat (B4B)	Second draft
04	20/03/2024	Emanuele Spinosa (CNR)	Third draft
05	13/05/2024	Anna Margenat (B4B)	Revision after comments by RINA
06	28/05/2024	Laura Herrera (ATD)	Revision after comments raised by CNR

Quality check review

Reviewer (s)	Main changes / Actions
Emanuele Spinosa (CNR)	Indications and suggestions for major improvements (part 1)
Cecilia Leotardi (CNR)	Indications and suggestions for improvements (part 2)
Amedeo D. Rinaldi (RINA)	Indications and suggestions for improvements
Alessandro Iafrati (CNR)	Check and comments on some tables in Annex I

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Acronyms

Acronym	Description
AoA	Angle of Attack
CII	Carbon Intensity Indicator
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency eXisting ship Index
EN	Equipment Number
GHG	Greenhouse Gas
IMO	International Maritime Organization
WASP	Wind-Assisted Ship Propulsion

Executive Summary

Maritime transport plays a pivotal role in the European Union's economy, being one of the most energy-efficient way of transport. Despite this, maritime transport also poses a significant challenge, due to its substantial contribution to Green-House Gas (GHG) emissions, which may have an important impact on climate change. Projections indicate a potential increase up to 130% in maritime emissions by 2050 compared to 2008 levels, posing a challenging obstacle to the goals outlined in the Paris Agreement (2015).

In response to this challenge, innovative solutions such as Wind-assisted Ship Propulsion Systems (WASP) have emerged as promising way for reducing emissions and enhancing energy efficiency in maritime transport. Among these solutions, the eSAIL® system developed by B4B stands out for its potential to revolutionize vessel propulsion using wind power.

This report focuses on elucidating the processes involved in the successful installation of WASP systems aboard vessels, within the context of their conversion for assisted wind propulsion. It delves into the procedures required, explores potential challenges, and clarifies best practices to ensure the seamless integration and optimal performance of WASP systems.

Throughout this document, the critical steps in the installation process are examined, from pre-engineering activities to the final installation phase. Detailed procedures are outlined, potential challenges are discussed, and best practices are presented to facilitate a smooth integration process and maximize their efficacy. This approach not only advances efforts to mitigate GHG emissions in maritime transport, but also propels the transition towards a more sustainable and resilient maritime industry in the face of climate change.

1.1 Introduction

Maritime transport plays an essential role in the EU economy and is one of the most energy-efficient modes of transport. Despite this, it contributes significantly to the rising levels of greenhouse gas (GHG) emissions. Approximately 2.9% of all emissions worldwide produced by human activity came from shipping in 2018, accounting for 1,076 million tons of CO_2 [1].

According to projections, by 2050 these emissions might rise by as much as 130% with respect to the 2008 levels. The goals of the Paris Agreement in 2015 (a global framework to prevent disastrous climate change by limiting global warming to far below 2°C and pursuing efforts to restrict it to 1.5°C) may be undermined if the impact of shipping activities on climate change increases as predicted. At the EU level, maritime transport accounts for 3 to 4% of total CO_2 emissions, or more than 124 million tons of CO_2 in 2021 [1].

To drastically reduce Green-House gas (GHG) emissions from international shipping, effective global measures are needed. In July 2023, the International Maritime Organisation (IMO) committed new targets for GHG emission reduction, to be developed and adopted in 2025. The EU action to make sure that maritime transport plays its part in achieving climate neutrality in Europe by 2050 is an essential step in incentivising the necessary reductions.

The International Maritime Organization (IMO) has established a set of specific mandatory measures, such as the CII (Carbon Intensity Indicator), EEXI (Energy Efficiency eXisting ship Index), and EEDI (Energy Efficiency Design Index) to monitor and reduce emissions from international shipping. In July 2023, IMO committed new targets for GHG emission reductions to be developed and adopted in 2025. The IMO strategy aims to reduce of 20% of the GHG emissions from international shipping by 2030, of 70% by 2040 and NET-ZERO by 2050, compared to 2008 [1].

A detailed road map to decarbonize the fleet is becoming more and more important, as emission regulations harden. Switching to renewable fuels will not be sufficient to meet these restrictions. Only when combined with other technologies, such as WASP systems, the GHG emission performance will be reduced enough, and the business asset will remain attractive. In order to comply with these regulations, shipowners and ship operators do not necessarily have to make the full investment all in one go, rather they have the possibility to split it up according to the regulatory compliance targets. Furthermore, at the end of a ship's commercial life, the wind propulsion systems can also be transferred to other vessels.

The goal of this work is to examine and define the best practices to be developed during the WASP system installation. This report will focus on the retrofitting of an existing vessel. Using the ship conversion experience acquired by Astander, as well as the WASP eSAIL® rigid prototypes already installed by B4B, the partners will investigate ways to improve the installation route, finding bottlenecks, inefficiencies, risks, and important operations. The result will provide an agile retrofitting process flowchart, which will allow shipowners to reduce costs and lead times (shipyard, class society and naval engineering firm if needed).

The report will describe the procedures for the installation and validation of the WASP systems. The report will exploit the experience of previous installations suggesting the installation sequence, the inherent risks, and the most critical steps. The flowchart will help the shipyard to reduce the time and costs for the installation in order for the ship owner to maximize the benefits.

It is estimated that wind energy reduces fuel consumption by 10-30%, depending on whether the weather conditions are more or less favourable during the journey. More interestingly for a sector that is moving towards decarbonisation, WASP may reduce CO_2 emissions by a percentage between 10% and 60%, depending on the technology used.

There are currently four types of Wind-assisted Ship Propulsion Systems (WASP) whose level of maturity and development is different:

1. Kites: they are systems similar to those used for kitesurfing, adapted to be installed on tow vessels. They are connected to the bow and operate at high altitude, performing an 8-shaped trajectory, capturing the wind, and pulling the vessel itself. The operation requires a launch and recovery system for the kite, as well as a complex autonomous operation of the kite in flight.

2. Flettner rotors: they are large cylindrical mechanical sails that rotate to create a propulsive force for the boats. This technology was developed by Anton Flettner during the 1920s. They exploit the Magnus Effect, which is an aerodynamic phenomenon for which a spinning object in an airflow develops a pressure difference on one side with respect to the other one, as a result of the local velocity field induced by the body rotation. Such a situation generates the aerodynamic forces of Lift (L) and Drag (D). In the case of Flettner rotors, the spinning object is a cylinder located vertically on the vessel deck. The aerodynamic characteristics are dependent on the spin speed of the rotor, so a rotation shall be constantly maintained.

3. Flexible and rigid sails: they are airplane-like wings, with a very similar working principle. They have an aerodynamic cross-section (airfoil) that, when exposed to an airflow, produces lift, because of the pressure difference between the upper and lower sides. The amount of lift is

manly related to the incidence of the airfoil with respect to the wind direction, commonly indicated as the Angle of Attack - AoA. Their operation is based on ensuring that the airfoil is correctly oriented with respect to the wind (appropriate AoA), with no additional requirement for power. It is a **passive system**, which typically does not offer a significant aerodynamic performance. In fact, the lift coefficient is generally around 1.5, resulting in larger and heavier systems for equivalent savings. Due to the large size and weight, the number of sails per vessel is limited, since they 1) require a large deck space, 2) impose limitations of visibility for the crew and of the on-board cameras, 3) require strong/heavy hull reinforcement at the installation points and 4) have a large impact on the cargo capacity. Finally, another challenge arises from the fact that most sails have to be lowered and stored when not in use, due to their side mounting, especially when loading or unloading cargo.

4. Suction sails: they are based on the use of **boundary layer active control systems** to avoid the detachment of the airflow from the surface. The airflow around a thick airfoil or at a large AoA typically detaches, generating a separation area, typically turbulent, which results in a large drag force. If a suction area is located at the detachment point and a small amount of boundary layer is aspirated, the flow remains attached to the airfoil. This results in a significant increase in the lift coefficient, well above the values obtained from a passive wing-sail, reaching values even higher than 6. In addition, a movable flap is installed, to generate asymmetry, increase lift, and cover the suction area not in use. The operation is somewhat equivalent to adjusting the AoA (angle of attack) to the wind direction and setting the appropriate aspiration to the wind conditions. The aspiration requires a low power consumption. Finally, another advantage compared to passive wing-sails is that the system can be tilted instead of folded.

In the context of this deliverable, the focus will be on the suction sails developed by B4B, referring to as **eSAIL®**, the commercial name given by the company. Therefore, some of the strategies and procedures may not be 100% suitable for other WASP technologies and will have to be adapted.

