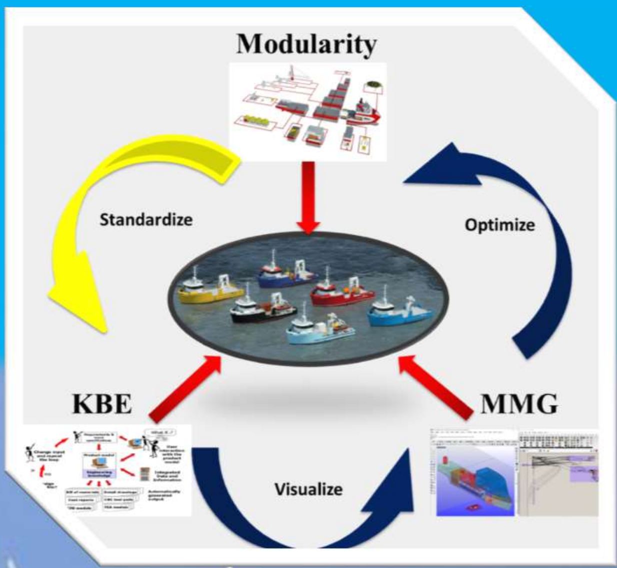
Knowledge Based Engineering (KBE) automatic layout generation framework for modular offshore wind service vessels

-Towards a Brand-New Multi-Model Generator for Modular OSV Product Families-

I-TING KAO

Oct. 2021



Knowledge Based Engineering (KBE) Automatic Layout Generation Framework for Modular Offshore Wind Service Vessels

Towards a brand-new multi-model generator for modular OSV product families

KNOWLEDGE BASED ENGINEERING (KBE) AUTOMATIC LAYOUT GENERATION FRAMEWORK FOR MODULAR OFFSHORE WIND SERVICE VESSELS

TOWARDS A BRAND-NEW MULTI-MODEL GENERATOR FOR MODULAR OSV PRODUCT FAMILIES

Master Thesis
ter verkrijging van de graad van Msc.
aan de Technische Universiteit Delft,

door

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-郁永河

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PREFACE

The present thesis has been written to fulfill the graduation requirements of the Master of Science Marine Technology in the field of Marine Technology at the faculty of Mechanical, Marine and Materials Engineering at the Delft University of Technology. I was engaged in researching and writing this research work from December,2020 to October, 2021.

I-TING KAO
Delft, October 2021

Acknowledgements

This thesis would not have been shape without the guidance of my supervisor Austin Kana. My greatest appreciation for his patient and enthusiasm throughout my research, especially in this difficult time in the pandemic. If it wasn't for his support, I could already give up in the summer of 2020 when the whole world is suffered from COVID-19. Also, I would like to thank Hans Hopman for his feedback for my literature review. Some critical advice has inspired a more powerful MMG than what I expected at the very beginning of my research.

I would like to thank Darpan Bansal for grouping with me in the KBE course. The meetings we have in the kitchen has clarified my doubt of my knowledge of KBE. Also, the program you made for the course has inpspred me for the whole structure of the MMG i made for this research. I would like to thank Yu-Sheng Li for your technical support. You are the pioneer of our group to explore the sustainable energy market in the EU. Your critical feedback has enabled the MMG to generate more accurate modeling result.

I would also like to thank my colleagues and leaders from CSBC, Taiwan for supporting me throughout my study in TUDelft. I knew that I left at the busiest season of the design work, but I do believe that one day we will work together for a project that we'll be proud of ourselves.

Last but not least, I would like to tank my family for supporting me from the first day I expressed my feeling for studying abroad. My deeply apologize for not being able to go back to Taiwan because I want to explore more possibilities in this foreign land far away from my home.

I-TING KAO
Delft, October 2021

ABSTRACT

The urgent development of green energy has become a worldwide trend in the war against the threat of global warming and the impact of extreme weather. The offshore wind farm is one of the solutions that are able to harvest energy sustainably from the environment. To erect these offshore windfarms, the debate about whether a new fleet should be designed and built or make the existed offshore fleet go under retrofitting has been raised. The stakeholder group involved in this issue is formed by the ship designers, ship operators, and market analysts. The difference between the existed offshore support vessel fleet and the offshore wind farm support fleet is the former is built to perform a certain operation and will require another considerable investment to be retrofitted while the latter is looking for solutions to switch from different equipment thus to keep the flexibility between different operation.

The main objective of this research is to propose a ship design methodology to enable the offshore wind farm's request in mission flexibility by improving the design process in the preliminary design phase. Modularity and Knowledge Based Engineering (KBE) are chosen to be the two main topics to support the research objective. To narrow down the research scope, the research object is limited to a small Offshore support Vessel fleet that is able to perform service throughout the lifecycle of an offshore windfarm.

The application of the modularity concept is to break down the vessel system into smaller subsystem or function blocks then reassemble them to be self-sufficient modules. Modules are the basic elements for forming a modular platform to provide a basic model that is able to perform various operations by mounting different equipment. In the former research done in NTNU, a methodology for manipulating the modularity to assemble a product platform by processing previous configuration scripts has been developed. It has greatly reduced the repetitive and iterative works in the design of similar vessels, especially the design for OSVs. Though the configuration scenarios are flexible to change, the pre-designed modules' properties are limited by the based configuration. On the other hand, the configurations are closely tight to the hull shape thus limited the freedom from both the hull design and configuration design. In this research, an improved configuration generator is developed to separate the configuration design and the hull design. The proposed methodology will also keep the flexibility in importing new configurations and the latest hull shapes without conflicts.

Knowledge based engineering is another topic included in this research. It has been proved and widely used in the aerospace industry. As for the ship design industry, the application is limited to local structure design. KBE is a bridge to bring the user and the designer together in the design project. It consists of a programming stage, Knowledge Based System (KBS), to process the selection of suitable design cases and a visualization stage, Computer-Aided Design (CAD) ,to give a direct review on the whole design project. The fundamental drivers for each KBE system are called "High Level Primitive" (HLP). They are the basic units for the knowledge stored in the database. KBS picks out suitable HLPs from the database and assigned them in a configuration script thus forming a design result stored in the digital world. CAD will take over the result and visualize it in the drawing window. This is the proposed methodology to fill the gap between the modularity re-configuration and the diversity of modules.

A Multi-Model-Generator (MMG) will become the final output of this research. It is designed to be able to reproduce several vessels in the OSV market. A further demonstration of the ability to generate a modular OSV product family at the end of the research. Though the modeling output has been proved to meet the index set for the research object, the MMG has the potential to be improved in the future by importing a well-constructed database from the industry.

1

Introduction

1.1. Problem Background

The boom in offshore wind farm construction has created a wave of prospective interest to ship builders nowadays (Huang, 2019). The EU countries have been constantly working in the last decade with this well-established offshore wind turbine technology but it wasn't until recently that this knowledge was exported to America and Asia to support the latest windfarm development trend (Huang, 2019). Along with the opportunities, ship designers and operators have encountered a new era in designing and running novel offshore support vessels(OSV) fleets specifically to support offshore wind.

There are several challenges that ship operators need to account for, among which the most important ones are oversizing, overweight and over performance (Rex, 2018). This stems from the fact that these vessels were built to support the conventional oil industry but might not be suitable nor optimal for the work at offshore windfarm (Rex, 2018). From an engineering perspective, there are some similarities between the work procedures at offshore wind farm and the petroleum extraction site such as anchor positioning, ROV support and construction unit deployment. Offshore wind farm requires faster and more precise work which can hardly be done by the huge platform support vessel involved in the oil industry (Edwards, 2011).Last but not least, another challenge for this particular market is to attract investors in the near future by providing them with supporting vessels at a lower price and delivered in a shorter time.

From the supply side, shipyards are looking for solutions to reduce design and construction time. A modularity-based approach is one of the ways being explored in the early design stages to help the industry transform from engineered-to-order to assemble-to-order business model. (T. et al., 2008) Building OSV platforms as a modular product family allows shipyards to modify the basic design easily thus to achieve better cost efficiency. By dividing systems into functional modules, designers can explore model concepts tailored to customers' needs by swapping module components within the same product family.

One of the main questions in the modularity building principles is how to exactly define what a module is (Tvedt, 2012). There are numerous ways to decompose the system: by function similarity, by structure continuity or by class regulations (Erikstad and Levander, 2012). These items are common initial input data. Then, the process begins by transforming previous design experiences into reusable knowledge and sorting it by methods, rules, heuristics, constrains, and guidelines related to their properties. The knowledge in the database then can be reused in new but similar product development (Devaraja, 2018). This is exactly how to setup a Knowledge Based Engineering (KBE) system. It enables designers to focus more on the mission oriented components while designing the whole platform system. With the shared modules stored in the database, reusing functional units can narrow down quickly to basic but reliable arrangements.

It is not enough to accelerate the design process by defining modules and set up the database. To better approach the conceptual design, automatically generated models in CAD software can help to find out several possible solutions to shorten the time from words in contract to first design (Charisi, 2019). By reusing the modules in the KBE database combined with previous general arrangement cases, it will facilitate the rapid exploration of configurations to support a product family. That is, an automatic generation algorithm has the potential to adopt the modularity concept under KBE structure to create a better solution for generating new offshore wind farm OSVs' general arrangement. A framework of this design methodology will be provided at the end of this research project.

In conclusion, this project is to build a framework for building a product family of the future offshore wind farm support vessels' with a common platform with different configuration according to their mission. The idea is to apply modularity principles to accelerate the processing of conceptual design. Since there is no specific method yet to define a module for this specific application, approaches of modularity vary from case to case. These including several types of modularity and interface design introduced by Ulrich (K. T. Ulrich, 2008). It results in designers continuously generating new design projects from scratch but hard to apply them in the futrue design. KBE system can help to formalize the engineering data thus to transform them into reusable engineering knowledge. From the dozens of designs generated by the KBE system by a single input, automatic generation algorithms can assist designers to focus on the more rational options.

1.2. Research Object

The research presented in this thesis aims at implementing a KBE-modularity concept in the early design stage using automatic layout generation framework for modular offshore wind service vessels. The framework should provide efficient, reasonable and accurate enough models to improve the preliminary design process. The primary research objective is:

Develop an automatic General Arrangement generation framework that is able to combine modularity principles with a KBE system to assist in designing a new OSV family for wind farms.

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The objective can be pursued by the answering the following research sub question:

- **Offshore support vessel**

  1. *What is the current state-of-the-art of OSVs for wind farms? What are their limitations?*

- **Modularity**

  1. *What are the potential advantages of modularity for improving the design process? - What are its limitations?*
  2. *What is the the state-of-art modularity concept applied in ship designs especially for OSV?*

- **Knowledge based engineering(KBE)**

  1. *What are the KBE principles and how can they be applied to support modularity design?*
  2. *Waht are the KBE design experiences in other engineering fields to support this modularity design concept?*

- **Automated layout generation algorithms**

  1. *How to build a trustworthy an automated layout algorithm to demonstrate this modularity-KBE system?*
  2. *How to use a OSV layout on the market to validate the design result?*

1.3. THESIS STRUCTURE

- **Chapter 2: Literature Review**

  This chapter provides a walk-through of the three main concepts involved in this research from literature aspect. This chapter start with a market analysis of the offshore industry and the growing offshore wind energy market. The difficult situation for the over supplied offshore support vessel capacity and the frustration at designing new OSV products will be taken into discussion. Following the market analysis, a short introduction of the ship design process and the direction for improving the design works are provided. The first two section will help readers to get more information about the background of this research. The next part is about the modularity concept and its application. The last part is a introduction of KBE.

- **Chapter 3: Part I: Modularity Application**

  In this chapter, several modularity researches that have been applied in ship design process will be further elaborated. A methodology for how to define a module will be provided in this chapter. These modules will be stored in the modular knowledge base ready for the use in the KBE design process.

- **Chapter 4: Part II: KBE-like Framework: Knowledge-Based System (KBS) Structure**

  In this chapter, the technical details of KBE are discussed. In addtion to an application of KBE in the aerospace model design, a process to define the HLP of vessels will be the main part of this chapter.

- Chapter 5: Part III: KBE-like Framework: Multi-Modeling-Generator
  The research is aimed to create a new approach to the early design stage of a series of OSVs that involving in a full life cycle of a offshore wind farm. Initially, an introduction and overview of various OSV is given. The main design problem will be elaborated with more details. Each step of the proposed method is applied and analyzed.

- **Chapter 6: Evaluation of the Results**
  A complete OSV product family will be generated based on the result of the case study. The ship performance and functionality will be validated with existed reference design.

- **Chapter 7: Discussion and Recommendations for future research**
  Finally, key research results are discussed. The further suggestions for future research are listed at the end of this chapter.

A flowchart that illustrated the design process is provided in Figure 1.1

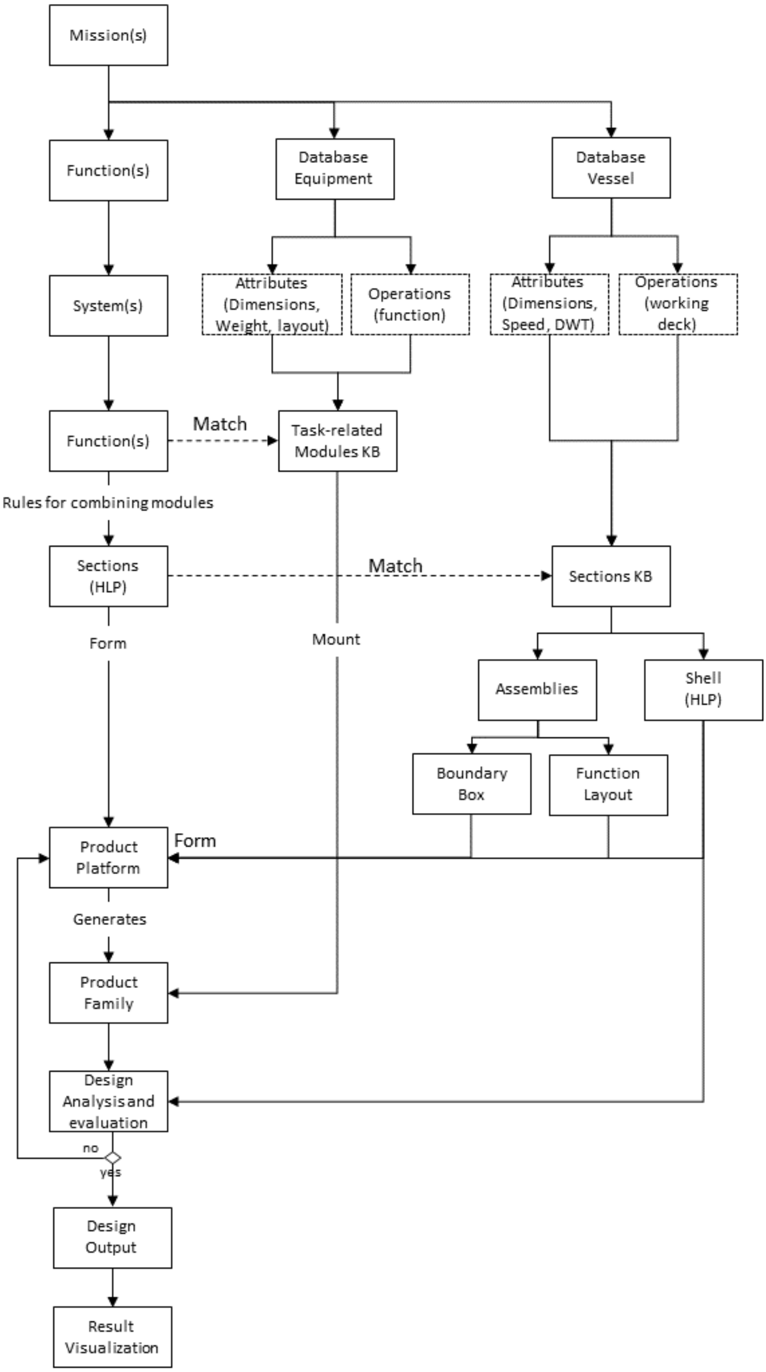

Figure 1.1: Design Flowchart

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Literature Review

In this chapter, a walk-through of the three main concepts involved in this research from the literature aspect will be provided. It starts with a market analysis of the offshore industry and the growing offshore wind energy market. Following the market analysis, a short introduction of the ship design process and the direction for improving the design works are provided. The next part is about the modularity concept and its application. The last part is an introduction to KBE.

2.1. State-of-the-art offshore wind farm

The growing demand for sustainable primary energy resources has gradually threatened the dominance of fossil and mineral fuels. Among all the renewable energy carriers, wind energy has been developed over thousands of years (Lee et al., 2020). The modern solution to convert kinetic energy into usable electrical energy is the usage of wind turbines. The first offshore wind farm was built in Denmark in the early 1990s. The growth of annual offshore wind farm installation and cumulative capacity is given in Figure 2.1. It took twenty years for the annual cumulative capacity in the EU to grow from 5 MW to 8045.2 MW (Ho et al., 2015). The recent statistical data shows that the strong increasing trend has increased the installed capacity by 2.5 times, around 21 GW, by the end of 2019 (Lizet Ramírez and Brindley, 2020).