2 eSAIL® general description

The eSAIL® is conceptually composed of the parts, shown in Figure 1:

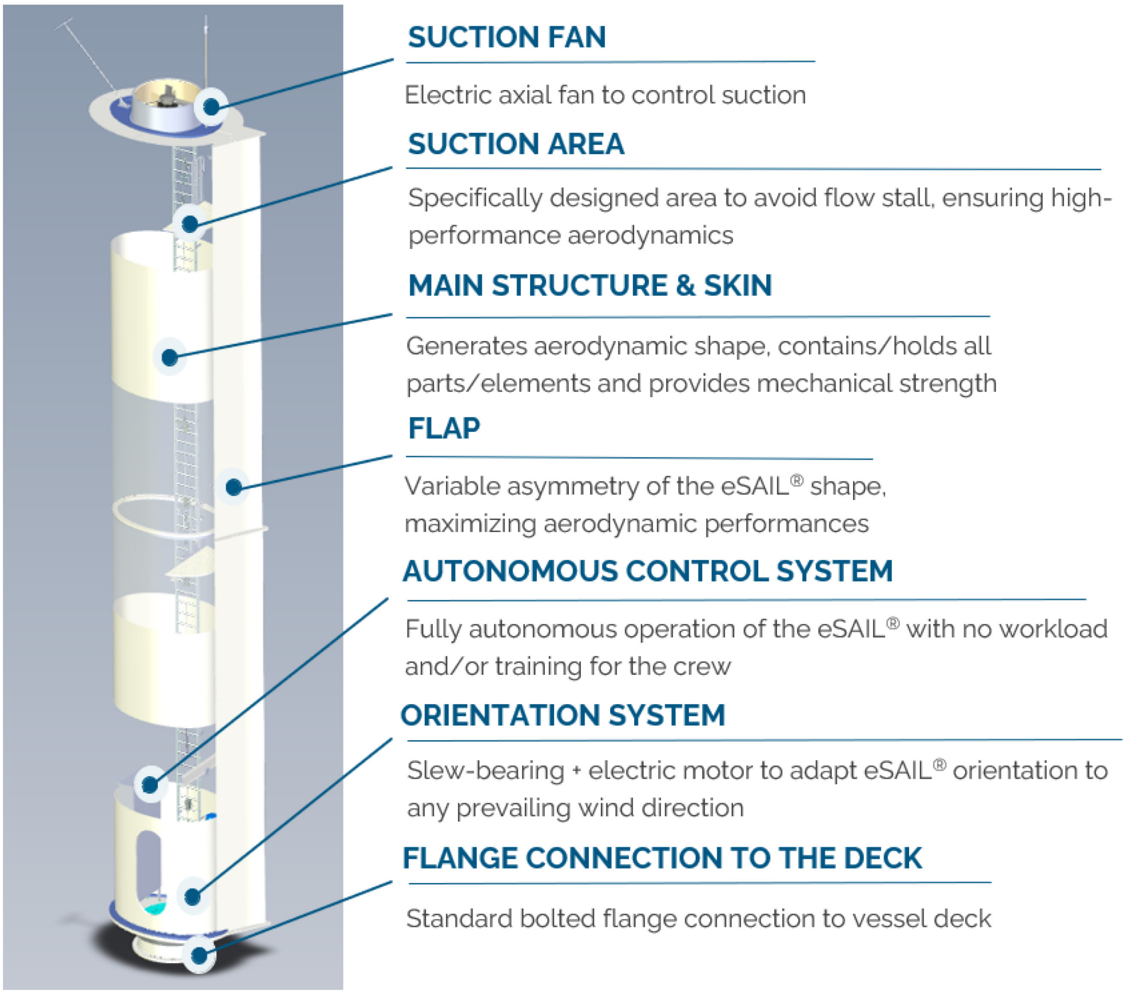

Figure 1: 3D view of an eSAIL® with its main systems and components.

Orientable pedestal: it is the structure connecting the vessel foundations to the eSAIL® itself. The pedestal contains a slew-bearing and a motor for the rotation of the eSAIL® body. This rotation is required to orient the eSAIL® to the wind direction as desired. This part is similar to those used in standard marine deck cranes.

eSAIL body: it is a tubular metallic structure that offers the main structural support and, at the same time, defines the aerodynamic shape of the airfoil. The eSAIL® body also contains the suction areas, the suction system, and the mechanism to position the flap.

Movable flap: it is a structure that can be inclined towards one or to the other side of the eSAIL® body, generating the desired airfoil asymmetry.

Autonomous control system: similarly to any other WASP system, the eSAIL® operation shall be fully autonomous and with minimal crew intervention. This becomes even more important to ensure a correct performance of the active boundary layer control system (suction). The autonomous control system shall trim, for each sailing condition, the suction power, the eSAIL® body rotation and the flap positioning in an autonomous way. In addition, it shall ensure safety in case of any malfunction or risk. An interesting advantage of the eSAIL® is that it is inherently safe, as failure modes cause the stop of the suction fan, removing all aerodynamic forces and taking the eSAIL® to a safe rest position. Note that the autonomous control system controls three actuators: the body rotation motor, the flap positioning motor, and the suction fan.

Moreover, eSAIL® could be equipped with a tilting system to ensure overhead clearance during port operations if needed.

Figure 2: Detailed view of two full scales eSAILs installed on the merchant vessel EEMS Traveller.

3 Pathway towards WASP equipped vessel.

The procedures for equipping an existing vessel with a WASP system through retrofitting and for its installation are covered in this section. The activities are organized into three different stages:

1. Pre-engineering activities.
2. Detailed naval engineering and vessel conversion.
3. WASP installation.

In the following sections, a general overview of each stage will be briefly detailed.

3.1 Pre-engineering activities.

The construction methods used in recent years in most shipyards are numerous, but the most frequently adopted is the so-called "integrated construction", which involves a subdivision of the ship parts and the classification of all production tasks into zones and stages. In general terms, this methodology is based on two basic principles:

1. Design oriented towards the product manufacturing.
2. Zone- and stage-based construction, with a high degree of preparation before the blocks are lifted onto the slipway.

3.1.1 Pre-retrofit study

The integration of a WASP on a conventional ship can be achieved by means of a series of intermediate steps, which focus on different "intermediate products". The intermediate products are the physical units resulting from the subdivision of the ship systems into smaller units, which are independent on each other during the manufacturing process.

The main geometrical/operational characteristics of a ship are usually given in terms of the flag, the IMO number, call sign, class society, construction year, total length, length between perpendiculars, beam, depth, draught (design), Gross Tonnage (GT), Deadweight (DWT), service speed, main engine and its MCR (Maximum Continuous Rating).

Based on the these and other characteristics, it is necessary to perform an aerodynamic study aimed to define the type and the number of WASP units that could be installed, to improve the ship performance.

Regarding this aerodynamic study, the following constraints for the ship on-board must be considered:

- Air draft, the distance from the water level to the highest point on the vessel
- Space available on the deck (the system must not extend outboard) including space for system in tilted position,
- Position and operability of the of cargo hatches on the deck,
- Possibility of keeping or removing existing equipment onboard (i.e. cranes)
- Visibility from the wheelhouse

It is worth pointing out some of the major technical and logistical challenges concerning the installation of large sails on merchant ships:

- **Available space:** modern merchant ships often have space constraints due to the necessity to load and unload goods efficiently. Fitting oversized sails into the ship structure without compromising load capacity is a major challenge.
- **Weight:** large sails can be heavy, and their installation can affect the balance and stability of the vessel. In addition, the mast and other components of the wing-sail must be robust enough to support the weight of the sails and withstand the wind-induced stresses.
- **Safety:** the safety of the vessel is of utmost importance. Oversized sails can create risky situations, especially in adverse weather conditions. Proper safety protocols and training for the crew who operate them should be considered.
- **Integration with existing propulsion systems:** sails are used as auxiliary propulsion systems in conjunction with conventional engines. Integrating these systems effectively and achieving a smooth transition between them is challenging.

3.1.2 Integration technical feasibility analysis

To evaluate the impact of installing the WASP systems, the following points must be checked:

- **Electrical load balance:** the part that requires the largest electrical consumption in the eSAIL® is the suction fan. A study is deemed necessary to check if the existing power supply on the vessel can provide sufficient extra power for the operation of the WASP system under any configuration.
- **Equipment number (EN):** a new EN is calculated for mooring and anchoring.
- **Navigation lights**
- **Radar visibility**
- **Stability in intact condition**
- **Structure for vessel reinforcement**
- **Visibility:** if the visibility with the WASP system is relevantly affected, new drawings are needed to verify the compliance with SOLAS Reg.22. [2]
- **Navigational area**

3.2 Detailed naval engineering and vessel conversion.

Upon the completion of all technical feasibility assessments, the vessel retrofit process starts with a meticulously project planning, encompassing detailed engineering, procurement, liaison with class societies, manufacturing, and final installation.

A pivotal aspect crucial to adhering to project timelines is the ad-hoc planning of the vessel operational schedule and the dry-dock periods. The ad-hoc strategy ensures efficiency in the system installation by leveraging planned halts to accommodate the WASP retrofitting activities.

The second key point is to establish where the various activities shall be conducted. To install the WASP system (eSAIL®) into an existing vessel (retrofit) WASP, the activities can be performed in a shipyard or, alternatively, in a port, taking advantage of a vessel port-call, with sufficient time to fit, connect the eSAIL® on the vessel.

Based on this, various scenarios emerge based on the timing and location of the conversion process, which are summarized in Table 1.

Table 1: Possible combinations for the implementation of the WASP installation process depending on the location of the main activities involved (shipyard or port).

ACTIVITY	Option 1	Option 2	Option 3	Option 4	Option 5
Vessel conversion for WASP installation	During a scheduled dry docking	During a scheduled dry docking	During a scheduled dry docking	During a dedicated shipyard stop	During a dedicated shipyard stop
Installation of the WASP systems (eSAIL®)	During the dry-docking	In a second phase with a successive stop in a shipyard	In a second phase in a port-call	During the shipyard stop	In a second phase in a port-call

A significant part of the work of naval engineers is dedicated to the identification of all requirements and limitations for the vessel retrofitting into a wind sail-assisted one, as a complementary action to the feasibility analysis conducted previously. These requirements, among others, take into account the vessel technical and physical characteristics, the existing regulations from the flagging state, the characteristics of the eSAIL® and the operational conditions provided by the ship-operator. In addition, requirements and rules from Classification Societies must also be considered.