According to Global Wind Energy Council's (GWEC) report (Lee et al., 2020), the European Union(EU) still has the leading edge in this field followed by the developing markets at the US Atlantic Coast and the Far East region. From the current state, suppliers and consumers are searching for new possibilities to enter the market.

Opportunities can be found throughout the whole life cycle of an offshore wind farm. In Figure 2.2, three biggest developing offshore wind farms around the world are stated (Lee et al., 2020). The following sections will focus on each of these wind farms to have a close look into them:

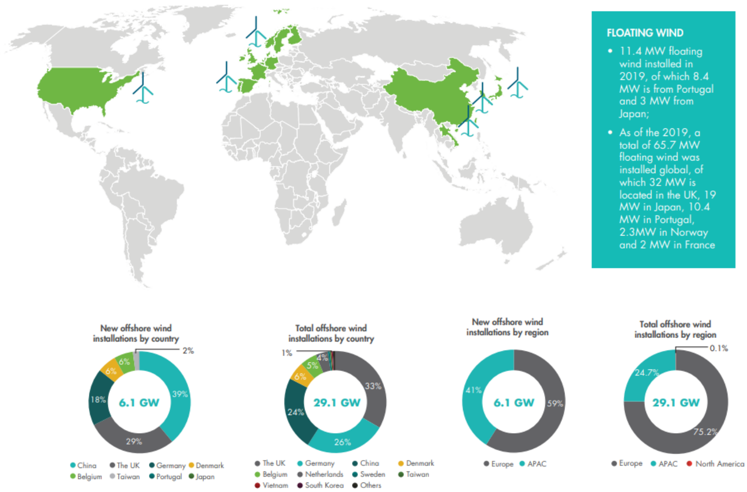


Figure 2.2: New offshore wind installation by country

- **EU** (Lee et al., 2020)
Europe is the homeland of the offshore wind industry. With the high annual growth in the offshore wind market, EU became the world's largest regional market at the

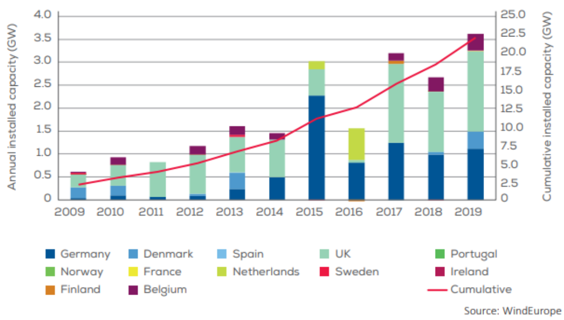


Figure 2.1: Annual offshore wind installations by country (left axis) and cumulative capacity (right axis) (GW) (Lizet Ramírez and Brindley, 2020)

end of 2019. According to the GWEC market intelligence market analysis made before the pandemic shown in Figure 2.3, it is believed that the EU still have the potential to grow and possibly meet the carbon neutralization goal by the year 2050. There is one thing to be mentioned in the figure is that the new installations in 2020 and 2021 are expected to be low but will dramatically increase after 2025. Specialists from GWEC do not change their scenario of growing in offshore wind market in the post-COVID scenario.

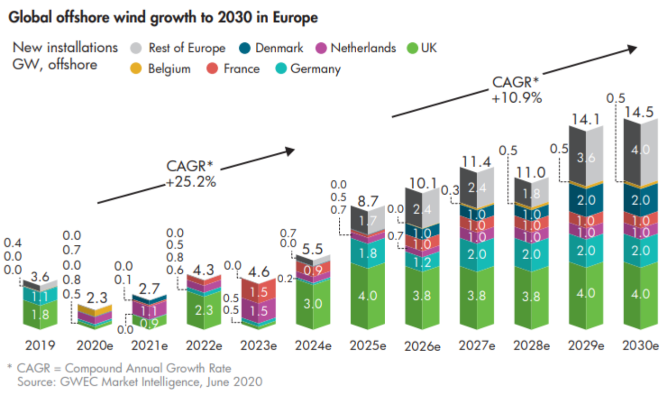


Figure 2.3: Global offshore wind growth to 2030 in Europe(Lee et al., 2020)

- **Asia**
  Asia is expected to become the leader in offshore wind energy prospecting to increase its share in the global offshore wind energy market Lim, 2020. China is currently the biggest investor in the offshore wind market with an extraordinary large market share in the Asian campaigns as shown in Figure 2.4. However, future growth is heavily dependent on the central government's future financial plan. The second-largest and widely recognized offshore wind farm is under construction by the Taiwanese government (Institute, 2021). They are aiming to form their own production line of wind turbine foundations and build their own support fleet to run their offshore wind farm in the future.

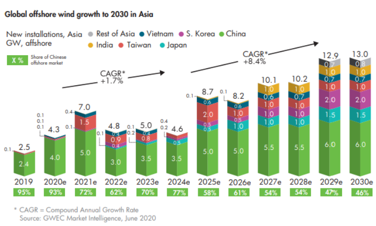


Figure 2.4: New offshore wind installation in Asia (Lim, 2020)

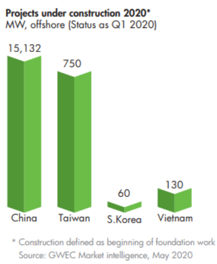


Figure 2.5: Projects under construction 2020 (Lim, 2020)

2

- **North America**(Lim, 2020)
  The offshore wind market in the North American region is a brand new market. The first test offshore wind turbine was erected in 2013, and connected to the grid in December 2016. According to GWEC's report, there will not be any utility-scaled offshore wind far running or constructing before the year 2024. The current prediction is shown in Figure 2.6. The expected 23 GW of offshore wind energy is expected to come from Canada.

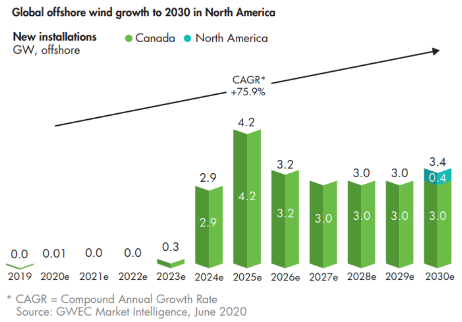


Figure 2.6: Global offshore wind growth to 2030 in North America
(Lee et al., 2020)

After a short introduction to the global offshore wind farm development, the following section will focus on the fleet that provide services for the offshore wind farm.

2.2. OFFSHORE SUPPORT FLEET

Offshore support vessels are namely the vessels built supporting offshore engineering sites. These sites include the traditional drilling platform, FPSO, and the currently developed offshore wind farm construction and operation. The OSV market is subject to fluctuations in charter rates, weather conditions. The high complexity and request for mounting up-to-date technology make the design of OSV a challenge to the naval architects (SNAME, 2003).

A new build offshore wind farm consists of 4 main stages which are: Pre-construction, Construction and installation, Operation and maintenance, and decommissioning. Each stage has its own unique fleet to fulfill the tasks at the current phase. According to the presentation given by the Scottish government in 2014 (Government, 2014), there are at least 17 types of vessels that are needed throughout the wind farm life cycle which are ROV Support vessel, Geotechnical survey vessel, Geophysical survey vessel, Multi-purpose survey vessel, Jack-up barge/vessel, Heavy lift vessel, Construction support vessel, Inter-array cable installation vessel, Export cable installation vessel, Tug boat, Service crew vessel, Diving support vessel, Safety vessel, Multi-purpose project vessel, Tailor-made Operation, and Maintenance vessel, Accommodation vessel and Multi-purpose cargo vessel Figure 2.7 (Government, 2014). The color code illustrated the urgency of new build vessel demand. Vessels marked as demand exceeds supply will be discussed in this section.

Vessel type	Pre-construction	Construction & installation	O&M	Decommissioning
ROV support vessel	●			
Geotechnical survey vessel	●			
Geophysical survey vessel	●			
Multi-purpose survey vessel	●			
Jack-up barge / vessel	●	●	●	●
Heavy lift vessel	●	●		●
Construction support vessel	●	●		●
Inter-array cable installation vessel		●		
Export cable installation vessel		●		
Tugboat	●	●		●
Service crew vessel		●	●	
Diving support vessel		●		
Safety vessel		●		
Multi-purpose project vessel	●	●	●	
Tailor-made O&M vessel			●	
Accommodation vessel		●		
Multi-purpose cargo vessel	Primarily provide the inbound services for wind turbine and BOP tasks			

Figure 2.7: Vessels involved in a wind farm life cycle (remake from OECD WP6 report) (Government, 2014)

2.2.1. Vessel Type

In this section,part of the 16 types of offshore support vessels' functions, and operations are further elaborated.Vessels that shared similar characteristics will be combined by stating the main differences between each other. Firstly, categorized by the main dimensions a table contains of the whole OSV fleet is provided as Figure 2.8.

Small Vessels	Medium Vessels	Large Vessels
OM vessels	Multi-purpose project vessel	Jack up barge/vessel
Service crew vessels	Multi-purpose cargo vessel	Heavy lift vessel
Safety vessels	construction support vessels	
Tug boats	ROV support vessels	
	Diving support vessels	
	Geophysical survey vessel	
	Geotechnical survey vessel	
	Inter-array/Export cable laying vessel	
	Accommodation vessel	

Figure 2.8: Vessels categorized by size remake from OECD WP6 report)(Government, 2014)

Small vessels such as O&M vessels, Service crew vessels, safety vessels, and conventional tug boats are not included in this section for they are considerably smaller than the other vessels. Multi-purpose project vessels and Multi-purpose cargo vessels have similar functions as construction support vessels but are building for different purpose.The former is designed as a transportation vessel, while the later provides specific services as anchor handling or offshore towing operation. ROV support vessels and Diving support vessels have highly overlapped functions thus they will be put under the same category. A diving support vessel nominated as a diving support vessel requires extra facility to support either surface or saturation diving. On the other hand, a ROV support vessel requires ROV support facility and a control station. Accommodation vessels provide services similar to passenger ships. Their mission is to provide a comfortable accommodation for people on the site. Unlike other vessels,these vessel also provides accommodation for visitors and people come to the site for other purpose. These people are categorized as passenger thus these vessels should also comply with the rules made for passenger ships. Since this type of vessel has little connection with other OSV types, it is excluded from the discussion.

Following the sorting OSVs by their dimensions and functions. The next step is to determine the potential OSV products. These vessel should have relatively longer working contract compared with other similar vessels involving in the offshore wind farm life-cycle. In Figure 2.9,medium sized OSVs are marked in red to show the stages they are involved in. The resource for performing design works can be better use in discovering new concepts for each specific offshore operation that are going to be installed on these platforms. The opportunity is that a common modular platform designed for these vessels all at once is possible. the advantage is to reduce the time from investigating different mission requirements to deciding the main specifications of each vessels.

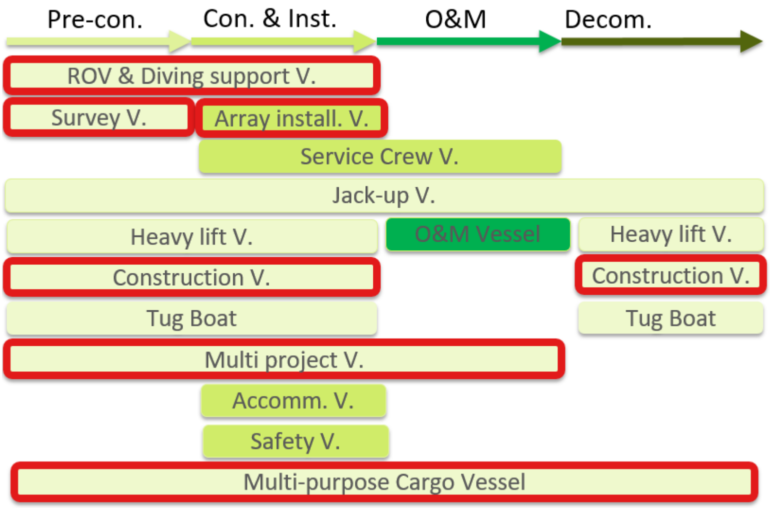


Figure 2.9: Selection of target OSV product remake from OECD WP6 report)(Government, 2014)

Developments of three main regions in the EU, Asia, and North America have been introduced in the previous section. Since the North American region is filled with uncertainties, the main targeted area will be the north sea (EU) and Taiwan(Asia). The former one is chosen while there is a sufficient number of offshore wind farm projects built in the last 30 years, the latter is the largest wind farm project outside the EU region.

The targeted OSV in this research will be able to fulfill the requirement in performing Geophysical/Geotechnical analysis, underwater investigation, piping/cable laying, and platform support service that is able to operate in any offshore wind farm in the future. These vessels represent the different phase in the offshore wind farms' life-cycle. Geophysical/technical analysis and underwater investigation plays an important role in the pre-construction phase. The data acquired from the investigation helps engineers to identify possible hazard to construction vessels that required support from the seabed. The pipe/cable laying represent the phase after the launching the foundations of wind turbines. The network of power cable and pipes need to be placed on the flat seabed and covered by rocks and mud to prevent damage from sea creatures and the current. Finally, the platform support vessel represents the operation and maintenance phase after the construction works. In this phase, technicians and engineers need to travel to each wind turbine to perform maintenance work. This mission can be done on a daily base if the offshore wind farm is built close to the coast line. If longer contract is assigned, the transportation vessels need to provide hotel service to accommodate crews and passenger.

2.2.2. SPECIFICATION

Compared with merchant ships, the size and capacity of OSV are relatively small. Since their missions are basically near the shore, capacity is not the main issue that needs to be taken care of. On the other hand, the ability to operate in heavy weather is the design factor for these vessels. In Figure 2.10 and Figure 2.11shows the relationship of ship length-deadweight and installed power-deadweight. These two diagrams give a glance at how long is an OSV can be. The installed power will mainly decide the size of the engine and further the size of the engine room.

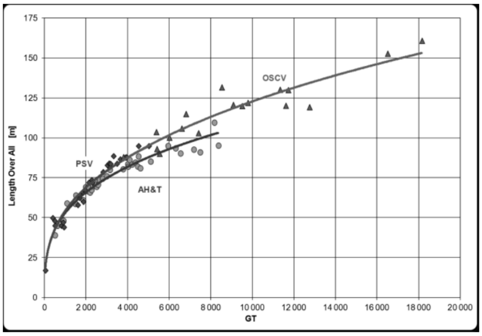


Figure 2.10: OSV vessel Length (Erikstad and Levander, 2012)

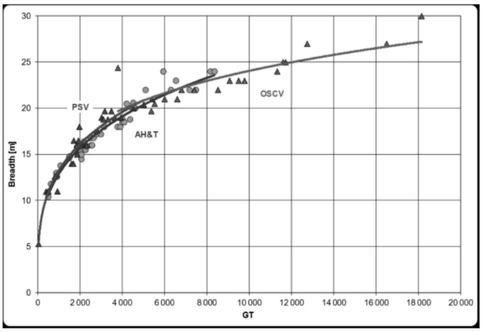


Figure 2.11: OSV vessel Width (Erikstad and Levander, 2012)

In addition to the data given in (Erikstad and Levander, 2012)'s research. Data of 100 OSVs have been individually collected and studied. Vessels' information came from the ship design companies, shipyards and offshore engineering service charters. A list of reference ship list is provided at the end of this subsection. In Figure 2.12 and Figure 2.13 shows the comparison of the vessels recorded in the literature and the reference vessels stored in the database.

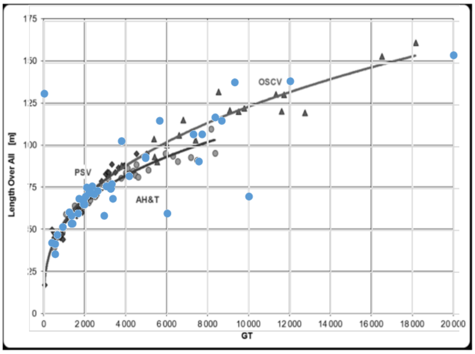


Figure 2.12: OSV vessel Length-GT in the database comparing with the literature

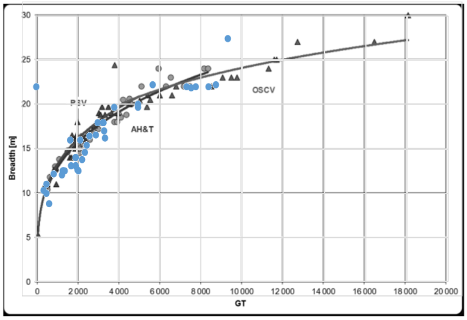


Figure 2.13: OSV vessel Width-GT in the database comparing with the literature

This work is done due to there is no data input from a certain company's product. The result shows that these vessels sharing some similar characteristics in their design and configurations. Most vessels built before 2000 received retrofitting to meet the current offshore wind farm requirements. OSVs built after 2010 have already introduced a new modular concept when designed to keep the flexibility to adapt different operation profiles at different levels. Among all, the Ulstein OSV series (Ulstein, n.d.) and Royal IHC supporter class (van der Harst, 2013) are the most representative projects for they provided a whole series of OSV products with a uniformed bow and stern structure while connected to mission-oriented mid-ship section.