Following this step, a detailed planning of the vessel conversion is defined, which include these tasks include, among others:

- Confirmation of the eSAIL® configuration, in terms of sail size, units and position
- Calculation of vessel physical characteristics (stability information booklet, hull hydrostatic parameters, hull resistance, power plant, etc.).
- Design, sizing and structural calculation of possible required vessel modifications (freeboard modification, keel, new equipment required, etc.).
- Structural calculation of the hull reinforcement in the area where the eSAILs will be installed.
- Impact assessment of the sail lateral forces on the route, which should not affect the manoeuvrability.
- Cabling and other services routing to supply power to the wing-sail aspiration system.
- Modification of vessel structures (bridge, decks, etc) to include the eSAIL® control system, the hydraulic power system, and the control panels.
- Evaluation of the expected performances of the of wind-assisted vessel, in terms of power, fuel consumption and GHG emissions.

Once the initial planning has been made, the vessel conversion for the installation of the WASP begins, which includes, for example, the installation of the local hull reinforcements, the deck adaptation, electrical/hydraulic works, and the integration of the WASP performance-monitoring system. All these activities can be performed in the shipyard and the main ones are:

- Acquisition of the required material and equipment for the vessel conversion
- Transportation of the pre-assembled pedestal and reinforcements to the shipyard.

- Preparation of the material and manufacturing of structures to be installed on the vessel.
- Transportation of the vessel to the shipyard (and dry-dock if necessary)
- Execution of the retrofitting works on the vessel as designed (i.e. hull reinforcement, sail integration, control panel installation, etc.).
- Execution of quality assurance test (NDTs, etc.).
- Paint corrections.
- Execution of stability test and class society survey to the final approval of the conversion.

To gain a comprehensive understanding of naval engineering and the vessel conversion phase, and leveraging on expertise of Astander in such activities, the Annex I provides a detailed summary of the activities undertaken by this shipyard in a recent project. This information enables a practical insight into the overall vessel conversion process. Annex I is included at the conclusion of this deliverable for reference.

3.2.1 WASP installation processes

According to the scenarios detailed above (Table 1), the project schedule and task breakdown must be adapted. In this section the focus is on the WASP installation activities that can be conducted in a shipyard or in a commercial harbour. The activities to be performed in both cases are quite similar, with the cost, the available space and resource plans as main topics to be analysed.

Based on the accumulated experience of B4B in the installation of eSAILs, the flowchart in Figure 3 describes the pathway to a successful installation of a WASP, detailing the most relevant activities and considering, as the starting point, the manufacturing of the system.

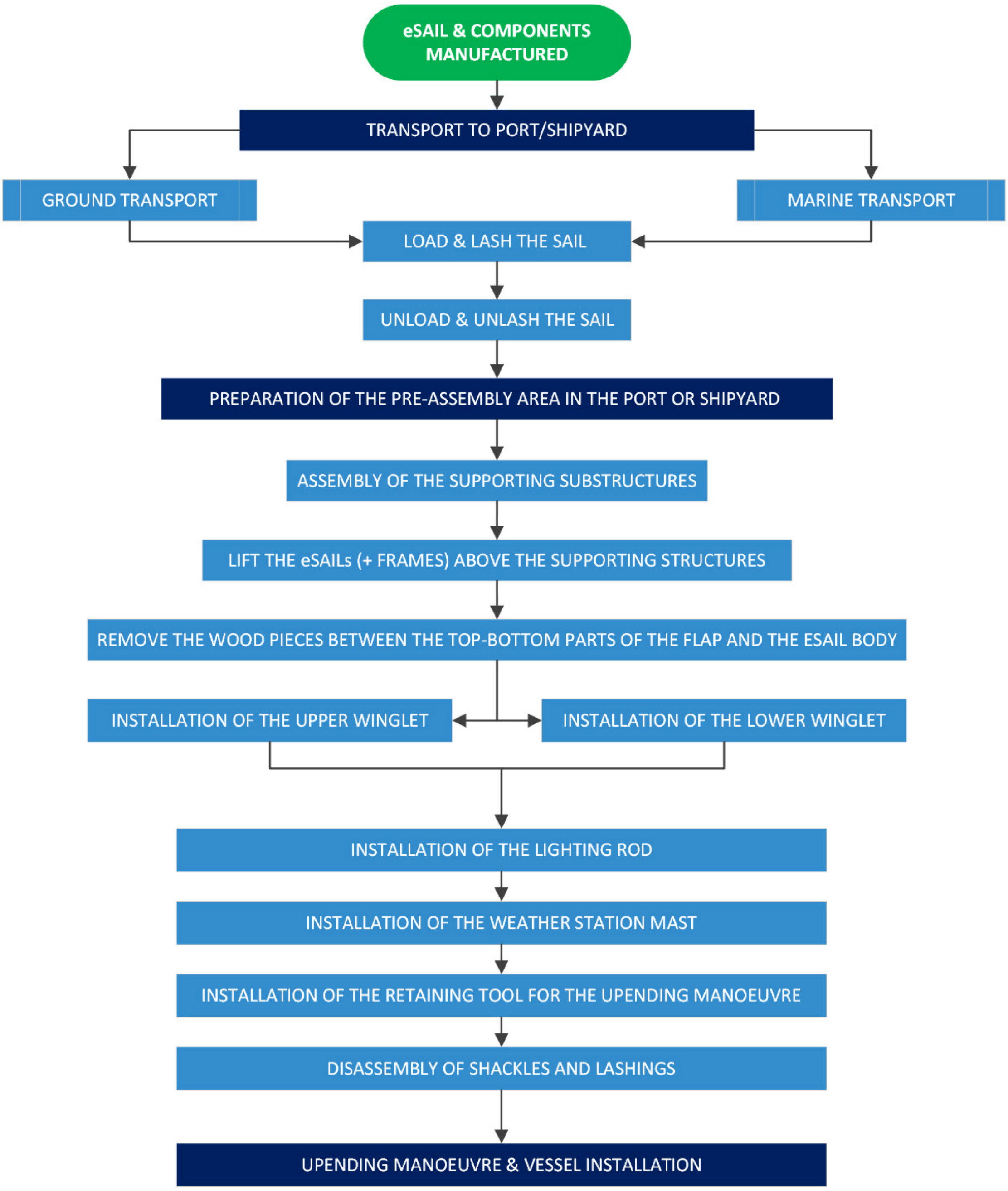

Figure 3: WASP installation flowchart.

The comprehensive flowchart emerges from the identification of bottlenecks and inefficiencies, their evaluation, and the formulation of alternative procedures to address these issues in subsequent installations.

The descriptions of some of the most pertinent lessons learned and the procedures implemented during the WASP installation process are listed below:

3.2.1.1 Activity: transport to port/shipyard.

- It is important to ensure that the sail is properly protected by using covers, see Figure 4. These covers must be securely fastened to prevent risks during the transportation and must have a sufficient resistance, to avoid tearing.
- In the case of road transport, it is recommended to carry out a road survey to identify potential restrictions for the truck along the route (roundabouts, close curves, air-draft limits, etc.).
- It is fundamental to perform a load simulation, to assess the suitability of the truck and of the trailer for the components to be transported and to check the load distribution and the potential interferences among the trailer, the WASP components and the lashing, see for example Figure 5.

Figure 4: Detailed view of the WASP protective covers applied by B4B during logistics operations.

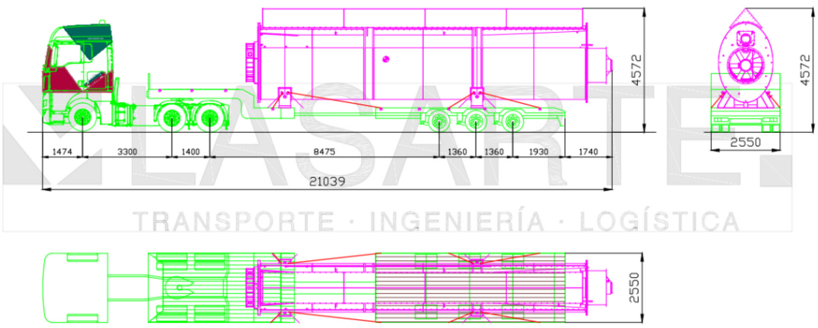

Figure 5: Sample drawing provided by the logistics operator to validate the proper positioning of the WASP during road transport.

3.2.1.2 Activity: preparation of the pre-assembly area

- It is recommended to conduct layout studies of the operational areas. This study should include the material storage areas, pre-assembly areas, as well as the final installation area alongside the ship, see Figure 6
- Prior to installation works, it is good practice to conduct an on-site verification visit to confirm and mark the positions of all critical elements (materials, cranes, vessel, etc.), see Figure 7 and Figure 8.