Vessels specifications are analyzed from two main aspects: Ship length and crew size. From the ship length, a similar C_b value can be adapted from similar vessel products for deciding the main dimensions of the vessel. The crew size, on the other hand will decide the area of deck and the required water storage. The former is to be compared with the data provided in Erikstad and Levander, 2012 and the latter is studied in order to validate the safety crew size for the final design of the thesis. The overall length and breadth result is provided in Figure 2.14. It roughly shows a similar trajectory as in (Erikstad and Levander, 2012)'s research. A group of similar ship lengths is located between the length of 75 to 90 meters from Figure 2.14 and Figure 2.10. The breadth is located between 15 to 20 meters, this is also agreed with the result as shown in Figure 2.14 and Figure 2.11. There is a voice of reducing crew size for the new build vessels thus the crew size is expected to change according to the new regulations. The current statistic result is given in Figure 2.15.

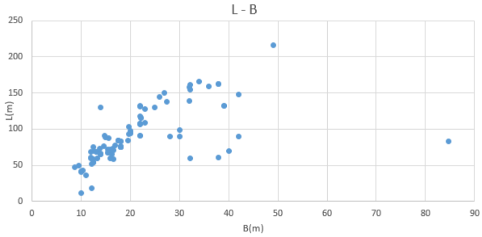


Figure 2.14: Vessels specification L(LOL)-B

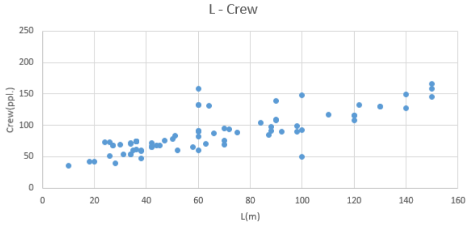


Figure 2.15: Crew size and ship length relationship

2.3. SHIP DESIGN

The term "Ship design" is an oversimplified term to describe the extreme complex works done by a massive group formed by shipowners, classification party, naval architects, structure engineers, mechanical engineers, electronic engineers, and the dry dock staff. The main objective goal is to design a platform that is able to float on the sea and able to provide all the services requested by the shipowner within the regulations. The level of complexity makes ship design so unique in comparison with other industrial products. The preferred final design result is not generating a product that is suitable in all situations but reaching a balanced platform from all aspects (Erikstad and Levander, 2012). In the following subsections, the detail of this design process will be elaborated.

[0]List of reference ships: ("Apollo", 2020; "ARBOL GRANDE", 2020; "BOKA ALPINE", 2020; "BOKA ATLANTIS", 2020; "BOKA DA VINCI", 2020; "BOKA EXPEDITION", 2020; "BOKA PEGASUS", 2020; "BOKA PERSEUS", 2020; "BOKA SHERPA", 2020; "BOKA SUMMIT", 2020; "CONSTRUCTOR", 2020; "DINA STAR", 2020; "EDDA FAUNA", 2020; "EDDA FLORA", 2020; "EDDA FREYA", 2020; "EDT PROTEA", 2020; "EGS VENTUS", 2020; "ESVAGT ALBERT BETZ", 2020; "ESVAGT ALPHA", 2020; "ESVAGT BETA", 2020; "ESVAGT DANA", 2020; "ESVAGT FARADAY", 2020; "ESVAGT FROUDE", 2020; "ESVAGT MERCATOR", 2020; "ESVAGT NJORD", 2020; "FAIRMOUNT GLACIER", 2020; "Flintstone", 2020; "Fugro Brasilis", 2020; "Fugro Discovery", 2020; "Fugro Enterprise", 2020; "Fugro Equator", 2020; "Fugro Equinox", 2020; "Fugro Etive", 2020; "Fugro Frontier", 2020; "Fugro Gauss", 2020; "Fugro Helmert", 2020; "Fugro Mercator", 2020; "Fugro Pioneer", 2020; "Fugro Proteus", 2020; "Fugro Searcher", 2020; "Fugro Supporter", 2020; "Fugro Venturer", 2020; Furgo, 2020a, 2020b, 2020c, 2020d; "GEO ENERGY", 2020; "Goliath", 2020; "GREATSHIP RACHNA", 2020; "HAVILA PHOENIX", 2020; "HORIZON 27", 2020; "HORIZON GEOBAY", 2020; "HORIZON NOMAD", 2020; "HORIZON SURVEYOR", 2020; "IHC OSV T3000-20", 2020; "Innovation", 2020; "Kobi Ruegg", 2020; "KOMMANDOR STUART", 2020; "Living Stone", 2020; "MAERSK CONNECTOR", 2020; "MAERSK FORZA", 2020; "NDEAVOR", 2020; "NDURANCE", 2020; "Neptune", 2020; "NORMAND JARSTEIN", 2020; "NORMAND OCEAN", 2020; "Omalius", 2020; "Orion", 2020; "POLAR ONYX", 2020; "PRINCESS", 2020; "QUEST HORIZON", 2020; "R.V. BOLD EXPLORER", 2020; "R.V. EGS SURVEYOR", 2020; "R.V. GEO RESOLUTION", 2020; "R.V. RIDLEY THOMAS", 2020; "R.V. RIDLEY THOMAS", 2020; "ROCKPIPER", 2020; "Rollingstone", 2020; "SAPPHIRE", 2020; "SEAHORSE", 2020; "SEVEN ATLANTIC", 2020; "SMIT KAMARA", 2020; "SOVEREIGN", 2020; "SPIRIT", 2020; "ST-266 OCV", 2020; "ST-268 OCV", 2020; "TERRA-SURF", 2020; "Toisa Pegasus", 2020; "UNION LYNX", 2020; "VOLANTIS", 2020; "Well Enhancer", 2020)

2

2.3.1. DESIGN PHASES

Similar to every industrial product, ship product also has its own product life cycle: introduction, growth, maturity, and decline. The design works basically take place in the introduction stage in the whole life-cycle. Though launching in the very early stage, it has the greatest impact over the whole product life cycle for the result will determine the market and performance of the vessel. The design process can be subdivided into two main groups (Gale, 2003): basic design and product engineering. Basic design can be further divided into four phases which are: **Concept design, Preliminary design, Contract design** and **Functional design**. Product design can be subdivided into two phases: **Transition design** and **workstation/zone information preparation**. Along with the processing of design work, details are adding accordingly to the design as shown in Figure 2.16. The increase in details has implications of the relationships between the committed cost, the design freedom, and the problem knowledge. The increase in details indicates that designers have more confidence in the design problem and are able to make more precise decisions to tune the design work. Though it seems that designers have more control over the problem but the interrelated design factors have limited the availability for each change being made. Design decisions focus on one aspect that will change not only the target but the whole project. It acts as a distribution of resources that increasing in one object will decrease the share of the others. On the other hand, the committed cost is locked in early in the design process before all the required information is available. The development of these three factors in The The design process is shown in Figure 2.17. Design process can be improved from three aspects: Delay committed costs, keep design freedom later in the design process, and reduce the time to gain problem knowledge (Kana, 2019a).

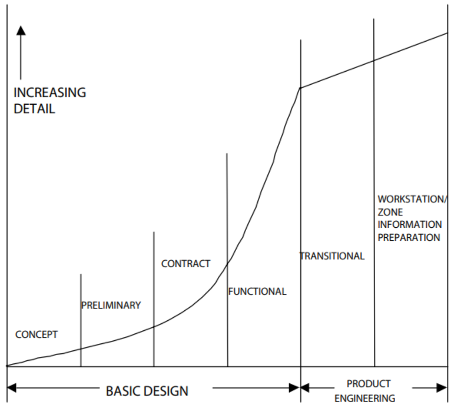


Figure 2.16: Design Phases

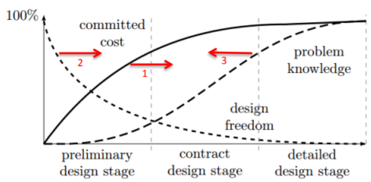


Figure 2.17: Relationship between design freedom committed cost and problem knowledge

2.3.2. CLASSIC DESIGN METHODOLOGY

In this section, how ship design work is processing will be elaborated. In 1959, Ervan introduced the "design spiral" (EVANS, 1959) to illustrate the iterative ship design works. Each spike in Figure 2.18 indicates the check points in the evolution of ship design process. Generally speaking, the design spiral is a "design-evaluate-redesign" structured methodology. Each design starts from knowing the requirements, generate a design, evaluate from different aspects and make the decision whether the design is accepted. It provides ship designers a structured method to design a ship but has implicit extra effort in iterative and repetitive works.

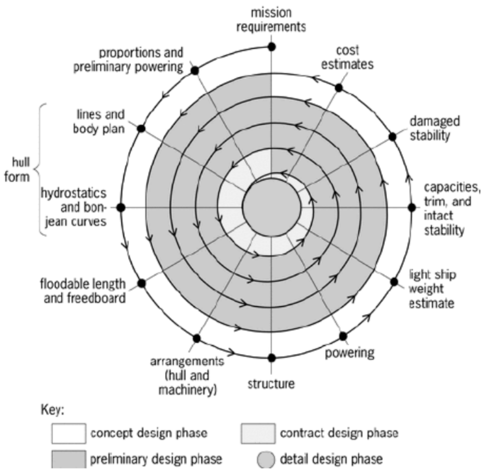


Figure 2.18: Design Spiral (EVANS, 1959)

2.3.3. SYSTEM BASED SHIP DESIGN (SBSD)

The design spiral is a mature and widely adapted methodology though nowadays it seems to lock the way naval architects approach the ship design. Kai levander introduced an innovative ship design methodology in 1991, the "System Based Ship Design (SBSD)" method (Levander, 2009). In the following 20 years, this design method has been successfully applied in the development of a large number of ship designs to prove that the original design spiral has the potential to be improved. Adapting the successful experiences in cargo ship design, it has been introduced to the design of OSVs around 2012 to show the capability of designing complex function vessels (Erikstad and Levander, 2012). Instead of initiating the ship design process from the main dimensions and performances, SBSD put more emphasis on the decomposition of mission requirements and the corresponded ship functions. In Figure 2.19, the mission requirement and corresponded ship performance are separated from the design spiral to form an independent information processing stage. This change to the design methodology makes the spiral become a "define systems and functions – estimate size and weight- select dimensions –check performance" structure. Systems, requirements and functions are transformed into simple and organized algorithms which enable automatic calculations processing by computers. Products become a collection of previous designed cases from different departments. The advantage is to rpevent designers continuously mining new information from the requirements in order to run the design spiral several times until a converged result appear. At the same time, they are able to invest more time in exploring innovative solutions (Levander, 2009).

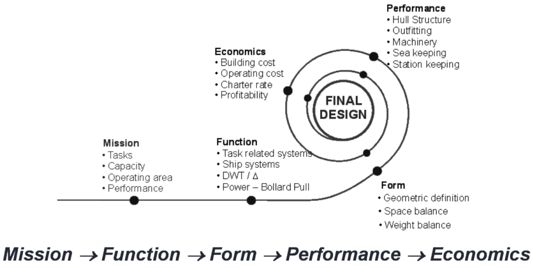


Figure 2.19: Refined Design Spiral (Erikstad and Levander, 2012)

2.3.4. CONCLUSION OF THE SHIP DESIGN PROCESS

In this section, two different approach of ship design are discussed. The SBSD method gives designer a different way to process the project initiated by investigating requirements and systems. In Levander's (Levander, 2009 article, it has developed the requirements further into formulated forms for future designers to follow. It has simplified the complicated design work by bringing ship designers closer to their clients by knowing clients' requirements in a standardized and formulated way. The missing piece for the design methodology is that the whole design remains as a package of data before visualized in a CAD software. Since the information is stored by vessel, ship designers need to repeat the designing process from the draft and hard to utilize the previous design experience in the latest design. A suggested solution is to decompose the vessel system into smaller package that is able to be accessed by different design department. Packages are assembled at the end of the design process to form the final product. This process of system decomposition and capitulation is a form of modularization.

2.4. MODULARITY AND MODULARIZATION

Modularity or modular design is already widely applied in computer science field before introduced to the industrial world. It is aimed to increase the competitiveness of products by bridging the advantages of standardization and rationalization with customization and flexibility (Thomas D. Miller, 1998). An over simplified definition is to break a large and complex system into several small but self-sufficient parts. In this section, the definition and application of modules, modularity and modularization will be discussed.

2.4.1. DEFINITIONS OF MODULE, MODULARITY AND MODULARIZATION

To make the topic explicit, definitions of the three terms given by Miller in 1998 are (Thomas D. Miller, 1998):

1. **Module :** an essential and self-contained functional unit relative to the product of which it is part. The module has, relative to a system definition, standardized interfaces an interactions that allow composition of products by combination.
2. **Modularity :** an attribute of a system related to structure and functionality. A modular structure is a structure consisting of self-contained, functional units (modules) with standardized interfaces and interactions in accordance with a system definition. Replacing one module with another creates a new variant of the product.
3. **Modularization :** the activity in which the structuring in modules takes place.

There are differences between "a module" and "a block". The most obvious one is that a module contains of a considerable amount of function while a block is a simple element in the whole system. Take bricks as an example, a single brick is not a module for a brick-built kitchen. But a kitchen built of bricks is a module in a "house" system.

2.4.2. ADVANTAGES OF MODULARIZATION

In this section, reasons for going modularization suggested by Miller (Thomas D. Miller, 1998) are provided as following :

1. Reduce complexity:
   - Break complex system into small and relative simple units.
   - Enable parallel work
   - Test seperately
   - Encapsulation structures makes human easy to understand and manipulate.
2. Utilize similarities
   - Avoid repetitive or simple works-dont go through the whole ship design process if a new jacuzzi is added to the design.
   - Working faster and better by learning effects and supporting tools.
   - Reduce risks by using well-known solutions.
   - Reducing internal variety
3. Create variety
   - Provide useful external variety.

Recall the three main objectives in subsection 2.3.1, modularization seems to give feasible solutions for each improving direction. The utilization of similarities accelerates the gaining of problem knowledge by investigating similar requirement from previous designs. It is also possible to delay the committed cost for the cost of each modules has been saved in the database in order to give a better estimation of the price. The reduction of complexity enables designers to focus on their own profession knowing that the decision they made within a single module will not affect the whole project thus the design freedom is enlarged.

2.4.3. MODULES AND FUNCTIONALITY

In subsection 2.3.3, the first two stages in ship design is to recognize the requirements and to connect them to corresponded systems. Each system provides task functions to meet a certain or multiple requirements. According to the definition given by Pahl & Beitz (Pahl et al., 2007), the modules can play as the carrier of a range of functions(basic, auxiliary, special, adaptive). In the book, modules are described as a physical representation of functions. One thing to be mentioned here is that an independent category is created to adapt elements that can not go into the modular system. In this research, the definition of basic modules and special modules are adapted and treated as main function carrier. The basic modules form the main platform system while the special modules perform certain task according to the operations.

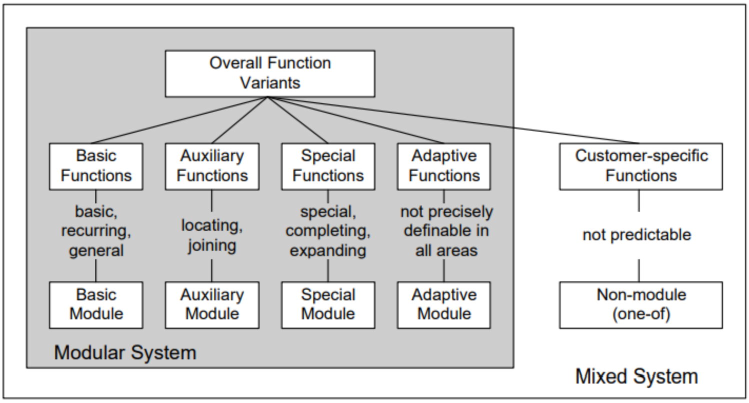


Figure 2.20: Function types and module types in modular and mixed product systems

2.4.4. PRODUCT ARCHITECTURE

The categorization of modules is explained in Pahl & Beitz book but the rules to assemble modules to form a product is not provided. The "Product architect" is an algorithm to organize the interaction and connection between modules. Product architecture, or more specific term "modular architecture" is the core of this section. In definition, modular architecture has two main components according to Ulrich (K. T. Ulrich, 2008):

- Chunks implement one or a few functional elements in their entity.
- Interactions between chunks are well defined and are generally fundamental to the primary functions of the product.

According to Ulreich (K. T. Ulrich, 2008), there are three different modularity types: slot modularity , bus modularity, and sectional modularity. The category is later being extended in order to access a specific type of modularity. In this research, the modularity types mentioned in Smit's (de Roo, 2019) and Elgard's research (Elgård and Miller, 1998) are adapted:

- **Sectional Modularity :** Any number and combination of different types of modules can be configured in an arbitrary way as long as they are connected at their interfaces. e.g. Systems Furniture
- **Bus Modularity :** a basic module can be matched with any number and combination of components from a set of component types. Attention, there is an critical distinction between the bus modularity and the later discussed component sharing/swapping modularity that bus modularity allows different number of variants at different location while the others only host certain type of varients at designed location with defined connection. e.g. USB expansion
- **Slot Modularity :**
  - **Combinatorial modularity :** Each module in combinatorial modularity has its own slots and can be connected to other modules that have the same type of slot.
  - **Component-swapping modularity :** two or more alternative types of a modules can be paired with the same basic module creating different product variants belonging to the same product family. e.g. laptops with different types of usb hub.
  - **Component-sharing modularity :** The same module is used in the entire product family or even across different product families. e.g. mobile phone chargers
- **Cut-to-fit:** Product variants are obtained by changing a continuously variable feature within a given component (K. Ulrich, 1991).
- **Mix Modularity :** Mixing together independent constituents into a final blend. e.g. a mixture of paint like the coating system in the ballast tank

The formats of different modularity are displayed in Figure 2.21. Ship building is possible to apply the Cut-to-fit modularity backed up by Ulrich (K. Ulrich, 1991). The proposed solution was scaling the Ship's mid-section without changing the shape in stern and bow section. This solution is adapted in some ship designs, for example the midship section in Figure 2.22

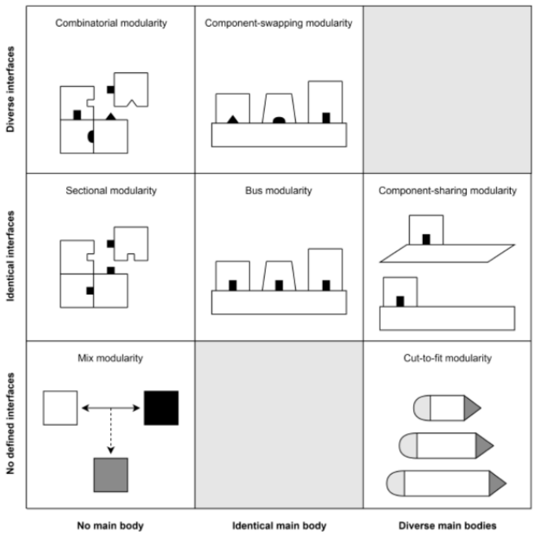


Figure 2.21: Illustration of Interface Types (de Roo, 2019)

2.4.5. PRODUCT PLATFORM

The product platform is the foundation for the development of product families.

"A product platform is a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced"– Meyer & Lehnerd

Products platforms can be built from two different architectural approach: **integral-** and **modular-approach**. Fuch & Golenhofen gives the definition and the differences of the two approaches (Fuchs and Golenhofen, 2019) as shown in Table 2.1. From the aspect of designing a modular platform, there is no certain right or wrong in designing a modular platform using either of them (Fuchs and Golenhofen, 2019).

With the two approaches, Fuch & Golenhofen are able to derive three typical platform types (Fuchs and Golenhofen, 2019) :

1. **Modular Platforms :**Enabling product differentiation through adding, removing and substituting different modules or building blocks.Modules that are identical to the entire product family are considered to be core platform modules (Thomas D. Miller, 1998).For example, a safety module is mandatory for a modular vessel. There are different types of safety module provide the safety function. Thus, the modular vessel is a modular platform for safety modules.

2. **Scalable Platforms :**Variants of a product can be produced through shrinkage or extension of scalable variables, such as airplanes and gas turbines etc.

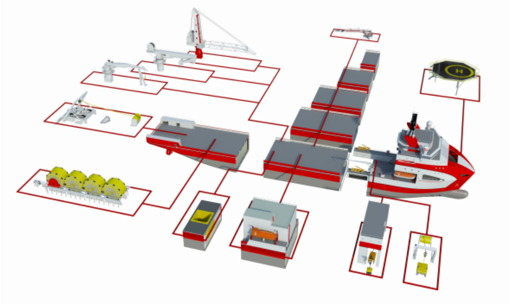


Figure 2.22: IHC supporter class, the mid hull section is an example of Ulrich's idea of cut-to-fit modularity

Table 2.1: Key differences between integral and modular architectures

	Integral architectures	Modular architectures
Performance	Can be trimmed for higher/highest performance (e.g. size, weight)	Typically compromises on performance (e.g. over-sizing)
Product definition	Complex mapping from functional elements to physical elements And/or interfaces between elements are coupled Interfaces poorly defined	Each physical elements implements one or a few functional elements in their entirety Interfaces between elements are not coupled Requires clear definition of interfaces
Product change	Any change in functionality impacts several elements Hard to change	Any change in functionality impacts only the element that carries the function High flexibility
Lifecycle	Integral architecture are typically in eras of a completely new technology development	Modular architectures are typically superior if technologies overshoot mainstream customer requirements
Organization	Tightly coupled development teams	Decoupled, independent development teams that work in parallel
Product variety	Effective for singular products and not effective for product families	Effective for product families and not effective for singular products

3. **Technology Platforms :**A certain technology which builds a base for products, other technologies or processes. For example, the unique Gortex technology is a given in all Gortex shoes

In the reality, products/systems are a mixture of different platform types, modules and building blocks. Especially for a complex and large scale product as a ship. Fujimoto (Fujimoto, 2013) performed a research to find the feasibility of applying modularity in ship industry. In the research, modules are put into two groups by their architectural approach : "Macro architecture" for representing modular architecture and "Micro architecture" for integral architecture in designing of complex vessels.

"Macro architecture" indicates that the components under this category can be directly reused in future design. "Micro architecture" represents a collection of subsystems without defined main platform but with defined interfaces to connect each other such as pieces in piping and wiring system. In Figure 2.23 shows the application of macro- and micro-architecture at different level in a modular ship suggested by Fujimoto.

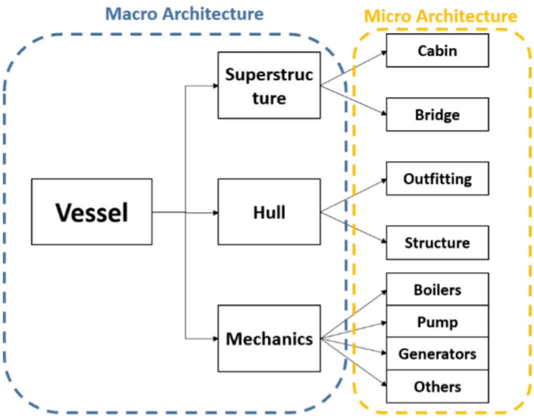


Figure 2.23: Macro and micro architecture in ship modules. (Fujimoto, 2013)

2.4.6. OFFSHORE SUPPORT VESSEL MODULARIZATION

From the previous sections, elements to form a modular product are discussed namely "platform", "modules" and "building block". As mentioned in chapter 1, one critical problem for a fully customized offshore support vessel is that they are mostly one-off product and thus difficult to go into mass production strategy. One of the modularization advantage is reducing complexity and utilizing similarities. It increases the flexibility in designing products to achieve efficiency in cost and mutability in operation.

The investment flexibility is addressed by Abbott et al. (J. et al., 2003) as "evolutionary acquisition". It is an investment strategy that allows investors to delay the decision in waiting for more available information. In Figure 2.24 shows the difference between the proposed evolutionary acquisition and the conventional ship acquisition. With the proposed evolutionary acquisition strategy, committed cost can be distributed over the lifetime of the vessel. The mutability in operation is an ability to switch between different mission. It enables a single platform to perform different operations with corresponding equipment as illustrate in Figure 2.25.

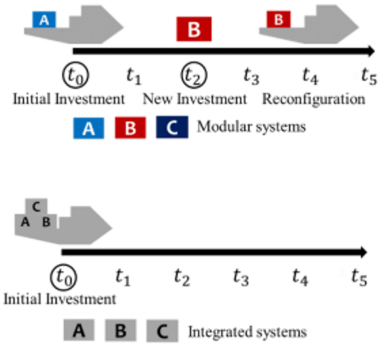


Figure 2.24: Different investment strategy (top) Evolutionary acquisition (bottom) Conventional ship acquisition (Choi, 2018)

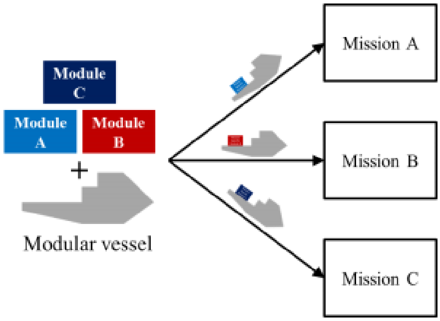


Figure 2.25: Mission flexibility by modularity. (Choi, 2018)

With the mutability in operation, the whole vessel can be divided into two different parts: "ship module" and "task related module" suggested by Erikstad and Levander (Erikstad and Levander, 2012).This setup enables the configure-to-order (CTO) strategy developed by choi (Choi et al., 2018) in ship design. CTO is a bottom-up design approach in prototyping new designs by configuring modules predeveloped and stored in the database. The most obvious advantage is the availability to perform fast and accurate modeling result thus to reduce the development time and cost (Choi et al., 2018). A schematic flowchart to explain CTO strategy is provided in Figure 2.26.

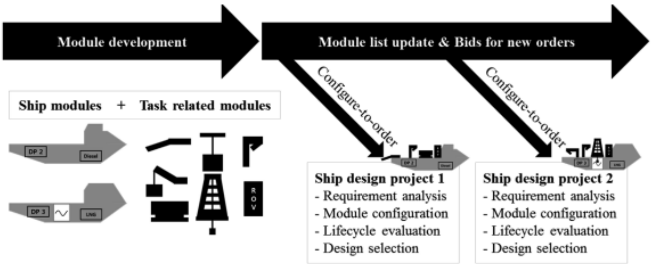


Figure 2.26: Configure-to-order strategy for Ship design (Choi et al., 2018)

Compared with the modularized equipment development, the modular platform development received less attention. In Erikstad and Levander's publication (Erikstad and Levander, 2012), it mentioned that standard ship modules comprises main hull, deckhouse, bridge, and tanks and voids. These modules are designed and reconfigured to provide basic ship functions as buoyancy, transition, storage, and accommodation. The latest literature related to designing basic ship modules found during the literature review is published in 2018. In this research, the proposed method in developing modules for platform is based on the function structure ,as shown in Figure 2.27, developed in SBSD of OSVs (Erikstad and Levander, 2012).

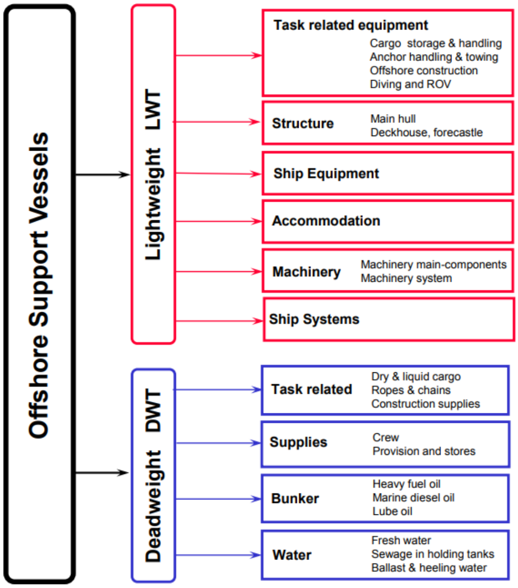


Figure 2.27: Function structure for OSVs (Erikstad and Levander, 2012)

A short conclusion of this subsection is illustrated in Figure 2.28. The vessel products is a modular platform consists of ship modules and task related modules. Ship modules are entities formed by functional modules such as hull modules and superstructure modules. Hull modules can be subdivided into a collection of smaller and more basic components as frames and plates. The ship modules and task-related modules are suitable for applying modular architecture, while the piping and bracket pieces are elements for integral architecture.

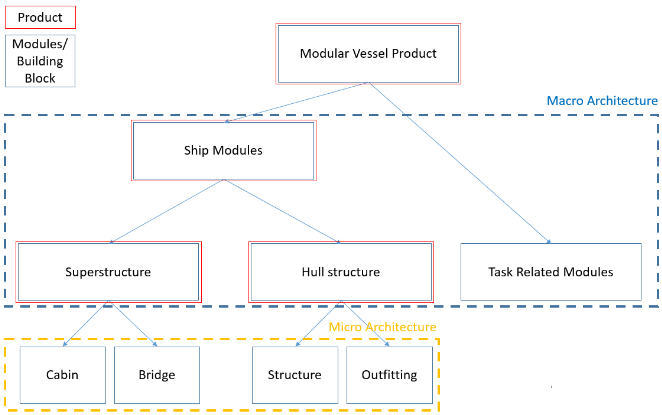


Figure 2.28: Modular Vessel building strategy (This is an example for illustrating the relationships between different level of modular products and modules)

2.4.7. MODULES AS CARRIERS OF KNOWLEDGE

The modularization process in the industrial field can be briefly described as an reuse of engineering resource. While the same mode is also applicable in the digital world, instead of the physical engineering pieces, the reuse of engineering specification in the early stage can also be treated as a type of "modularity". This approach has broken the boundary between the "knowledge management" and "traditional modularization" (Sanchez and Mahoney, 1996).

When modularity goes digital, the concept can also applied to the early product design work (Alexander, 1964). There are two ways for this approach according to Thomas' research (Thomas D. Miller, 1998). The first approach is that the engineering specification can be treated as products that are generated by the regulations and standard from external resources. The external resources are translated into reusable "module" with self-contained functional units. This is the process for companies to form their own standard in the factory. The whole process takes place within the circle in Figure 2.29. The second approach is that engineering specification, regulations ,previous CAD-drawing and the way to assemble these modules together can be seen as knowledge modules in the preliminary design stage as the whole process in Figure 2.29. The later approach is mainly adapted in this research.

Anderson & Pine have foreseen the benefit for using functional units carrying knowledge in 1997 (Anderson and Pine, 1997). They create a term "virtual modules" to link the product development and mass customization. Since ship design in the preliminary stage is a product of a combination of engineering specification, classification societies' regulation and industrial design methodology, the concept of treating modularity as a knowledge carrier will lead to the next topic "Knowledge Based Engineering".

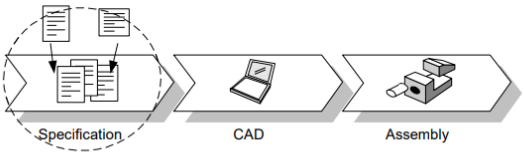


Figure 2.29: Modular application in knowledge management (Thomas D. Miller, 1998)

2.5. KNOWLEDGE BASED ENGINEERING

Knowledge Based Engineering (KBE) is a branch of knowledge based system (KBS) developed in the artificial intelligence (AI) field dated back to 1970's. It is designed to solve multidisciplinary problems by rule based reasoning process then perform the output in a computer assist design (CAD) software. It is able to capture, structure and record knowledge of a complex system to make it reusable, transferable and expandable in order to reduce time and costs for engineering design by automating repetitive design tasks (Cooper, Fan, et al., 2001). It acts as a merger of artificial intelligence and CAD software as illustrated in Figure 2.31.

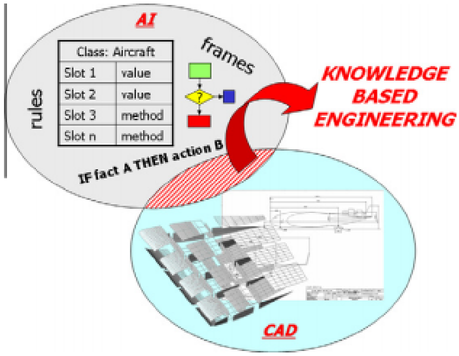


Figure 2.30: KBE systems: computer programs containing knowledge and reasoning mechanisms augmented by geometry handling capabilities to provide engineering design solutions (Rocca, 2012)

In this research, a framework to show that preliminary design of a product family of OSV is feasibly to apply KBE will be developed by adapting the KBE product model development suggested by Cooper et al. (Cooper, Fan, et al., 2001) in Figure 2.31. The input values are a set of parameters used in the product model. KBE system uses the stored rules to process the input value. Finally, a engineering design is generated. The whole process is aim to minimize the human intervention.

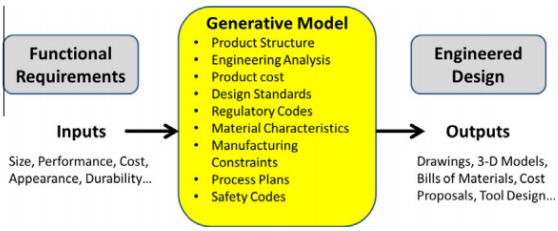


Figure 2.31: The product model of a KBE application takes input specifications, applies relevant rules and produces automatically an engineered design. (Cooper, Fan, et al., 2001)

In the aerospace industry, KBE product tool has been widely applied in aircraft design known as the Design and Engineering Engine (DEE) with an additional analysis and optimization process. A schematic diagram of DEE is provided in Figure 2.32.Requirements from the customers are transformed into the design parameter that can be accepted by the system to initiate the model design in the multi model generator (MMG). MMG is constructed via Object Oriented Programming (OOP) which enable the system to achieve different airplane configurations as shown in Figure 2.33. Data to process further analysis in terms of structural strength, aerodynamic performance and manufacturing cost are extracted from the output model. The analytical results will be the input of the optimization and qualification process until a converged design is generated which fulfilled all the requirements.