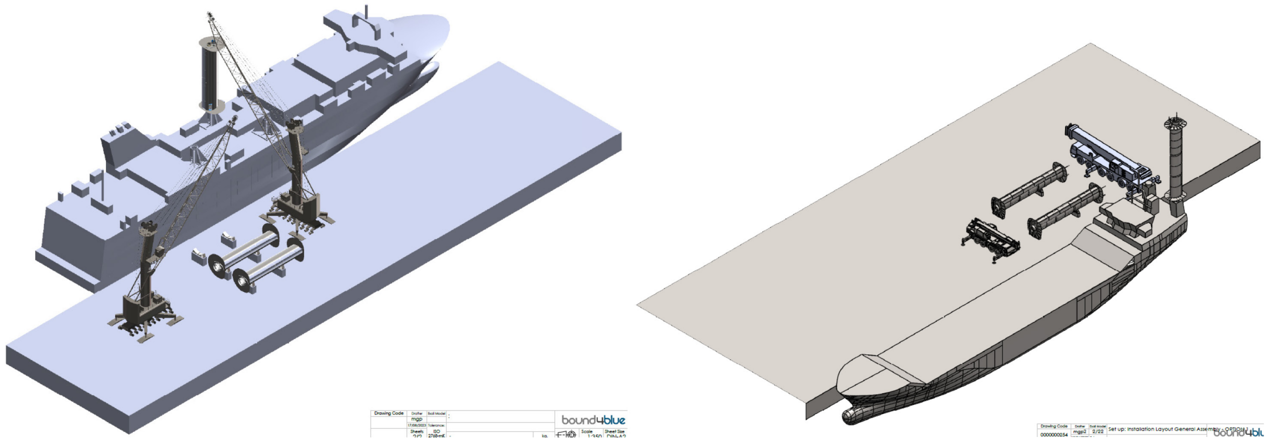

Figure 6: 3D lay-out designs for WASP installation operations.

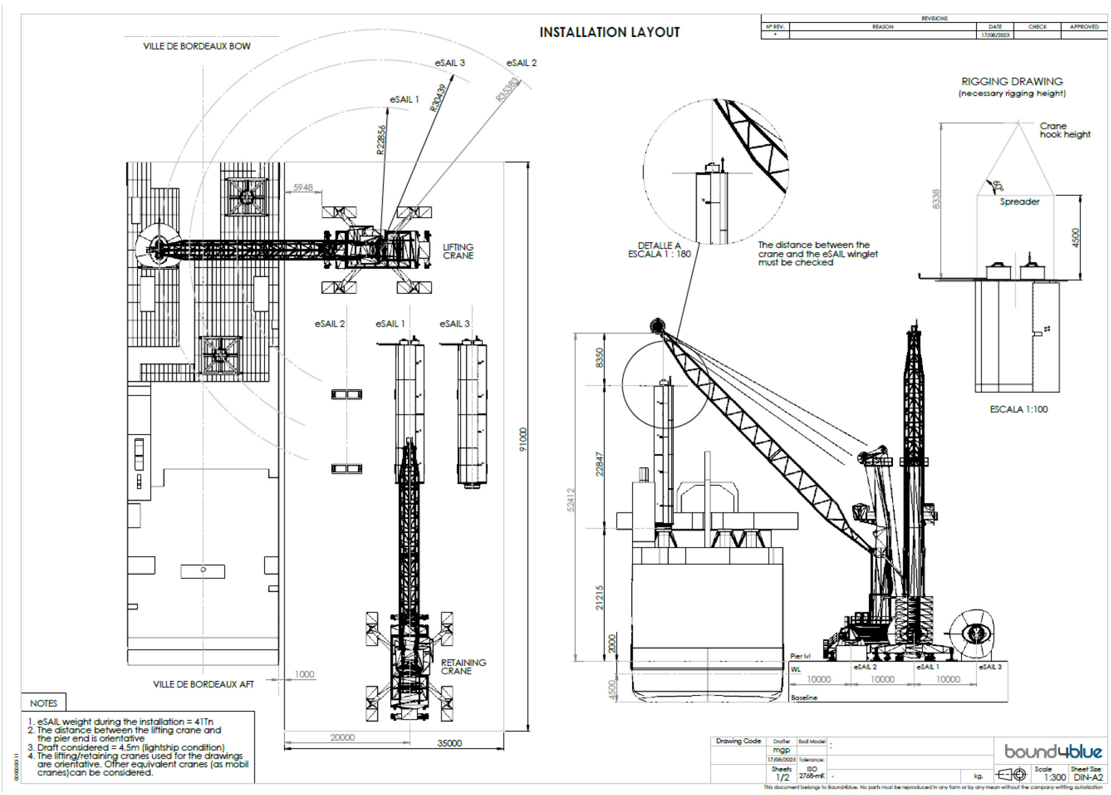

Figure 7: WASP installation drawing with crane manoeuvring details.

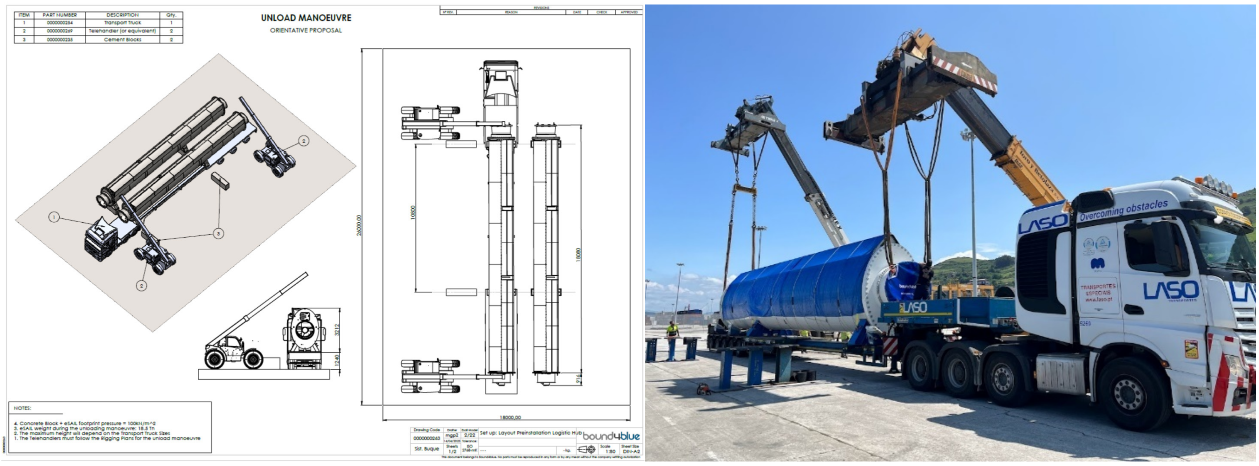

Figure 8: WASP storage area and unload related operations: (r) lay-out drawing; (l) real unload operation.

3.2.1.3 Assembly of supporting structures

- For the pre-assembly of the WASP, it is important to make use of auxiliary substructures, capable of safely supporting the system while allowing an easy accessibility, as shown in Figure 9. For example, in the case of the B4B eSAILs, similarly to the general case of aerodynamic components, a horizontal positioning of the sail is required and the access of the working men up to a height of 3 meters must be guaranteed.
- It is important to use extremely flexible auxiliary and low-footprint substructures. The reason behind this recommendation is to allow fast and easy movements to relocate the sub-structure and prevent potential interferences with auxiliary elements such as lifting platforms, scaffoldings, etc. After several tests with different solutions (steel feet, concrete blocks, etc.), B4B has selected the modular structures commonly used in civil works for bridge construction, building retention and ground shoring, as the best solutions, as shown in Figure 9 and Figure 10.

Figure 9: Modular structures used for WASP final pre-assembly.

Figure 10: Modular structures used by B4B during final assembly of eSAILs.

3.2.1.4 Final assembly of the WASP

For this specific task B4B has not identified any significant critical point regarding the procedures, therefore what follows are only general recommendations and best practices. Most of them are well-known across various industrial and offshore sectors, although it is crucial to adapt them for each specific WASP installation. These general recommendations are:

- The site manager should organize a daily meeting with all the personnel involved in the maneuver operations, to ensure a correct comprehension the procedures, the related risks and safety aspects.
- All materials required for the installation (bolts, tools, etc.) must be selected, identified and ready for pick-up next to the assembly area. Preparation should start prior to the maneuver operations.
- Critical elements such as torque tools, large diameter bolts or lifting materials must be redundant, in a way that, in case of failure, the installation is not interrupted.
- Since the installation of the WASP takes place in wide open areas, exposed to changes in the wind direction, it is very important to implement safety anchor lines to the ship deck for a safe control of the WASP during assembly to the pedestal, avoiding an undesired twisting WASP. The anchor line systems are shown in Figure 11 and in Figure 12.
- Time "buffers" during the installation schedule should be considered, to cope with possible adverse weather conditions and other unforeseen events, which could delay the operations. These "buffers" must be clearly communicated and discussed with the shipowners or other stakeholders, since an unexpectedly long-time delay can cause a variation of the vessel sailing program, implying a different stop schedule in ports or different labour shifts of the technicians.

Figure 11: Lifting and verticalization manoeuvres operations for eSAIL® installation at port.

Figure 12: Verticalization procedures of manoeuvres during an eSAIL® installation at a shipyard.

In addition to WASP this, in the framework of the WP7 of the RETROFIT55 project, B4B has developed a detailed installation procedure that can offer deeper insight on:

- the technical documents that must be prepared to support the installation of the eSAIL®,
- the different tasks to be performed during the installation itself, including safety recommendations and best practices.

A guide version of this “eSAIL® installation procedure” is provided as the Annex II to this deliverable.

It is important to note that this template document has been used to develop the formal “eSAIL® model 2 installation procedure” for the upcoming installation on the vessel “Ville de Bordeaux”, operated by the French company *Louis Dreyfus Armateurs*.