In this research, the objective is to develop a MMG for developing OSV products which is never performed before.The proposed programming environment is the grasshopper tool combined with IronPython which will be further discussed in chapter 5. The new MMG is expected to:

- generate different OSV configurations with self defined HLPs
- generate different working deck configurations according to different operations
- display feasible hydrostatic performances

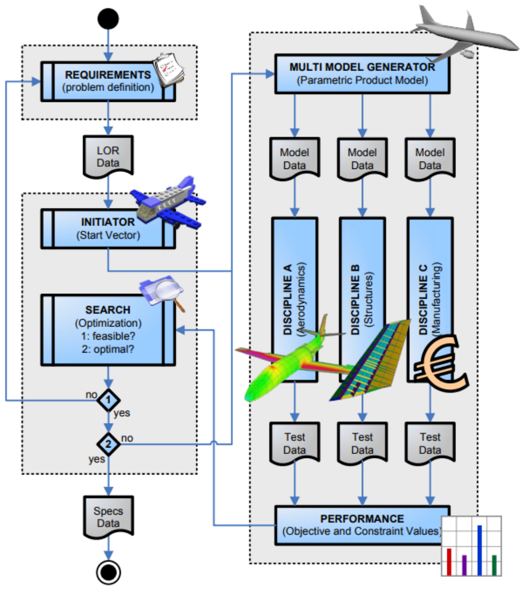


Figure 2.32: A Design Engineering Engine (adapted from (Schut and van Tooren., 2008)

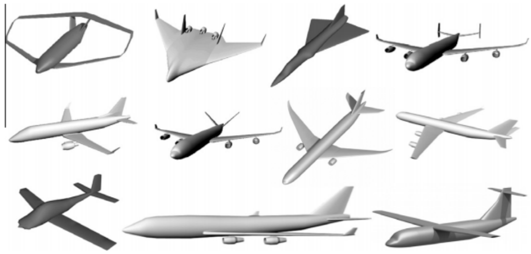


Figure 2.33: Examples of different aircraft configurations and variants, all generated as different instantiations of the same product model (Rocca, 2011)

2.6. PARAMETRIC MULTI-MODULAR-SHIP-MODEL GENERATOR

In the preivous section, the MMG pieces together different "LEGO-like" blocks to create different aircraft configurations as shown in Figure 2.33. These blocks are called High Level Primitives (HLPs) by La Rocca (Rocca, 2011). In his MMG, four types of HLP were defined as shown in Figure 2.34.

HLPs capture a certain set of engineering knowledge. For instance, a wing trunk HLP can be used to generate a (piece of) aircraft wing,vertical tail or aileron if assigned as an type of lifting surface. Further more, if a wing trunk is assigned to be lifting surface and fuselage , two very different instantiations of the same wing trunk HLP can be generated as shown in Figure 2.34.

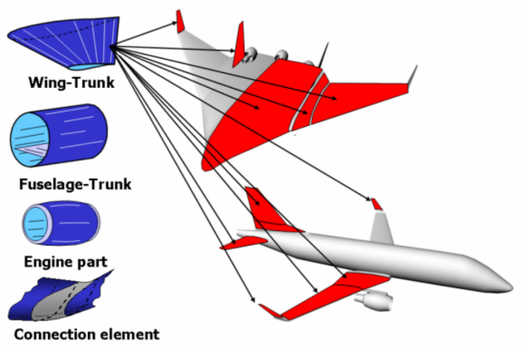


Figure 2.34: HLPs in La Roca's aircraft MMG (Rocca, 2012)

The development of MMG will adapt the suggested steps developed by (Koning, 2010) due to the similarity in creating a new MMG. The difference is that there is no desinged analysis tool to be integrated with, thus the format of the output model is a 3DM file for Rhinoceros software.

2.6.1. PARAMETRIC SHIP MODELING

In this section, a design concept of the Parametric Multi-Modular-OSV-Model Generator will be elaborated. The research will demonstrate two different types of KBE applications : parametric model generation and layout generation. The parametric generation will define the main hull shape of the vessel and later used as an boundary box for the layout generation. The layout generator will be performed in two different level: modular section and working deck layout.

- **Hull Section object geometry requirements**
  Modular platform and task-related equipment are the two main parts to form each OSV in this research. Recall the modular vessel building strategy in Figure 2.28 and the SFI system. The modular vessel platform can be subdivided into two groups, the hull that provides the buoyancy and the system that provide the functions. The hull structure is a type of float structure in a general way and can be further described as the three parts that makes a vessel: Fore hull, Mid hull and Aft hull. Different hull structure are listed in Figure 2.35. One thing to be mentioned in Figure 2.35 is the children categories under mid hull is not distinguishable from the appearance but from the functions and the inner structures. The MMG in an ideal case should provide the availability to generate models includes all of these types.

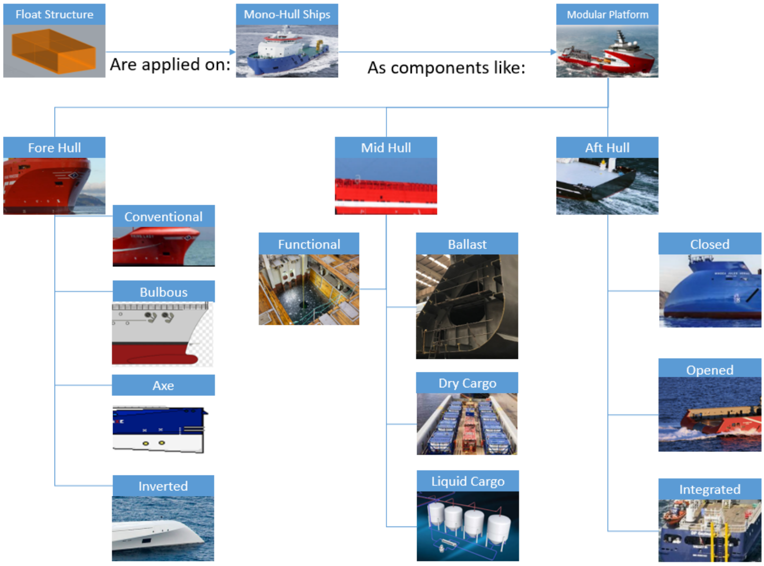


Figure 2.35: Types of floating structure configurations

- **Super Structure object geometry requirements** Super Structure is a movable elements limited by the main deck outline. It is expected to not only represent forecastle and aftercastle types but also floating superstructure types as shown in Figure 2.36. This elements is shaped by the deck out line and further defined the working deck constraint boundary.

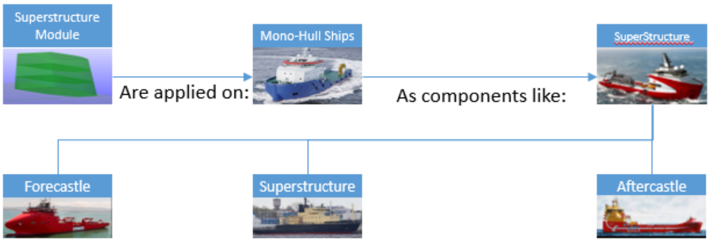


Figure 2.36: Types of Superstructure configurations

- **Task Related equipment and Module equipment layout object geometry requirements** Task related equipment layout and modular section layout are categorized similar as the factory layout.

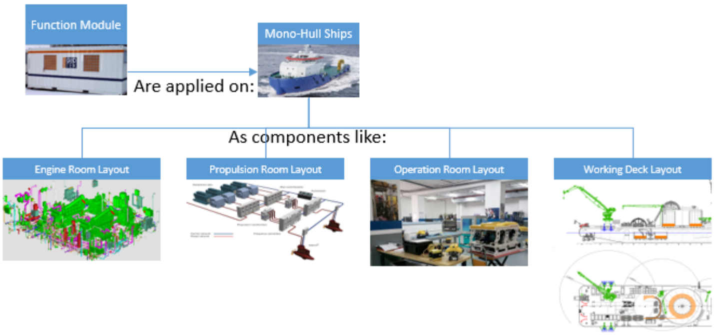


Figure 2.37: Types of layout configurations

- **Additions to basic parts** The additional parts consider physical interfaces between products and platforms. Interfaces are connection between part/part, part/system, and system/system. The part/part connection takes place to bring two or more sections in the modular form together to form an entity. It works like a seam between large ship blocks or a water tight bulkhead. Part/System interface are designed within a section like a diving support room layout with an moonpool open on the main deck. System/system connection happens at the working deck plane to integrate the modular ship platform and the task related equipment layout. These connections are physical joint for individual smaller products to form a final product.

2.7. PRODUCT PLATFORM DESIGN

The division of ship modules and task-related modules subsection 2.4.6enables the modular platform to be improved separately. Though it seems to be simple to combine the two main modules by intuitively installing the task-related modules on the working deck, it does not promise a suitable or feasible design. As mentioned in the section 2.3 a satisfied ship design is a balanced result from all aspects. Product platform optimization is an example suggested by the experience in manufacturing industries. This direction of optimization is introduced in seeking for the reduction in manufacturing cost and design leading time (Olivier L. de Weck and Chang, 2004). The latest and most adapted development in this optimization is the two-level (sometimes indicate as two-stage) optimization methodology. The methodology divided the product platform literally into two stages: the first stage involves individually optimizing each product, the second stage optimizing the product family with constraints on performance losses due to commonality (SIMPSON, 2004). The overview of a product platform strategy is shown in Figure 2.38. The first stage of optimization is to optimize the platform family (the pink circle at the center). The second stage is to optimize the products on the branch with the limitation carried from the optimized platform.

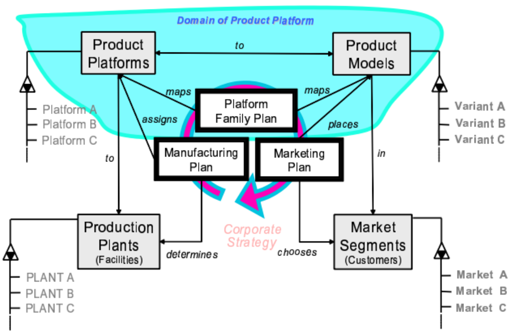


Figure 2.38: Overview of corporate product platform strategy (Olivier L. de Weck and Chang, 2004)

3

Part I: Modularity Application

Modules and building blocks are the basis of modular platforms. With the contained rules, modules and blocks are positioned and scaled thus to generate a product family. This chapter will focus on how to identify a system's functions and related attributes for defining modules and building blocks in a modular platform. System Based Ship Design (SBSD) and Quality, Function, Deployment (QFD) methodology are the main tools for developing this chapter.

These main groups consist of several sub-components that can be followed to describe the whole system. SFI code will be considered as the main categorization system for the following sections.

3.1. Reference Study

A set of mission requirements for designing various OSV modular products in an OSV product family is essential to initiate the design process. In this section, several vessels' parameters, mission statements, and features will be investigated. Each vessel type will be expressed in three parts: a definition from the classification rules, a reference ship with distinguishable equipment, and chances for modular systems.

3.1.1. Reference Vessels

In subsection 2.2.1 mentioned that an offshore support fleet covering the whole offshore wind farm life cycle consists of the following vessels: Geographical/Geotechnical Survey Vessel, Diving support Vessel, Cable laying Vessel, Construction Support Vessel, and Multi-purpose project/cargo vessel. There will be at least one vessel related to each ship type in each category in order to collect sufficient information for the design work. A list of vessels being investigated in this section is provided in Table 3.1

Table 3.1: Reference Vessels

Type	Vessel	Year(new/re)	Class	L	B	D	Draft	DWT	GT	speed	Power	Propulsor	Propulsor	Bow Thruster	F.O.T	F.W.T	B.W.T	Crew	Main systems	General System
				m	m	m	m	T (weight)	T (volumic)	knot	kW	set	type	set	m^3	m^3	m^3	person		
GSV	Fugro Gauss	1980	DNV-GL	68.87	13.09	-	5.2	-	1684	12	3900	1	FPP	1	279	99		30	1.Echo sounder 2.Multibeam 3.echo sounder 4.side scan sonar 5.Sub-bottom profiler	1. Crane 2. A-frame stern 3. A-frame side
GSV	Fugro Synergy	2009	DNV-GL	103.7	19.7	15	6.5	3775	6593	12	2188	2	Azimuth	2	1357	1399	2560	84	1. Drilling derrick 2. Mud tanks (220 m^3) 3. MoonPool 7.5*7.5	1. Crane 2. Crane stern
DSV	BOKA DA VINCI	2011	DNV-GL	115.4	22.2	9	7	5662	8691	13	11290	2	Azimuth	2	1440	1160	5122	120	1. Saturation equipment 2. Gas Storage 3. Air Diving 4. MoonPools (2 x 3.9 x 3.9)	1. Crane(STB)
CSV	BOKA SHERPA	2007	LR	75.05	18	8	6.8	3568	3239	17	12000	2	CPP	1	539	216	-	36	1. Towing Winches 2. Shark jaw 3. Tow pins 4.Gypsy Wheels	1.Crane
CSV	SOVEREIGN	2003	BV	67.4	15.5	7.5	6.2	-	2263	17	24000	2	CPP	2	1482	420	-	27	1. Towing Winches 2. Shark jaw 3. Tow pins 4. Stern Roller 5. Gypsy Wheels	1.Crane
CLV	Nexus	2014	DNV-GL	122.68	27.45	-	5.82	7015	-	12.4	4200	2	Azimuth	2	1511	180	-	90	1. Cable carrousel (D=26) 2.Tensioner	1. Crane
CLV	NDURANCE	2013	LR	99	30	-	4.8	12287	7417	11.5	7500	4	Azimuth	1	-	-	-	98	1. Cable carrousel (D=26) 2.Tensioner	1. Crane
PSV	Bibby WaveMaster1	2017	DNV-GL	89.65	20	8	4.8	2260	-	13	4300	2	Azimuth	2	890	610	1130	90	1. W2W 2. Winch	1. Crane

GEOGRAPHICAL/GEOTECHNICAL SURVEY VESSEL

A geophysical/geotechnical survey vessel will be deployed in the fieldwork before each offshore construction. Adapting the DNV-GL's definition of seismographic research vessels, these vessels are designed for seismographic research operations with a particular focus on the robust design of the seismic equipment hangar, the ability to maintain propulsion power, and vessel maneuverability through adapted bridge design and navigation systems ("RULES FOR CLASSIFICATION Ships Part 5 Ship typesChapter 10 Vessels for special operations", 2020). Their mission is to gather seabed information, hydrographic and oceanographic surveillance, sampling, and analyzing seabed composition. The purpose is to achieve the derisking and cost-effective design of general marine structures and subsea installations. Authentic missions adapting from commercial geographical/geophysical survey companies ("FUGRO GEOPHYSICAL SURVEY", 2015) related to offshore wind farms are *Site \ Route surveys:* to identify, assessed, and mitigate obstructions and potential operational hazards; *Cable Route Surveys* to plan the power network laid on the seafloor including an internal connection between wind turbines and the export of electricity to the shore or offshore transmission station; *Hydrography* to achieve accurate water body information; *Environmental Surveys* to minimize the impact on the local sea creatures' inhabitants. An example of a geophysical survey vessel and an example of a Geotechnical survey vessel are shown in Figure 3.1

(a) Geographical Survey Vessel - M.V. FUGRO GAUSS

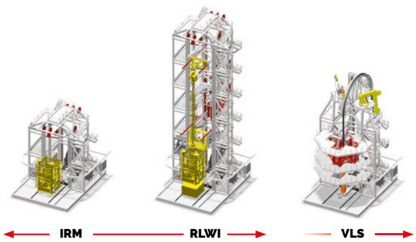
(b) Geotechnical Survey Vessel - SYNERGY

Figure 3.1: Geophysical/Geotechnical Survey Vessel ("M.V. FUGRO GAUSS", 2017, "FUGRO SYNERGY", 2020)

Two vessels from a Geophysical/Geotechnical analysis service company are chosen to be the reference of this research vessel type. Common functions provided by both vessels are Echo sounder, Side scanners, drilling/grabbing facilities, seabed sampling equipment, and laboratory. The difference is the geotechnical survey vessel has equipped with heavy load drilling equipment thus required a moonpool facility to perform the drilling work. Both vessels have onboard laboratory facilities including storage for samples, a survey room, and a monitoring system. A laboratory can be a permanent facility or container modular units mounted on the working deck. In addition to this specialized equipment, there is also common equipment for a subsea investigation like ROV/AUV, underwater structure, and underwater positioning. Equipment can be subdivided into three groups: deck mounted, permanent built-in, and hull attached. Deck-mounted equipment will be categorized as a payload on the main deck. Permanent built-in and hull attached equipment are part of the vessel platform. ("M.V. FUGRO GAUSS", 2017, "FUGRO SYNERGY", 2020)

Applicable modular equipment for this type of vessel is the containerized laboratory. These laboratories can be treated as deck cargoes welded on the working deck. A modular drilling system is another option to enable the moonpool to perform alternative operations from a life-long aspect.