3.2.1.5 Sea trials

The following tests are recommended to be performed during the sea trials:

- performance tests with WASP on (active) and off (tilted or retracted) during navigation at established service speed of ship
- testing of all the operational modes and configurations of WASP foreseen during navigation
- manoeuvrability tests with WASP on (active) and off (tilted or retracted),
- emergency stop/shutdown of WASP according to the class society directives.

4 Closing remarks

In this deliverable, a comprehensive summary of the WASP installation process is detailed, paying special attention to the critical points that should be observed to guarantee a safe, reliable, and cost-efficient installation.

Maritime transport is crucial to the EU economy and energy-efficient, however it contributes significantly to greenhouse gas emissions, posing a challenge to climate change goals. With emissions expected to rise, the GHG reduction targets set by the International Maritime Organization (IMO) and by the EU, are deemed necessary. The IMO aims to reduce GHG emissions by 20% by 2030, 70% by 2040, and to achieve net-zero emission by 2050. To reach these targets, innovative solutions are required.

Wind-assisted Ship Propulsion Systems (WASP) is a very promising technology, which may significantly reduce the GHG emissions. Among the various types of wing-sails, the suction sails, particularly the eSAIL® system developed by B4B, have shown a great potential. The eSAIL® consists of an orientable pedestal, on which a wing body in installed, equipped with a movable flap. The flap control is achieved by using an integrated autonomous control system.

The eSAIL® developed by B4B, requires a meticulous design approach to ensure seamless integration and optimal performance. This report delves into the detailed procedures required for the successful installation of eSAIL® systems, focusing on the vessel conversion to wind-assisted propulsion.

Pre-engineering activities involve a study of the ship characteristics, an aerodynamic analysis, and a technical feasibility assessment.

Detailed analysis design, structural calculations, and stability assessments. This phase ensures that the vessel can accommodate an eSAIL® without compromising its integrity or stability. It includes planning for structural modifications, such as reinforcing the hull, and the evaluation the impact of eSAIL® on vessel performance.

The vessel conversion process encompasses retrofitting works and the final installation of the eSAIL®. A precise project definition of these activities is crucial, including procurement, liaising with class societies, and scheduling installation during dry-dock periods. This ensures an efficient integration of the eSAIL® into the vessel structure.

Installation processes require careful coordination, including transportation, pre-assembly preparation, supporting structure assembly, final installation and sea trial tests for class approval. Critical lessons learned include the necessity of redundant critical elements, daily meetings to ensure understanding and safety, and time buffers to cope with possible adverse weather conditions.

In conclusion, the integration of WASP systems, like the eSAILs developed by B4B, presents a viable pathway towards reducing emissions in maritime transport. However, a successful implementation requires rigorous planning, engineering expertise, and adherence to safety protocols. The development of detailed installation procedures, such as the eSAIL® installation procedure, helps to streamline the process and ensuring successful outcomes.

References

[1] International Maritime Organization, Fourth IMO GHG Study 2020 Full Report, 2021

[2] International Maritime Organization (IMO), SOLAS - International Convention for the Safety of Life At Sea, Chapter V – Safety of Navigation, *Regulation 22- Navigational bridge visibility*, https://www.imorules.com/GUID-95B39DFD-3930-4FDF-89B6-1F7FFBCF7B1D.html

ANNEX I

EXAMPLE OF THE PROCESS OF VESSEL RETROFITTING REQUIRED FOR WASP SYSTEM INSTALLATION IN A SHIPYARD

I.1 Introduction

The main challenge of this work is the design of a steel structure to support rigid sails higher than 17m, with the additional difficulty that the structural components are not standardized. In this sense, a new optimized design is proposed through the realization of infographics and 3D designs of the support system. To do this, it is necessary to determine the variables involved in the operation of deploying the sail.

Another challenge is the computational modelling of the elements that make up the prototype according to the distribution of loads and the following analysis of the system, which will determine the critical points and identify the areas in which it is recommended to reinforce the structure based on the local stresses deformations, as well as on the maximum loads allowed.

I.2 Pre-Retrofit Activities

Some of the technical problems that are analysed in the pre-retrofit activities are:

- an advanced foundation design: aerodynamics and sail design require the design of advanced auxiliary support systems. This design is optimized by using lightweight but sufficiently resistant materials.
- the development of a new workflow methodology adapted to the new specifications and that, using analytical techniques, allows the identification of interferences as well as of the design constraints for the sail installation, and enhanced safety systems to mitigate the risks associated with oversized sails.

I.2.1 Analysis of the technical specification and general drawings of the installation.

Preliminarily to the retrofitting, research on the current state-of-the-art, is performed, in order to collect all available information (internally and externally to the company). This work provides a knowledge increase, which represents an added value when making decisions, and allows for incorporating eventual changes and new developments.

A preliminary study of the technical requirements and technical specifications of the vessel under study must be carried out, together with the construction drawings and systems already existing on the ship, analysing the critical points to be considered for the installation of the new pole system.

The technical characteristics of the sail to be installed on the pole has to be studied to carry out the identification of weights and loads that the system has to support. The technical analysis lays the groundwork to start the design of the construction strategy.

I.2.2 Design and development of a foundation for the installation of the wing-sail.

In the second phase of the retrofitting, based on the technical specifications, on the construction plans, and on the layout of the ship, a design of the construction strategy is performed, together with a **detailed design of the foundation**.

During this phase, all the structural drawings of the new foundation are prepared. In addition, a structural (FEM) computer simulation of the system is carried out, to derive the stresses/strains undergone by the structure to validate the results of the load/weight study carried out in the previous phase.

Successively the required materials are retrieved and the manufacturing of the prototype can start.

In details, the various activities of this phase are the following ones:

- design of the construction strategy
- stress/strain analysis using a FEM 3D simulation
- preparation of the drawing of all the structural elements
- issue of the quality certificates for the materials
- manufacturing of the prototype and of the auxiliary elements
- assembly and installation of the different parts
- quality tests (weld inspection, magnetic testing, analysis with liquid penetrants, functional tests).

To carry out these activities, B4B has also made use of **mixed reality**, which is one of the most common tools used nowadays for retrofitting. Mixed reality is a space in which the virtual reality and the visual power of augmented reality coexist and interact. This combination of forces allows the user to fully enter a real environment, with the particularity of being able to interact with virtual elements. The process is carried out by scanning the outside environment, generating a 3D map. The surface is then analysed, and the device is enabled to place the visuals in the exact places. This ability to combine the best features of the two realities suggests that mixed reality will become the future of immersive technology. In the field of construction, architecture and engineering, immersive realities are changing the ways of working and representation. Mixed reality allows engineers to measure, draw, crop, or apply textures to surfaces, materials, and environments that have been previously scanned. This procedure is carried out with an HMD headset, which renders virtual elements on the transparent display. The most popular mixed reality system has been developed by Microsoft, by using HoloLens glasses. Windows 10 provides a common mixed reality platform for developers and device manufacturers, for example concerning the design of pulleys to support sails and auxiliary structures on ships. Mixed reality is a tool that allows a system integration without making use of invasive techniques, in preparation of the real work. For example, the application of mixed reality to the design of the WAPS foundation is shown in Figure 13.

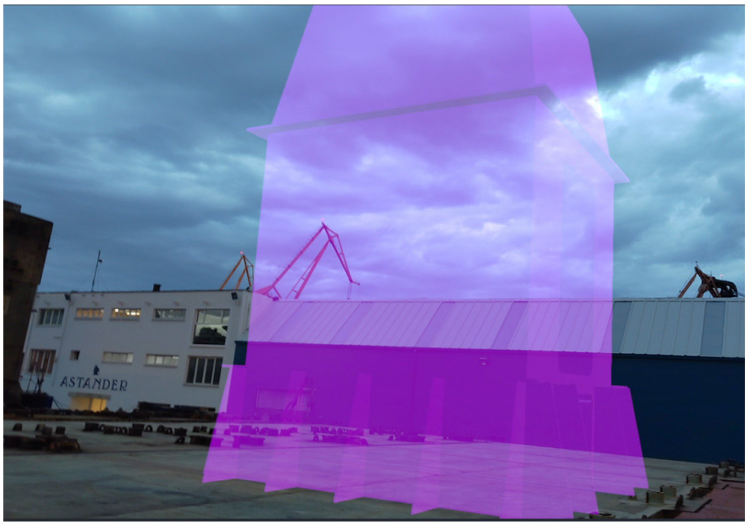

Figure 13: WASP Foundation structure view using mixed reality.

I.3 Retrofitting activities prior to the WASP Installation

From a strategic point of view, the aim of this phase is to consolidate the ship conversion operations, offering to the naval sector the competitive advantage of specific technological processes and technical solutions, while respecting the environment.

The technological objectives are to integrate a new support system for the installation of WASP on a ship deck. It should be noted that the installation is challenging also because each ship has its own layout. In this case we analyse a cargo ship, because it is the most common type of ship and because on this type of ship WASP has shown the best performance.

A detailed list of the technological objectives of this phase is:

1. Identify the critical parameters involved in the process.
2. Develop a method for calculating the weights and the centre of gravity of the WAPS structures.
3. Speed up future repair and/or maintenance tasks.
4. Carry out operations with high quality and safety standards.
5. Adapt the existing structure to the weight of the equipment to be installed, minimizing the impact of existing systems, as well as the load capacity of the vessel.
6. Select the materials suitable for the specific conditions of the equipment and for the environmental conditions (temperature in the different installation areas, volume, etc.).
7. design of an appropriate electrical regulation and specific auxiliary systems, which can be regulated for different running conditions of the WASP.
8. Implementation of mixed reality technologies to improve and optimize engineering work and improve the construction strategy in this type of facility.
9. Selection of the location of work, which is one of the hardest tasks for this construction, since the conversion process presents several challenges compared to a new construction.
10. Design a structural solution for the new installation allowing a minimal loss of cargo of the ship.

Technical specification and general drawings of the installation, once the critical points have been analysed and the details of the work have been defined (detail engineering).

During the first activity of retrofitting, a preliminary study of the requirements and technical specification of the vessel is carried out, together with the construction plans and existing systems, identifying the critical points to be considered and the ideal location for the installation of the new system.

Relevant documents considered according to vessel and carry out once all the drawbacks in the basic engineering have been identified:

- Technical specification of the vessel.
- Construction drawings of the vessel with existing systems.
- Technical data sheets of the materials.
- Reference Vessel.

The reference vessel is a Ro-Ro type with the following characteristics:

- **Gross tonnage** (GT): 25995 t
- **Deadweight tonnage (**DWT): 7150t

- **Length**: 186 m
- **Beam**: 15.6 m

The main tasks of the installation are:

- Installation of a reinforced foundation (see Figure 14 and Figure 15) WASP.
- Installation of a dedicated hydraulic system.
- Installation of an electric generator to power the WASP with the related systems.
- Installation of a cabinet for the control of the WASP.

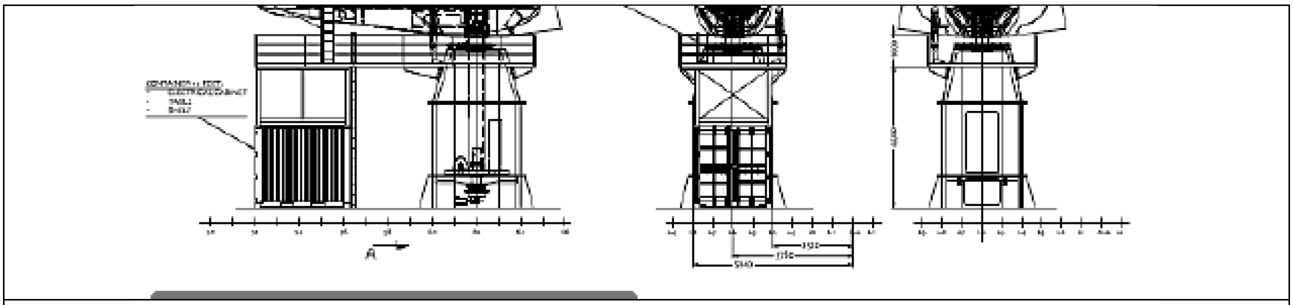

Figure 14: Drawing of the foundation.

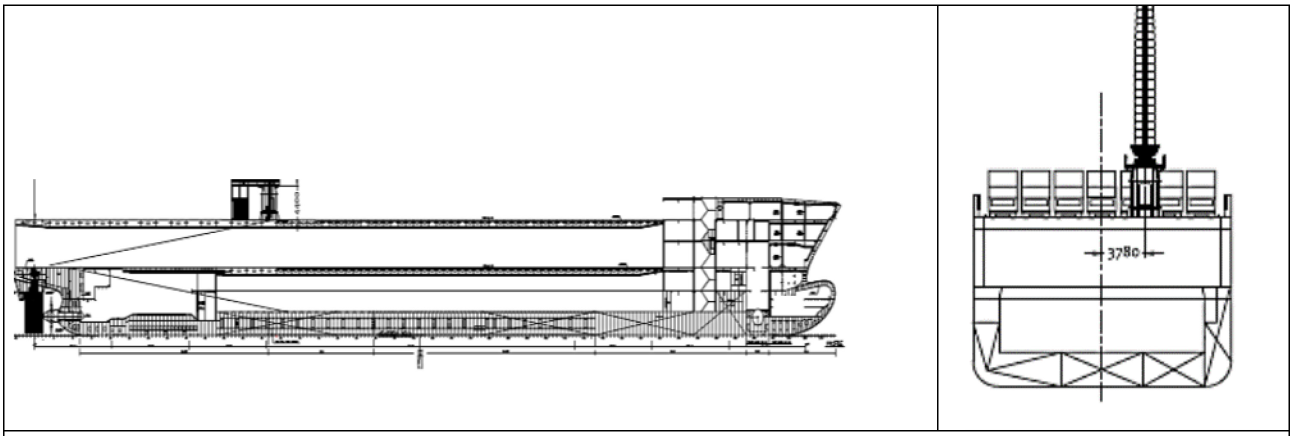

Figure 15: General Assembly of the WASP installation.

I.3.1 Determination of the Centre of Gravity (COG)

In general, a rigid body is considered in a state of equilibrium when the results of all the forces and moments acting on the body are zero. When addressing the static stability of a floating body, we are interested in the state of equilibrium associated with the floating body standing upright and at rest in a calm water. In this case, the resultant of the gravity force (weight) acting downwards and the buoyant force acting on the body are of equal magnitude and applied in the same vertical line.

(A) Stable balance

If a floating body, initially in equilibrium, is disturbed by an external moment, there will be a change in its angular attitude. If, by eliminating the external momentum, the body returns to its original position, it is said to be in stable equilibrium.

(B) Neutral balance.

If, on the other hand, due to an external moment, a floating body that is inclined remains in the displaced position when the external momentum is removed, the body is said to be in neutral equilibrium and has neutral stability.

(C) Unstable Balance.

If a floating body, displaced from its original angular position by an external moment, continues to move after the moment is withdrawn, it is said to be in unstable equilibrium.

A ship can tilt in any direction. Any inclination can be composed of an inclination in the transverse plane and an inclination in the longitudinal plane. In ship calculations, the transverse inclination, called heel and the longitudinal inclination, called TRIM, are usually treated separately.

Total weight or displacement of a ship can be determined from draft and shape curves. The position of the centre of gravity can be calculated or determined experimentally. For ships both methods are used. The weight and centre of gravity of a ship that has not yet been launched can only be established by a weight estimate, which is a sum of the estimated weights and moments of all the different elements that make up the ship. Once the ship is afloat, the weight and centre of gravity can be accurately determined by a tilting experiment. To calculate the position of the centre of gravity of any object, it is assumed that it is divided into infinitesimal particles, the momentum of each particle is calculated by multiplying its weight by its distance to a reference plane, adding the weights and moments of all the particles, and the total moment divided by the total weight.

To summarize the location of the centre of gravity G be calculated:

- from the sum of all the ship component weights, multiplied by their relative distance from the baseline or from a plane perpendicular to the stern, divided by the total weigh;
- by a tilt experiment.

The total moment of the forces relative to a fixed point is equal to the sum of all individual moments relative to the same point. If there is balance between all the moments on the port and starboard sides, there is no heeling. The axis of rotation is located in the central plane.

Table 2 summarizes the relevant data for the estimation of the COG (weight is expressed in tons and distances in meters), moreover VCG is the vertical position of center of gravity, LCG is the longitudinal position of the ship's center of gravity, and TCG is the transverse position.

Table 2: Estimation of the COG.

	WEIGHT	**VCG**	**TCG**	**LCG**	**Weight x VCG**	**Weight x LCG**	**Weight x TCG**
Ship before retrofitting	5370,976	11,10	-0,036	55,522	59655	298207	-193
WASP contribution	3,03765	5,789	6,857	57,185	22.21615	219,45601	26,31476
Estimated 3% Weld contribution	0,0911	5,789	6,857	57,185	0,665735	6,576275	0,788555

Base contribution	2,488	2,895	0,263	58,318	7,203946	145,11909	0,654451
Pipe DN 200 contribution	1,000	2,895	0,263	58,318	2,895	58,318	0,263
Other components	0,960	1,8	3,2	51,1	1,728	49,056	3,072
Total	5378,552	-	-	-	11,09145	55,525622	-0,035379
Variation %	-	-	-	-	-0,140	0,007	-0,725

The results summarized in Table 2 show that the installation of the sail on the foundation does not produce a significant variation of the location of the centre of gravity, hence the stability of the vessel is not significantly affected.

I.3.2 Structural verification of the foundation resistance under the external loads

In the design calculations, the foundation is treated as a beam to which a certain pressure is exerted. The pressure is transmitted through the WASP to the structure of the vessel. The beam transmits the force to the foundation, so the foundation must be able to withstand such a load. There are two types of force that must be considered:

- aerodynamic forces
- weight of the WASP system

The force exerted by the wind depends on:

- the wind speed (m/s)
- the surface area of perpendicular wind resistance
- the drag and lift coefficient
- ρ i.e. density of air, assumed to be 1.29 kg/m^3

In Figure 16 it is possible to see the WASP mast in its position inside the foundation. With this arrangement the wind forces are transmitted over the mast to the pulley and then to the deck of the ship. Subsequently, in the second activity, the design evidence is shown through computational simulation (FEM) where it is verified that the roof does not suffer any type of deformation.