(a) containerized laboratory ("GEOTEK CUSTOMISEDCONTAINER LABORATORIES", 2021)



(b) modular drilling system (Lamb, 2004)

Figure 3.2: Modular system for GSV

DIVING SUPPORT VESSEL

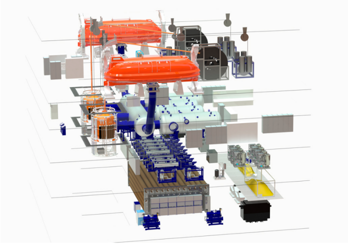
A diving support vessel is designed especially for underwater investigation, construction, and maintenance. According to DNV-GL's definition ("RULES FOR CLASSIFICATION Ships Part 5 Ship typesChapter 10 Vessels for special operations", 2020), a DSV is a vessel intended for diving support service with a particular focus on the ability to maintain position safely during diving operations through built-in redundancy. Diving support facilities can be subdivided into two main categories: unmanned vehicles and divers.

The unmanned vehicle support is performing by ROVs or AUVs. They provide an excellent view of the seabed with operators staying safely on board. It is a widely applied technology for seabed investigation, subsea pipeline maintenance, and first-aid for leaking pipes. The ROV system consists of three main subsystems: the vehicle, launcher system, and a control station.

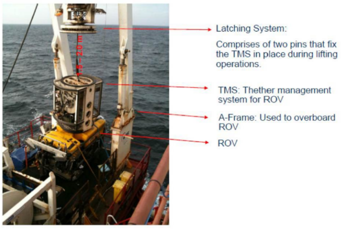
Divers support system two main categories which are: Surface diving and saturation diving. The main difference is the operational depth. When diving deeper into the sea, the insert gas breathed by the diver dissolved into the body's tissue thus reaching the equilibrium with the ambient pressure at the diving depth. A collection of diver support facilities should be qualified to achieve the corresponded notation. A system-wide equipment list suggested by DNV-GL is provided as pressure vessels, saturation chambers, saturation control system, dive control system, diving bell, diving bell handling system, gas storage system, and safety system.

Figure 3.3: Diving Support Vessel-BOKA Da Vinci

A picture of the diving support vessel is providedFigure 3.3. This vessel is a diving support vessel with both surface and saturation diving support .Main features provided by the operators are a saturation diving system for 300m deep diving, a 140-ton main crane, hyperbaric lifeboats, LARS for surface diving,a working-class ROV, an 1120 m^2 main deck, and accommodation for 120 persons.
This DSV is chosen for its modular saturation diving equipment as shown inFigure 3.4a. It shows the possibility to decouple the saturation diving system from the ship design process and can be treated as self-contained equipment. In addition to the saturation diving system, the ROV system can be treated as a collection of a modular systems. The vehicle, the handling system, and the tether management system (TMS).



(a) Saturation Diving module



(b) ROV system (IMCA, 2021)

Figure 3.4: Modular system for DSV

CABLE LAYING VESSEL

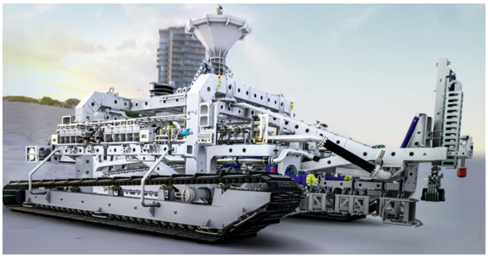
A cable laying vessel is designed for installing a power network, including an internal matrix and export cable. From the regulation, the equipment for positioning during cable laying will be specially considered. A cable laying system consists of four main systems: the storage of cables, the handling crane, the tensioner to stretch the cable, and a trencher to lay cable on the seabed. The form of the systems varies from case to case according to the equipment providers. Thus the main parts mentioned above will provide a representative layout of this type of vessel.

(a) Cable Laying Vessel - NDURANCE

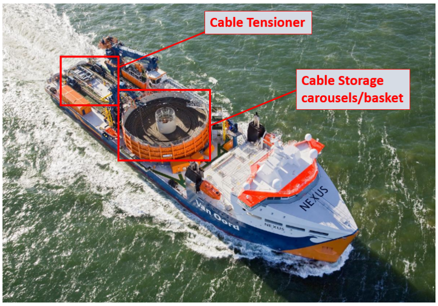
(b) Cable laying vessel - Nexus("Cable-laying vessel Nexus", 2015)

Figure 3.5: Cable Laying Vessels

In Figure 3.5two cable-laying vessels are provided. As seen in the figure, they have an on-deck carousal as a storage of the cables. While from installed the cable laying system aspect, the ENDURANCE (Figure 3.6a) uses a trench for laying cable while the Nexus (Figure 3.6b) uses a specially designed underwater vehicle to perform the deployment.



(a) Cable Laying Vessel - NDURANCE



(b) Cable laying vessel - Nexus ("Cable-laying vessel Nexus", 2015)

Figure 3.6: Modular system for CLV

Construction Support Vessel

A construction Support Vessel is a term for a series of auxiliary vessels designed to support light construction works for example anchor handling. In this research anchor handling and towing vessels (AHT) is chosen to represent this type of vessel. Their function is to assist construction vessels to handle mooring and positioning tasks. The characteristics are similar to tugs in the harbor.

Figure 3.7: CSV - BOKA SHERPA

In Figure 3.7 shows, a CSV is used for anchor handling and towing work. There are usually two sets of winch for either anchoring or towing tasks. A shark jaw and towing pin are provided to maintain the position of the chain and ensure tension. At the end of the deck is a roller to launch anchor and appended buoy. Both winches and shark jaws have modular products on the markets. With a strengthened deck and corresponded foundation, this equipment can be easily installed on the deck.

Multi-purpose project/cargo Vessel

Multi-purpose project/cargo vessel is another category of auxiliary vessels for offshore wind farm maintenance and inspections. The main difference between PSV and CSV is the former focuses more on the accommodation and transportation of offshore workers and the latter focuses more on the construction operations.
In Figure 3.8, two different Multi-purpose project/cargo Vessels are provided. The SOVEREIGN in Figure 3.8a is designed for transporting supplements for workers at the offshore construction site and provides capacity for transporting works going back and forth to the working site. The vessel in Figure 3.8b shows a vessel designing for transporting inspectors with a Walk-2-Walk system and has a small capacity for transporting supplement.

(a) Multi-purpose project/cargo Vessel - SOVEREIGN

(b) Multi-purpose project/cargo Vessel - BIBBY WAVEMASTER 1

Figure 3.8: Multi-purpose project/cargo Vessel

3.2. SYSTEM FUNCTIONS

A system is formed by multiple subsystems and interacting elements. These subsystems are products that to provide certain functions such as generating power, moving, maneuvering, navigating, transporting crew and cargoes, drilling, investigating and cable laying. These functions come from the customers' requirements and are translated by ship designers into organized input of different systems such as power plant, driving chain, bridge, accommodation, and functional payloads. Adapting the SFI code and SBSD process developed by (Levander, 2009), the OSV function is shown inFigure 3.9. The colors for task-related functions in the diagram mark the section where they originally come from.

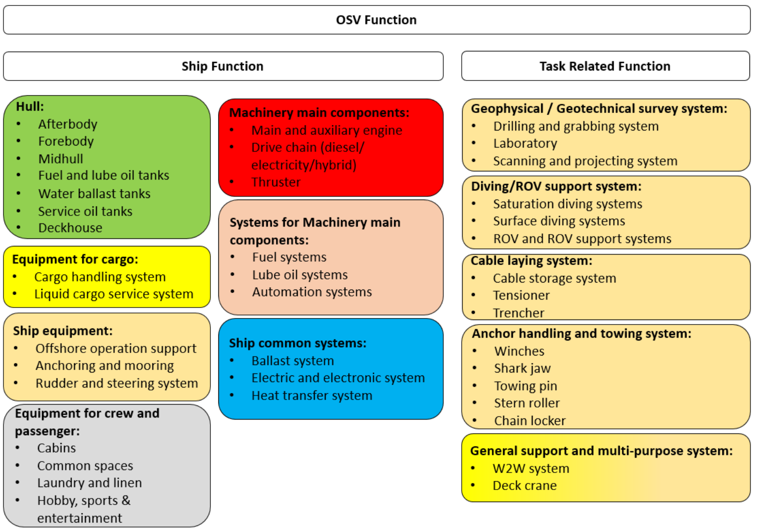


Figure 3.9: OSV functions

One thing to be mentioned in this diagram is a single system function consists of three elements: a space/tank for the whole system (hull section), the system components, and the interaction part between elements(ship equipment). An example of this structure is an "engine room" is the boundary of the "power plant system" which has "main engine(s)", "gearbox(es)" and "shaft(s)" as main components. Following this concept, the OSV function hierarchy structure can be reformed as shown inFigure 3.10. The boundary boxes are important for later defining the border of modular subsystems which will be further discussed in the next section.

3.3. MODULARIZATION

In this section, the modularizing process of a OSV system is performed. It will go through three main stages before the requirements are translating into a computer-readable format to undergo the programming process. The three main stages will cover the decomposition of the system, creating connections between requirements and modules, and standardizing the storing of information.

3.3.1. MODULAR SUBSYSTEM

The main driver for designing a modular platform is the way to access required functions. It will greatly influence the structure of the modular system by defining what is a "self-sufficient" part. To ensure the complex OSV platform system can be efficient in space- and system-wise, the interaction between two subsystems should be minimized to make it easier for integration.

Ideally, each subsystem can be treated as an independent modular platform to perform a certain function. The definition of a modular platform has been discussed in subsection 2.4.5, thus the next step is to clarify what are the modules and building blocks for building each modular subsystem. Recalling the system structure in Figure 3.10, it has roughly listed the required subsystems of a OSV. Some of the subsystems required more than one boundary boxes for they are divided into a storage space and a operation space like the fuel storage and supplying system is divided into main fuel storage tanks, daily fuel tanks. A detailed system component list with physical boundary, building blocks and modules is provided in Table 3.2.

Table 3.2: Modular subsystems derived from OSV system(*This is a mix modularity **This item will be elaborated by ship types in the complexity managing section)

System	Physical Boundary	Blocks	Modules
Main power plant system	Main engine room	Main engine room	Main engine Auxiliary engine Main generator
Technical space	Technical space	Changing room Garage	Auxiliary outfitting Leather machine
Fore Mooring system	Fore mooring deck	Fore mooring deck	Mooring winch Spare anchor
Bow thruster system	Bow thruster room	Bow thruster room	Bow thruster
Water Ballast system	Side water ballast tank(s) Bottom water ballast tank(s)	Side water ballast tank(s) Bottom water ballast tank(s)	Pump Sounding device *Coating system
Stabilization system	Anti-Rolling Tank(s)	Anti-Rolling Tank(s)	Pump Sounding device
Fuel storage and supplying system	Main fuel storage Tank(s) Day fuel tank(s)	Main fuel storage Tank(s) Daily fuel tank(s)	Fuel treating system
Lube oil storage and supplying system	Lube oil storage Tank(s) Service lube oil tank(s)	Lube oil storage Tank(s) Service lube oil tank(s)	Lube oil treating system
Cargo hold	Cargo hold	Cargo hold	Liquid cargo containers Special cargo containers
Propulsion system	Aft engine room	Aft engine room	Motor ShaftPod thruster
Task related and reserved space	Diving support room Diving control room	Moon Pool Diving support room Diving control room	Gas storage Saturation vessel Office furniture
Task related systems	Weather/Working deck	Stern roller	**Task related modules

3.3.2. QUALITY, FUNCTION, DEPLOYMENT(QFD) (KANA, 2019B)

A structured methodology is necessary for developing a good product design. QFD is chosen to be the tool for this research. It is designed to assure customer satisfaction by design in addition to process quality control. The advantage for applying this methodology is by bringing design engineers, manufacturers and marketers on the same table thus to ensure the voice from different parties can be heard. Each party has their own priority in the design process but none of them can represent the opinion of the whole stakeholder groups. QFD is widely used for developing a priorities that is reasonable for all the parties involved in the design process.

The first thing enters the QFD is the voice-of-customer (VOC). In this research there is no external customers involving in the design process, thus the functions of the OSV modular platform and the relative task related modules represent the internal customers. On the other hand, the proposed modules play as voices from the engineers namely the Substitute Quality Characteristics (SQCs) to match and fulfill the requirements from the customers . In section 3.2, the OSV system has been broken down into different subsystems. Furthermore, in Table 3.2 has proposed a number of different modules and building blocks in accordance with the systems requirements. The next step is to relate the functions to the modules.

House Of Quality (HOQ) is the most commonly implemented part of QFDs. It helps to identify and to visualize the relationship between the requirements of different vessels and the interrelationship between modules. Figure 3.11 illustrates the developed HOQ for developing a modular OSV product family. Some characteristics are inherited from Tvedt's research (Tvedt, 2012). In his research,modules for several OSV systems (AHTs, DSVs and PSVs) are created according to the SBSD approach for decomposing and grouping of functions. In this research, the definition of modules is improved by separating building blocks from modules. As mentioned in subsection 3.3.1, these blocks play the roles as the boundary of each modular subsystem. This concept is chosen to meet the later modeling structure which has been briefly discussed in subsection 4.3.1.Subsystems are no longer directly related to the OSV platform, but a functional entity to provide a certain service for example the auxiliary system is decoupled with the main machinery and form a module itself. There are still exceptions for this hierarchy system such as the moon pool will have influence on the hull and affect the tanks and voids above or beneath it. In addition to the inevitably modules interaction, there are also modules that are not expected to position near by such as high energy density space and gas storage. Relationships between modules are provided in Figure 3.12

In this research, Multi-purpose project/cargo vessel, construction support vessel, cable laying vessel, diving support vessel, geophysical/geotechnical survey vessel are the ship types being investigated. The modules of Multi-purpose project/cargo vessel are highly overlapped with general modules thus they are not marked as its own type. These vessels are chosen due to their similarity in size and able to carry on various operations throughout the life time of a offshore wind farm.

Function Type	Vessel Type	Operation Type	Functions \ Modules	Notation	Basic modules/modular platform									Operation modules/blocks																								
														General modules				CSV					DSV								GSV				CLV			
				"o" stands for optional	Hull	Machinery	Technical space	Fore mooring deck	Tanks, Rooms and voids	Working Deck	Tunnel passage	Navigation Deck	Accomodation	Deck crane	Gate crane	Helipad	W2W system	Winches	Chain/Rope storage	Shark jaws	Towing pin	Stern release Roller	Working class ROV	TMS modules	Handling system	ROV control station	Saturation vessels	Air storage	Diving control station	Moon Pool	Seabed projecting and seismic wave analysis m	Seabed sampling module (drilling module)	Containerized Laboratory	ROV support Module	Carrosel module	Tensioner	Stern Release roller	Seabed trencher
General functions	Common vessel	Transportation	Structure		9																																	
			Propulsion & maneuvering			9																				-3		-3	-3	-3	-3	-3	-3					
			Crew & client facility								3		9																									
			Common ship service facility					9																														
			Tanks and voids						9		3																											
			Technical systems				9																															
			Weather/working deck							9																												
Task Related functions	Multi-purpose proje	General	Crew size (Avg:30)										9																									
			Station keeping: DP-2			9						3																										
			Crew transportation	o									9			9	9																					
		Supply	Deck cargo							9				9	1																							
			Dry bulk cargo	o					3																													
			Liquid cargo	o					3																													
	Construction support vessel(C	General	Crew size(Avg:30)										9																									
			Station keeping: DP-2			9						3																										
			Crew transportation	o									3			9	9																					
		AH	Anchor handling Winch															9																				
			Deck project Storage						3	9									9																			
			Handling equipment											9	1					9	9	9																
		Towing	Towing Winch															9																				
			Chain Stopper							9										9																		
			Towing pin							9											9																	
	ROV/Diving support vessel(DSV)	General	Crew size (Avg: 100)										9																									
			Station keeping: DP-2/3			9						3																										
			Crew transportation	o									3			9	9																					
		Diving support	Diving bell/chamber											1	1												9											
			saturation vessel						1																			3										
			Gas supply Management System						1						9													9										
			Moon pool	o					3					1													3			9								
			Diving control station						1																				9									
		ROV support	Work class ROV																				9															
			Tether Management System																					9														
			Handling equipment											9	9										9													
			Moon pool	o										3	3															9								
			ROV control station						1																	9												
	Geophysical/Geotechnical su	General	Crew size (Avg: 40)										9																									
			Station keeping: DP-2			9						3																										
			Crew transportation	o									3			9	9																					
		Survey	Seabed sampling																													9						
			Seismic wave scanning											1	3																9							
			Seabed scanning											1	1																9							
			Laboratory																												3	3	9					
			ROV	o										1	1																			9				
			Moon pool	o					3		1			1	1																			3				
	Cable laying vessel(C	General	Crew size (Avg: 100)										9																									
			Station keeping: DP-2			9						3																										
			Crew transportation	o									3			9	9																					
		Cable laying	Cable laying system							9				9	1																					9	9	
			Subsea installation							1																												9
			Cable storage							1				9	1																				9			

Figure 3.11: HOQ: Module identification based on OSV functional requirements

	Hull	Machinery	Technical space	Fore mooring deck	Tanks, Rooms and voids	Working Deck	Tunnerl passage	Navigation Deck	Accomodation	Deck crane	Gate crane	Helipad	W2W system	Winches	Chain/Rope storage	Shark jaws	Towing pin
Hull		+	+	+	+	+											
Machinery			+	+	+		+										
Technical space				+	+	+											
Fore mooring deck				+	+		+						+				
Tanks, Rooms and voids						+	+						+		+		
Working Deck										+	+	+	+	+		+	+
Tunnerl passage													+				
Navigation Deck									+								
Accomodation																	
Deck crane											-				+		
Gate crane												-	-				
Helipad																	
W2W system																	
Winches															+		
Chain/Rope storage																	
Shark jaws																	+
Towing pin																	
Stern release Roller																	
Working class ROV																	
TMS modules																	
Handling system																	
ROV control station																	
Saturation vessels																	
Air storage																	
Diving control station																	
Moon Pool																	
Seabed projecting and seismic wave analysis module																	
Seabed sampling module (drilling module)																	
Containerized Laboratory																	
ROV support Module																	
Carrosel module																	
Tensioner																	
Stern Release roller																	
Seabed trencher																	

Hull	Stern	Working cla	TMS modules	Handling system	ROV control station	Saturation vessel	Air storage	Diving control stat	Moon Pool	Seabed proj	Seabed samp	Container	ROV support M	Carrosel m	Tensioner	Stern Releas	Seabed trench
Machinery									+								
Technical space					-	-		-	-	-							
Fore mooring deck																	
Tanks, Rooms and voids																	
Working Deck	+				+	+	+	+	+		+						
Tunnerl passage	+	+	+	+	+					+	+	+	+	+	+	+	+
Navigation Deck																	
Accomodation																	
Deck crane																	
Gate crane				+							+			+			+
Helipad		+	+	+						+	+					+	+
W2W system																	
Winches																	
Chain/Rope storage																	
Shark jaws																	
Towing pin	+																
Stern release Roller	+																
Working class ROV																	
TMS modules			+	+	+								+				
Handling system				+													
ROV control station																	
Saturation vessels																	
Air storage							+	+	+								
Diving control station								+	+								
Moon Pool									+								
Seabed projecting and seismic wave analysis module																	
Seabed sampling module (drilling module)											-	+	+				
Containerized Laboratory												+	+				
ROV support Module													+				
Carrosel module																	
Tensioner															+		
Stern Release roller																+	+
Seabed trencher																	

Figure 3.12: HOQ: Module interrelationships

3

3.4. QUANTIFICATION AND QUALIFICATION OF MODULES

This section is created to bridge the modularization and the knowledge based engineering which will be discussed in chapter 4. Each module has its own physical and functional properties. These information are treated as "attribute" in the programming language thus to standardize the form of input and output information. Briefly introduced in subsection 2.4.7, modularization has the potential to integrate the physical world with the digital solutions. The standardized information format enable the complexity to be manageable and make it possible to go under automatic calculations. On the other hand, categorized information reduce the difficulties to adapt latest or modification to the existed system. Furthermore, it allows the users to access a complex system by easily tracking down the system diagram.

An simple way to understand the process is to add on all the attributes. An example is provided as following: In Table 3.3 shows a system consisting of 5 components (C_i). Each component has its own volume (V_i), weight(W_i), energy consumption(E_i), lifting force (LF_i) and unique function (F_i). Among all, C_1 is a modular platform consists of two modules m_{11} and m_{11}. Modules m_{11} and m_{11} are independent from other components thus their information will not access by other components. This information structure prevent the interaction between components belong to different hierarchy.

Table 3.3: Example of information storage form

Components	Volume	Weight	Energy consumption	Lifting Force	Function
C_1	V_1	W_1	E_1	LF_1	$F_{1,3}$
m_{11}	v_{11}	w_{11}	e_{11}	lf_{11}	f_1
m_{12}	v_{12}	w_{12}	e_{12}	lf_{12}	f_3
C_2	V_2	W_2	E_2	LF_2	F_2
C_3	V_3	W_3	E_3	LF_3	F_4
C_4	V_4	W_4	E_4	LF_4	F_5
C_5	V_5	W_5	E_5	LF_5	F_6

3.5. CONCLUSION OF PART I

The main idea of this chapter is to show how to decompose the OSV system into compact and self-sufficient system. It applied the SBSD methodology to divide the OSV system into a modular platform (the vessel) and several task related module groups. This first step enables the optimization of the modular platform by optimizing the platform and task related modules separately as mentioned in section 2.7. section 3.4 introduces the data storage format which is a preparation for the knowledge based engineering process that will be further elaborated in the next chapter.

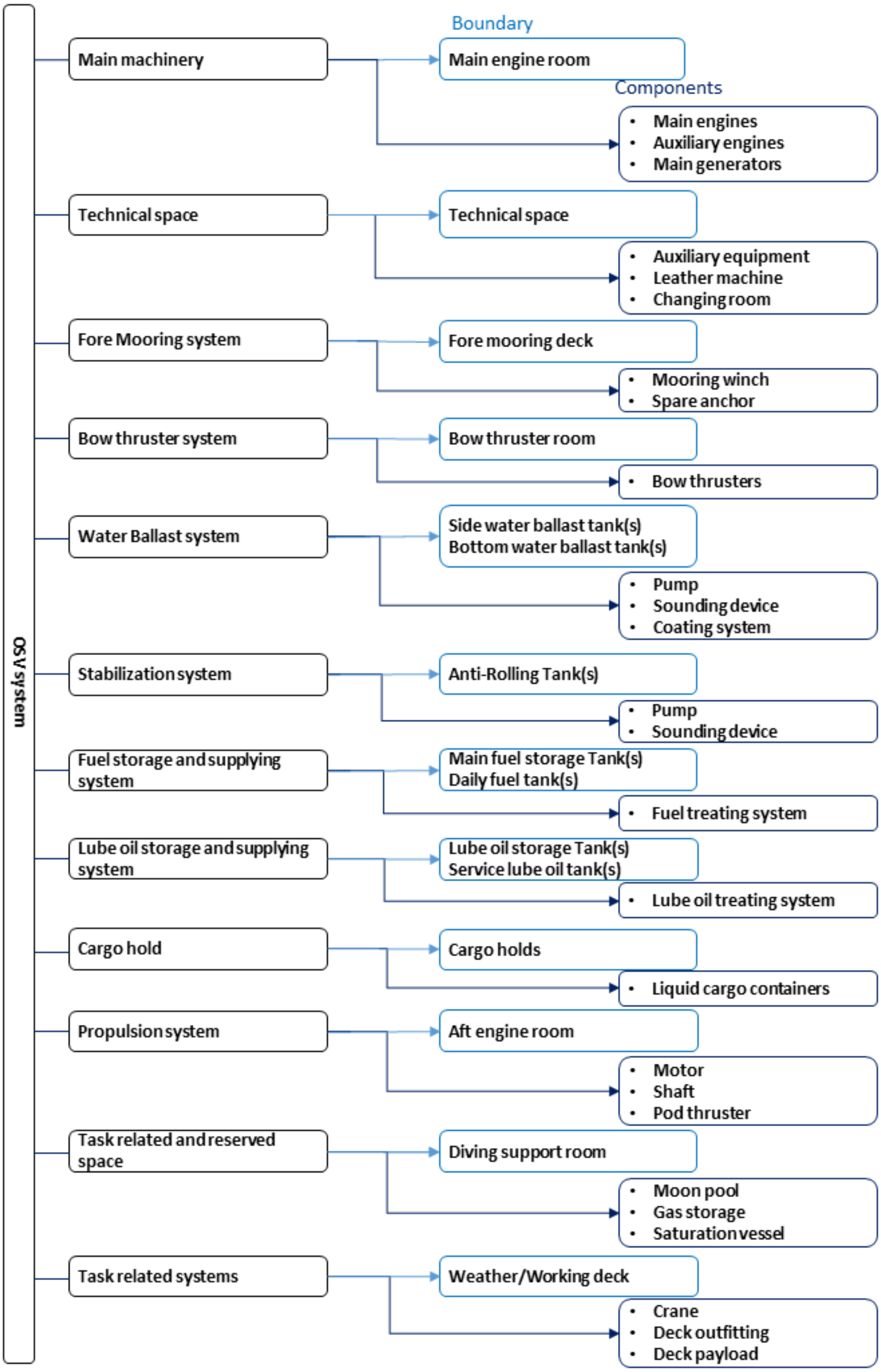


Figure 3.10: OSV System

4

PART II: KBE-LIKE FRAMEWORK: KNOWLEDGE-BASED SYSTEM (KBS) STRUCTURE

Following the conclusion of chapter 3, the information of OSV system can be translated into a readable format for computers. In this chapter, the reconstructed data structure will be reshaped to fit in the proposed Object Oriented Programming (OOP) structure provided later in this chapter. It will become the guideline to develop a knowledge-based system (KBS). Together with the next chapter explaining the development of a MMG, a Knowledge-Based Engineering-like (KBE-like) framework can be established.

4.1. OBJECT-ORIENTED SHIP MODEL FRAMEWORK DEVELOPMENT

At the end of the previous chapter, the information storage structure built of components and modules is a type of OOP system structure. It expressed a program in a way that each component is an object, which contains attributes of the object and codes for interactions between objects. It is also known as the process to transform random information into standardized "knowledge". Knowledge is the form that can be accepted, analyzed, and reused by the computer thus initiating the automation and optimization process. For designing a similar product in a product family, these knowledge can help ship designers to come up with solution when a similar problem appears. This advantage prevents ship designers to investigate the problem from the very beginning thus to reduce a lot of repetitive works. It is the first step for accelerating the gaining of problem knowledge in a design project for designers can focus on exploring and solving new problems in the design process.

Adapting the conclusion of chapter 3, the OSV system can be expressed as the following equation:

$$OSV = Bow + MidHull + Stern + Superstructure + TaskRelatedModules \tag{4.1}$$

$$Bow = \sum_{(i,j,k)\in\mathbb{N}} ForeHull\_room_i + room\_layout_{i,j} + layout\_component_{i,j,k} \tag{4.2}$$

$$MidHull = \sum_{(i,j,k)\in\mathbb{N}} MidHull\_room_i + room\_layout_{i,j} + layout\_component_{i,j,k} \tag{4.3}$$

$$Stern = \sum_{(i,j,k)\in\mathbb{N}} AftHull\_room_i + room\_layout_{i,j} + layout\_component_{i,j,k} \tag{4.4}$$

$$S.Structure = \sum_{(i,j,k)\in\mathbb{N}} S.Structure\_room_i + room\_layout_{i,j} + layout\_component_{i,j,k} \tag{4.5}$$

$$WorkingDeck = \sum_{(j,k)\in\mathbb{N}} function\_layout_j + layout\_component_{j,k} \tag{4.6}$$

A prototype of the OOM system structure of the OOM system can be derived from this equation indicating the object and their properties. The properties will later use the term **"attribute"** for physical properties and the term **"operation"** for functional properties.

4.2. UNIFIED MODELING LANGUAGE (UML)

OOP helps to reason out the development of model generator. Unified Modeling Language (UML) is a widely applied modeling language to visualize the design of a system. In this research, the class diagram is applied to show the hierarchy of different systems. The class structure is a knowledge storage form for knowledge based system to access and to manipulate. Part of the developed diagram is provided in Figure 4.1. On the left hand side, it shows that the modular platform class has a mandatory subclass named "Connection". To make the connection class functional, a sub-class "Compartment_Function" is necessary. The "Compartment_Function" class is able to perform function by applying a "layout" class in this component with a interface "Layout_compartment". The "Layout" class has different instances represent different functional layout such as "DivingSupport", "GeoAnalysis" and "Cargo" included in the figure. The full OOM class-diagram is provided in Appendix I .

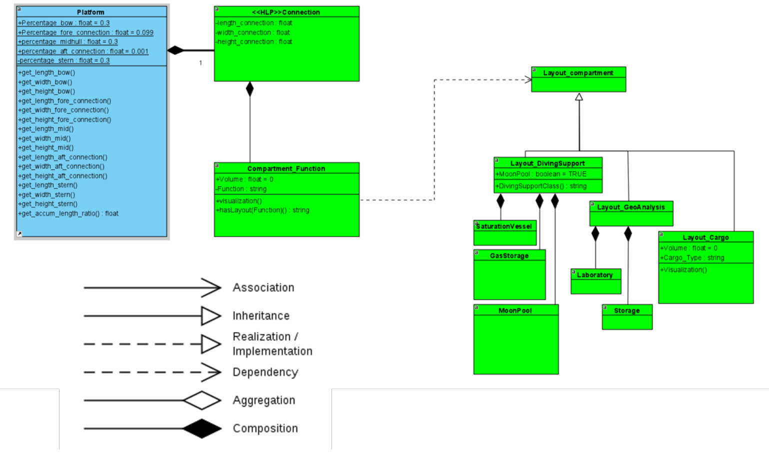


Figure 4.1: Example of the OOM structure

4.3. DEFINING HIGH-LEVEL PRIMITIVES

This section will provide a walkthrough of what HLPs are, how to define HLPs, and their character in the OOP system. This process is based on the authors' subjective point of view for defining and manipulating this concept. HLPs can be defined in totally different forms based on each designer's recognition of the OSV system.

4.3.1. INTRODUCTION OF HIGH-LEVEL PRIMITIVES

High-level primitives must be defined individually for different types of KBE applications. In this section, two types of HLPs are going to be introduced to better get readers to understand how should an HLP be defined by different levels of usage in programming and modeling. A simple example for explaining the meaning of HLP is its application in CAD software (Koning, 2010). In a CAD application, HLP means dot, curve, surface, and planes for forming different geometry. Each level contains a different amount of information from the coordinate, vector, and length. More mature HLP types in modeling products are curves, cylinders, and boxes for they contain more information such as area, volume, weight, the center of gravity, densities, and specific physical characteristics. To sum up, an HLP is a basic unit of a product that contains a certain amount of knowledge, including attributes and operations. The final product is a collection of HLPs with certain inputs to generate a product at the right position with the right size.
The first type of HLPs in this research is a mimic of CAD application. It is defined as the basic element for designing a modular platform. They contain information as position, vector, length, and curve blend types (attributes) and are assigned with different typical functions (operation). Adapting the experience from Koning's research (Koning, 2010) and requirements from maritime societies, an overview of the ship hull geometry requirements are shown in Table 4.1.

Table 4.1: Overview of the modular platform geometry requirements

Item	Requirement
1.	The floating structure object should be applicable to more than just a certain type of offshore structure
2.	Enable the modeling of different OSV platform configuration
3.	Model Vessels with extra dry cargo hold or special operational facilities
4.	Model Vessels with different bow shape configurations
5.	Model Vessels with different stern shape
6.	Model Vessels with different bilge shapes without an open edge at the boundary
7.	Enable the final model to be a close-brep to enter the external analysis software.
8.	Allow modification to be visualized in a CAD software
9.	Enable the modeling of different types of moveables.
10.	Implement different modular configurations in a single section
11.	Enable the working deck plane adjustable according to the deck layout
12.	Enable different numbers and types of main propulsors
13.	Enable different numbers of side propulsors
14.	Enable different types of movables
15.	Make movables blend with the deck outline

The second type of layout HLPs is adapted from the factory layout application. In this case, HLPs are individual modular equipment that forms a functional layout following certain rules and relationships. Each HLP contains basic dimension information (attributes) and functional information (operation). This layout will be validated by the classification rules to show whether it satisfied the safety requirement. The requirements are listed in Table 4.2

Table 4.2: Overview of the modular equipment layout requirements

Item	Requirement
1.	The function modules object should be able to represent different types of equipments
2.	Enable the modeling of different operational deck arrangement
3.	Enable to modeling different number of movables
4.	Enable the equipment to be distributed evenly on port and starboard side
5.	Enable objects that integrated with hull placed in negative z-direction
6.	Enable objects that required open to the sea to be placed at the board side
7.	Enable open structures under main deck outline reflect to the main deck
8.	Make sure the objects not collapsing with modular movables
9.	Enable objects to be movable after placed on the designed plane
10.	Enable the collapse with other element after changing the position

The MMG that will be created as one of the results in this research is aimed for a broad use in different kinds of offshore platform systems that need not to be only OSVs. With the knowledge in creating a smooth connection between curves in the proposed CAD environment, it makes the hull line to be represented in continuous curves but not segments [1]. It is also expect that each HLP within the parametric modeling will become an independent modular platform to allow further optimization process. On the other hand, the HLPs in layout generations are designed to enable evolutionary process along with the development of modular equipment in various sub-systems.

[1] For example, in NURBS environment, there are requirements for creating a blend curve between two segments. It can either be achieved by locking the position of the two ends or maintain the curvature of the two segments. The result will greatly affect the modeling result if a kink appears during the blending process.

4.3.2. HLP:FLOAT STRUCTURE

A floating structure provides the following functions: sailing and maneuvering, carrying cargo and payload, dynamic positioning, support offshore operations. This categories contains three basic instances and one supportive instance. The details of these instances are derived from the introduction given in subsection 2.6.1. The three main instances are:

1. **Forehull-like block**: energy supply, mooring, dynamic positioning, technical space for manufacturing, parking and changing clothes and a water ballasting system.