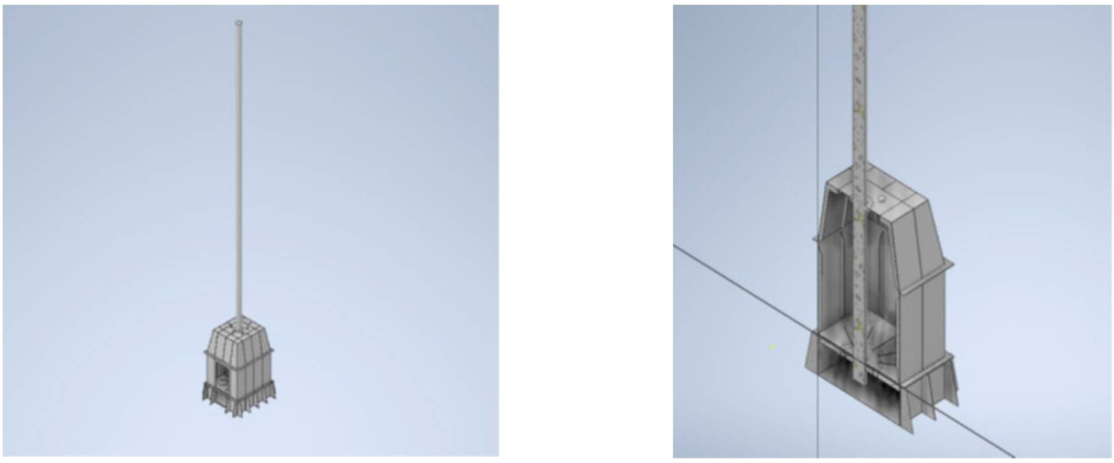

Figure 16: 3D design of the foundation with the sail.

Based on the technical specifications and the results of the analytical study of weights and loads, the results of the foundation stress analysis study are shown in Table 3.

Table 3: Properties of the FEM simulation.

Physical Properties	
Part Name	Foundation
Mass	909,998 [kg]
Area	188,806,000 [mm^2]
Volume	909,998,000 [mm^3]
Coordinates of the Center of Gravity	x=2677.91 [mm] y=50.4195 [mm] z=2004.17 [mm]
Mesh Properties	
Average Element Size (Fraction of Model Diameter)	0.1
Minimum Element Size (Fraction of Average Size)	0.2
Modification Factor	1.5
Maximum Swivel Angle	60º
Material Properties	
Material	Steel
Mass density	7.85 [g/cm3]
Yield strength	207 [MPa]
Maximum resistance to traction	345 [MPa]
Young Modulus	210 [GPa]
Poisson's coefficient	0.3
Shear modulus	80.7692 [GPa]

The calculation is carried out by means of a computer simulation.Two situations are taken as a basis for the calculation (see Table 4) to determine which is the most restrictive, the first is assuming that the foundation is welded to the deck of ship and the second is assuming the foundation plus the mast.

- Fixed constraint 1 – foundation plus mast:
- Fixed constraint 2 – foundation weld to deck.

Table 4: Test cases main data.

Constraint name	Reaction force [N]		Reaction torques [Nm]	
	Magnitude	Component (X,Y,Z)	Magnitude	Component (X,Y,Z)
Fixed constraint 1	37602.9	2209.92	28363.6	22817.7
		4052.96		-16874.6
		37318.4		-85.0491
Fixed constraint 2	9174.85	-2214.95	28664.6	-22407.8
		-4101.75		17875.9
		-7902.37		0.0

Table 5, Figure 17, and Figure 18 summarize the results of the simulations indicated in Table 4, whereas Figure 19 shows the 3D view of the system.

Table 5: Constraint force 1 and 2 – summary of results. SU means non-dimensional units

Name	Minimal	Maximum
Volume	909998000 [mm^3]	909998000 [mm^3]
Von Mises stress	0 [MPa]	65.164 [MPa]
First Tension	-17,2197 [MPa]	87,8185 [MPa]
Third Tension	-55,8468 [MPa]	32,2956 [MPa]
Displacement	0 [mm]	2.90976 [mm]
Safety coefficient	3,1766 su	15 su
Tension XX	-54,6988 [MPa]	70,3934 [MPa]
Tension XY	-25,4635 [MPa]	24,3528 [MPa]
Tension XZ	-21,0592 [MPa]	32,7574 [MPa]
Tension YY	-51,0536 [MPa]	63,4883 [MPa]
Tension YZ	-18,8016 [MPa]	27,8329 [MPa]
Tension ZZ	-55,8159 [MPa]	65,5759 [MPa]
Displacement X	-1,7933 [mm]	0,419923 [mm]
Displacement Y	-0,874345 [mm]	0,917908 [mm]
Displacement Z	-2,90976 [mm]	0,61708 [mm]
Equivalent deformation	0 su	0,000294232 su
First Deformation	-0,00000750709 su	0,000340952 su
Third Deformation	-0,000236863 su	0,00000901914 su
Deformation XX	-0,000206988 su	0,000271189 su
Deformation XY	-0,000157631 su	0,000150756 su
Deformation XZ	-0,000130367 su	0,000202784 su
Deformation YY	-0,000173734 su	0,00022887 su
Deformation YZ	-0,000116391 su	0,000172299 su
Deformation ZZ	-0,000236368 su	0,000289183 su
Contact Pressure	0 [MPa]	300,003 [MPa]
Contact Pressure X	-141,014 [MPa]	164,242 [MPa]
Contact Pressure Y	-142,729 [MPa]	161,599 [MPa]
Contact Pressure Z	-116,6 [MPa]	255,758 [MPa]

Funded by the European Union
Horizon Europe programme, grant agreement No. 101096068

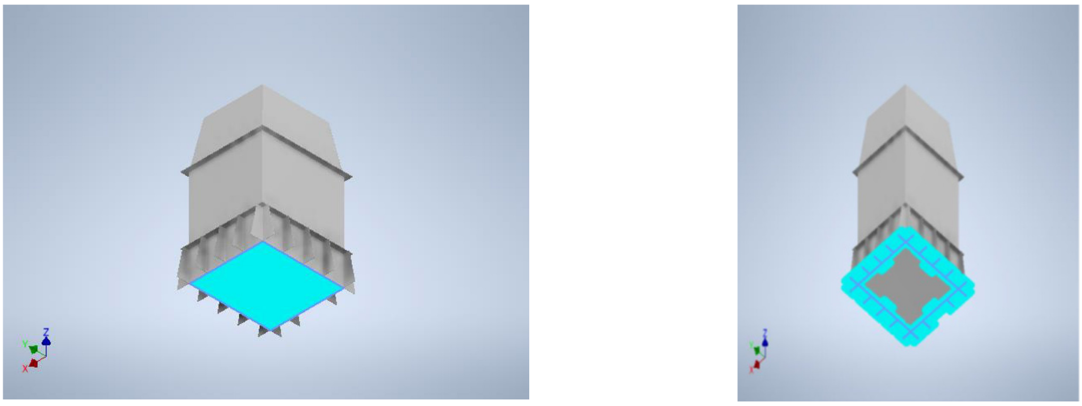

Figure 17: Simulation fixed constraint 1 and 2.

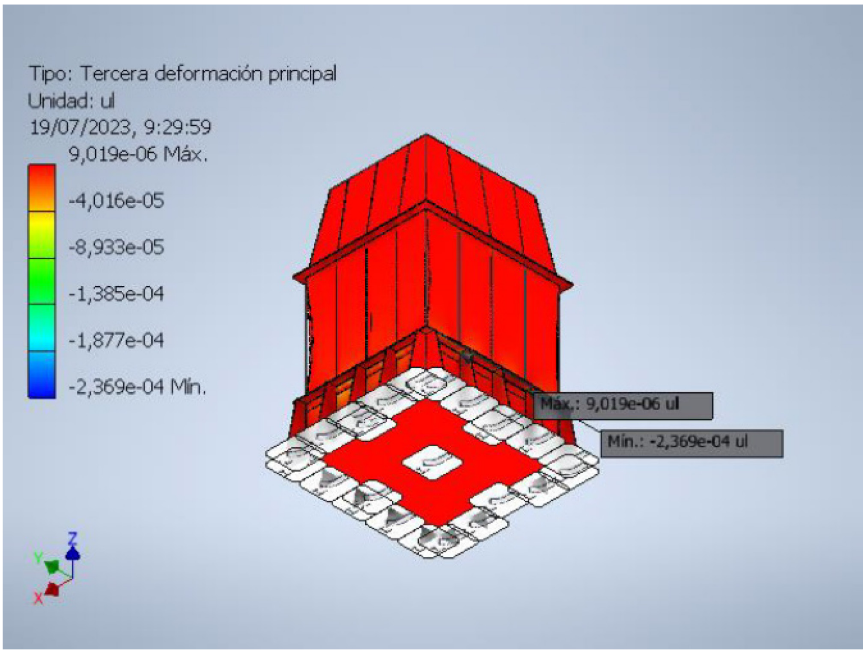

Figure 18: Simulation fixed constraint 2 - foundation plus mast.

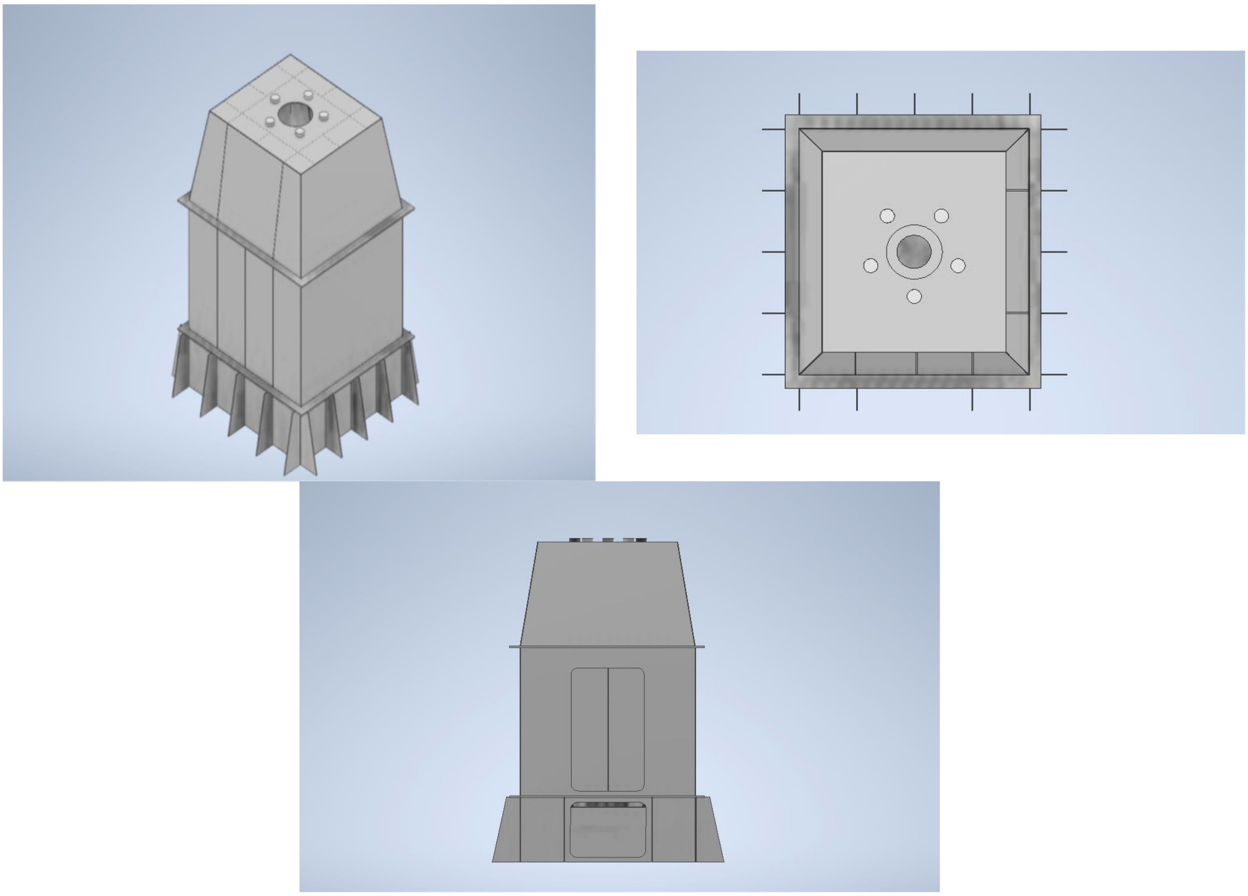

Figure 19: Below are 3D designs of the system, from different views.

Based on the design calculations of the structure, the drawings of the prototype are shown Figure 20.

The designed structure meets the required design conditions. The simulations carried out show that the foundation can withstand the required loads and stresses.

It is determined that the shape, the materials used, the geometry and the reinforcements are suitable, based on the simulations carried out. The critical areas and/or points of the structure have been identified in terms of deformation and stress, being irrelevant in the overall ensemble.

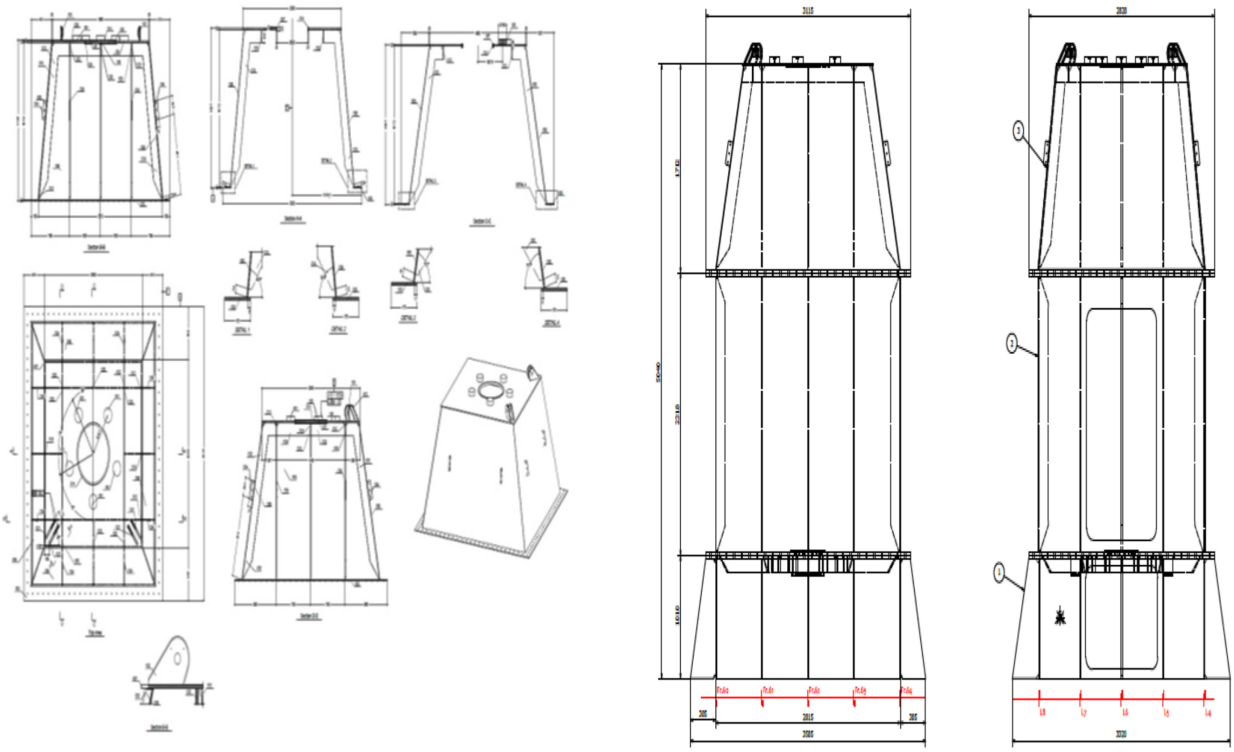

Figure 20: Foundation construction.

I.4 Pedestal manufacturing and installation

Once the distribution plan is defined, the retrofit process begins on the ship, the photos of the manufacturing process of the various parts of the prototype and installation of the foundation on the deck of the vessel are respectively shown in Figure 21, Figure 22, and Figure 23.

Figure 21: Prototype manufacturing.

Figure 22: Preparation on deck for prototype installation. Structures have been reinforced and the deck flattened.

Figure 23: Installation on the ship deck

After the structure was installed on the vessel deck, the WAPS mast was placed on the pedestal axis, as shown in Figure 24.

Figure 24: Sail mast installation

I.5 Retrofitting of the electrical system

The available electrical system does not have enough extra power for the operation of the WASP at maximum power. For this reason, an independent electrical system is designed to power the sail, an electro-hydraulic group and the consumptions associated with the control system. This system is composed of:

- an independent electric generator;
- an electrical control panel;
- protections and wiring.

A schematic of the refitted system example is shown in Figure 26.

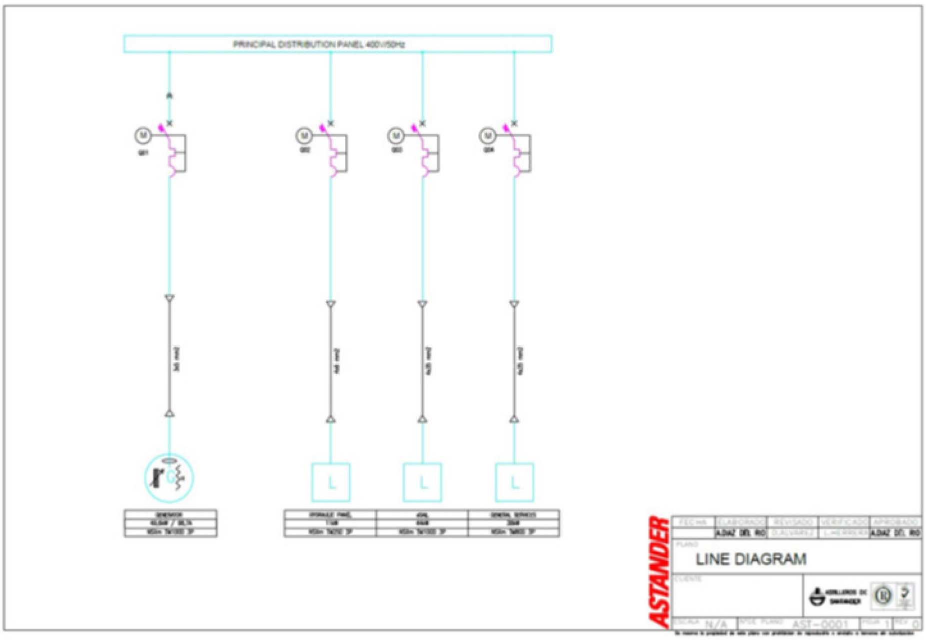

Figure 25: Refitting of the electrical system diagram example