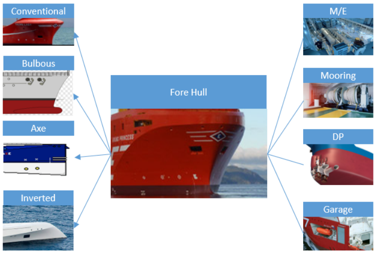


Figure 4.2: ForeHull-like block variants and its' function assemblies

2. **Midhull-like block**: water ballasting function, cargo hold, liquid cargo hold, liquid cargo tank, fuel and lube oil storage, special compartment for offshore operation and optional under-deck tunnel passage.

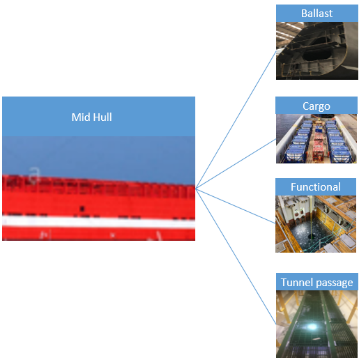


Figure 4.3: MidHull-like block variants and its' function assemblies)

3. **Stern-like block**: main propulsion equipment ,a reserved compartment for stern roller installation and a auxiliary ballast system to compensate the trim motion.

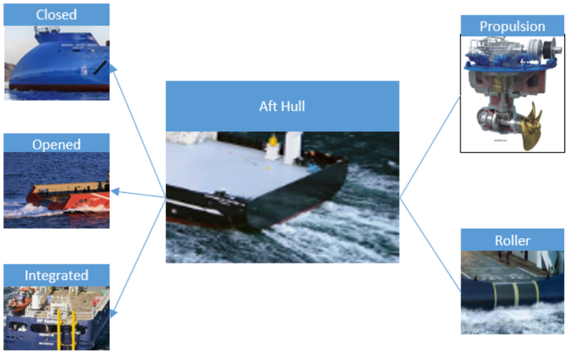


Figure 4.4: AftHull-like block variants and its' function assemblies

The three instances above have included most functions of a floating platform. To meet the requirements not included in the basic HLPs, the supportive **connection HLP** is added to the list. This HLP is built to represent a physical boundary as the water tight bulkhead or a functional block to mount a modular system as modular diving support facilities. It can be seen as a subdivision of the Midhull-like block.

4.3.3. HLP:SUPERSTRUCTURE

The HLP superstructure is a **geometry box**. It provides functions for crew and clients service including HVAC, hotel, entertainment, sport and navigation. It is expected to create different superstructure configuration including forecastle, aftercastle and general deck houses.

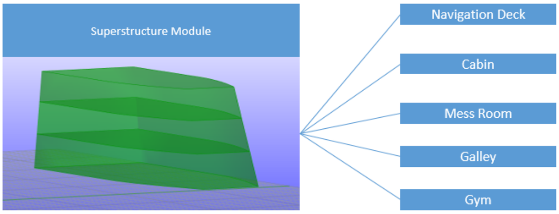


Figure 4.5: Superstructure and its' function assemblies

4.3.4. HLP: MODULAR EQUIPMENT

The modular equipment HLP are elements with different function that to form a subsystem. It is different from the previous two types of HLP for it can be treated as an independent KB system. The working deck configuration for different types is an intuitive example for this application. However, this concept can be extensively used for generating layouts for engine room, bow thruster rooms and main propulsion rooms.

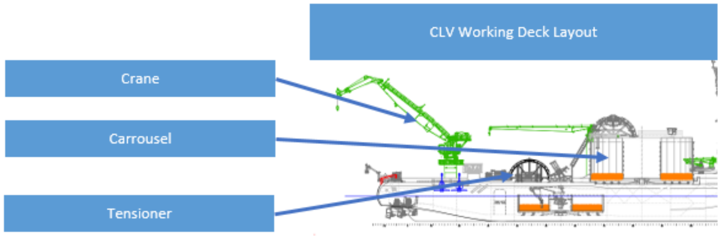


Figure 4.6: Modular equipment as HLPs in a layout (CLV working deck as an example)

4.4. THE STRUCTURE OF MMG

The modeling hierarchy of the MMG is shown in Figure 4.7. This modeling structure is developed in two different tracks following the definition in the previous section. Following is the description of each element mentioned in this structure diagram.

Firstly, the modular platform is starting point of the whole design. The modular platform consists of 5 main parts: Fore hull, Mid Hull, Aft Hull, connection ,and superstructure. The first four of them are instances of float structure HLP. Under each category there are various sub-instances or namely variants. For example, on the left hand side of Figure 4.7, the *ForeHull* instance has four variants listed as Type 1 to 4. The *ForeHull* is called the parent while the four variants are children objects. Each variant of *ForeHull* consists of an object *Shell* and one or more *hull assemblies*. The object *Shell* inherited the idea of "clean wing" from Koning's research (Koning, 2010). It is created for estimating hull performance. The *hull assemblies* class can be seen as parts of float structure HLPs. The term "*hull assemblies*" contains a complete shell, boundary boxes, assemblies and movables in a particular section of the floating structure. These assemblies are placed within the hull in accordance with a scenario created for each section.

Secondly, the layout generator is another track in this diagram. A walkthrough of this track starts from the right hand side marked as the task related modules. It is an typical object for applying this concept as the modular equipment for different offshore operation is designed to work independently but bringing together to meet all the operational requirements. Each module can be randomly placed on the platform but also needs to be integrated with other modules for forming a functional layout. An example is that the towing winch should be firstly placed on the deck then following by a towing pin and a shark jaw. This order needs to be strictly followed in order to create a capable towing system. The concept is also applicable in designing main engine room, bow thruster room and propulsion room.

With this setup, the MMG is able to generate a shell for hull performance analysis, a collection of assembles to form a functional section and a layout to provide certain function or a subsystem.

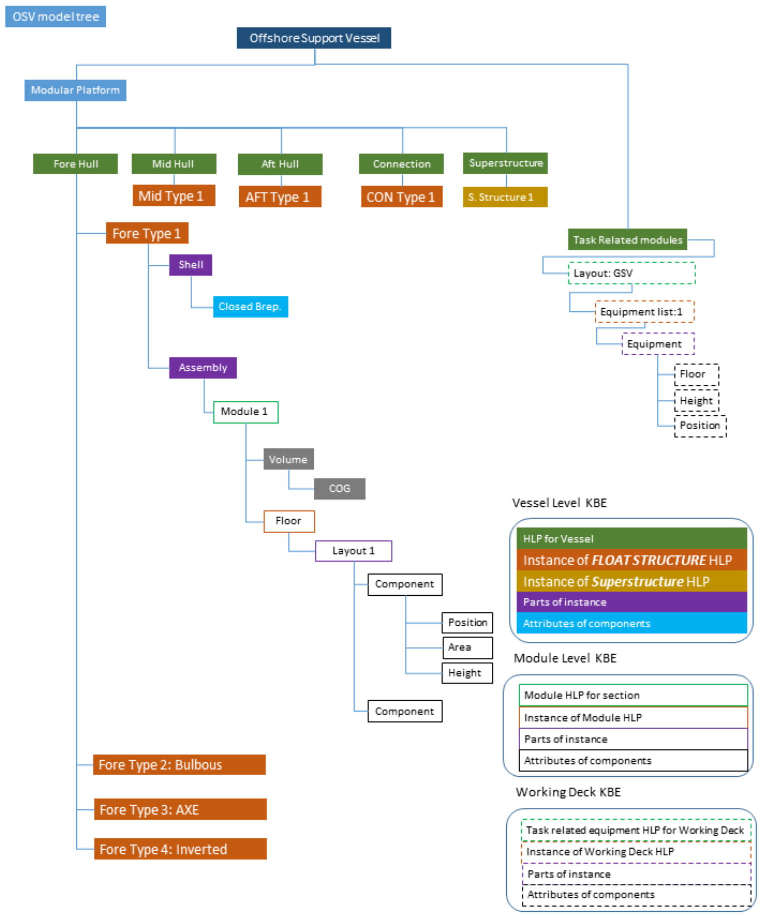


Figure 4.7: Modeling hierarchy in MMG

4.5. Conclusion of Part II

In this chapter, the first half part of the KBE development is setup. This process for capturing and categorizing information into a class diagram is a form of standardization to transform information into "Knowledge". Knowledge enables the computer to process automatic calculations and optimization. The reason for the system is called KBE-like but not KBE is due to a missing optimization engine in the system. According to the definition of a KB system, a optimization engine and a database are required. In this research, the optimization engine is missing but replaced by a manually modification function, a pre-programmed scenario and a connection slot for future plug-in for making it become a true KB system. The database applied in the research comes from the vessels investigated in the literature review. Since the information are randomly provided by the shipyards or operators, it is difficult to form a capable database to support development of the KBS.

5

PART III: KBE-LIKE FRAMEWORK: MULTI-MODELING-GENERATOR

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5.1. INTRODUCTION OF GRASSHOPPER

The structure of the MMG has been established at the end of the previous chapter. In this chapter, the development of the MMG will be elaborated. To enable real-time monitoring of the changes done in the modeling result, a platform that allows both programming flexibility and an intuitive demonstration of modeling results is preferable. Rhinoceros 6-Grasshopper is a powerful developing package that has already been widely used for architectural modeling. Furthermore, it also includes the python and C framework in the recent update. Thus it is chosen to be the main developing tools for the MMG in this research.

Rhinoceros uses a Non-uniform rational B-spline (NURBS) model to generate points, curves, and surfaces. Grasshopper is a plug-in that is built in the system from Rhinoceros6 ("Rhino Training Guides", 2021). The combination of these two systems allows users to create models based on algorithms. The interface for using this combination is provided in Figure 5.1. There are four main features (Wirz, 2014): **A:** Grasshopper editor where the user can create algorithms for generating various geometries. **B:** Rhinocreos window where the user can monitor the modeling process. **C:** Grasshopper's visual modeling environment. Users can create their unique algorithm for modeling, scaling, positioning, and rendering. **D:** modeling result.

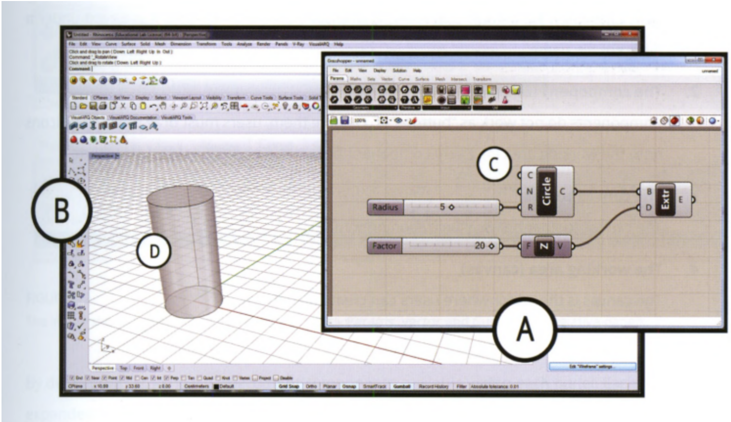


Figure 5.1: Rhinoceros-GrassHopper User Interface (Wirz, 2014): **A:** Grasshopper editor, **B:** Rhinocreos window, **C:** Grasshopper's visual modeling environment, **D:** modeling result.

Models are built by a process of "point-curve-surface" (Wirz, 2014). The application of this chain to the research into OSVs will be presented in the following sections. The modeling procedure is similar to the process of building a simulation model in the SIMULINK® environment but is for CAD modeling. The advantage for this programming form allows user to track the building history of each step by following the connection between blocks. Grasshopper provides a library of different blocks and allows the user to build their own functional blocks. Plug-ins can be found in an official forum founded by McNeel®. With the plug-ins sharing in the platform, it is possible to import functions as simple CFD solvers, gravity simulators, and various analysis tools to the modeling process. Another advantage is that Grasshopper supports Python and C scripting, which makes it more friendly to users who are used to the programming process.

5.2. HULL SHAPE

5.2.1. HULL BLOCK BUILDING CONCEPT

KBE is not complete without the input of an existing hull shapes database. In this research, the database does not exist thus the hull shape will base on educated guesses. By adapting the development of the geometry shapes and parametric model in literature (Koning, 2010). The three steps for creating the shell of ship hulls are built:

1. Generate front and after section line.
2. Place sweeping rails and intermediate section lines.
3. Generate the surface by sweeping the section lines along the rails.
4. Close the openings

The four steps are visualized inFigure 5.2. Further description of each step will be elaborated.

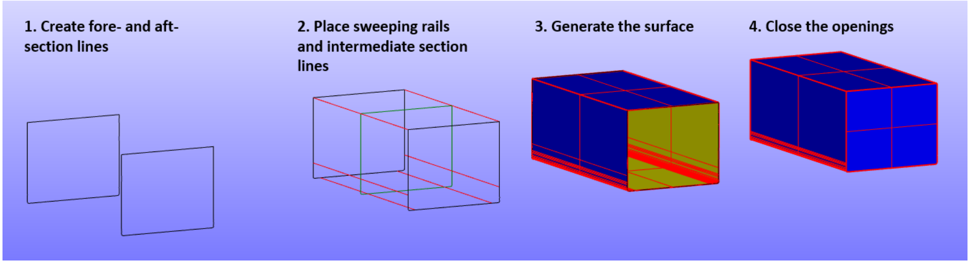


Figure 5.2: Shell hull construction concept

The black lines in step **1.** are fore- and aft-section lines. They give the start and end position of the block object. The lines are created first at the original point, namely (0,0,0) in the coordinate system then relocated to the place. For example, the *MidHull* block is placed after *AftHull*. They are called *"Rail"* for they act as a kind of two-side curtain rail to constrain the surface.
In step **2.**, two characteristic curves are added to the block. Intermediate lines in green represent the section lines in the longitudinal direction. They are created to define the sectional shape between both ends, like the bottleneck of a vase. Red curves are the sweeping section lines created according to the corresponded points on aft-, intermediate- and, aft-section lines at the same altitude acting like the railway sleeping on the rail. With these two sets of curves, it is able to process the shell of the block by running the two-rail sweeping process as shown in step **3.**. The last step is to close the openings on both ends to form a *"closed-Brep"* in the software as shown in **4.**. This property as a closed-brep must be checked as an indication of a successfully modeling result.
The following provides more details of the input for each block. The variables for defining the hull are adapting from Charisi's research (Charisi, 2019) and being modified according to Sanches' (Sanches, 2016) and Koning's (Koning, 2010) research. In order to reduce the confusion in naming objects, a unified naming rule is applied:

1. **Mid_Hull_line_A:** This is the Aft-section line. Since the *MidHull* block is the first built section for prototyping, the name is inherited by the later designed sections.

2. **Mid_Hull_line_F:** This is the Fore-section line.

3. **line_maindeck_CL:** This is the center line of the main deck. Together with the keel center line, it will formed the surface for mirroring the port-side to starboard-side.

4. **line_bilge_t:** This is the bilge top line.

5. **line_bilge_b:** This is the bilge bottom line.

6. **line_keel_CL:** This is the keel line.

7. **line_trans #_p:** This is the section control line. There can be multiple lines in different sections to create more complex shape.

An Important feature in this system is users' knowledge of the use of knots and steps in the Rhino modeling system. They help to define whether a curve is built properly. The correct use of these two factors will lead to a smooth line and reduce the possible results in a model with open edges when finishing the model. For more detail about these two elements, please check the Rhinoceros manual. Another thing that needs to be mentioned is the sweeping process. The sweeping process requires the user to define the rails and intermediate section lines before generating the surface. A missing assigned rails or section lines can lead to a failed result. Also, if the curvature on the rail changes dramatically, the system will ask for a rebuilt process to achieve a curve accepted by the system and most time will change the curvature of the original curve. Thus, a **"lock"** feature is required to control the ends of each curve. This lock can be observed in the following section expressing the construction of *Shell_ForeHull*.

- **ForeHull Shell**
  1. Length
  2. Beam
  3. Height
  4. Bilge continuity
  5. Parametric description of the curves: line_bilge_t, line_bilge_b, line_keel_CL, line_maindeck_CL, line_trans1_p, line_trans2_p[1], Mid_hull_line_F, Mid_hull_line_A.

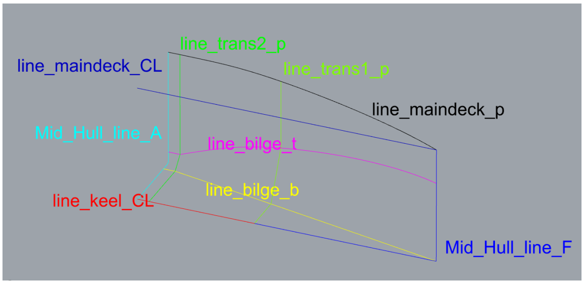


Figure 5.3: ForeHull curves

[1]It is called shape control curve in the program. The reason is to assure the connection between the Shell_ForeHull and another shell object maintains the continuity in curvature.

- **MidHull Shell**
  The variables to describe the MidHull are:
  1. Length
  2. Beam
  3. Height
  4. Bilge continuity
  5. Parametric description of the curves: line_bilge_t, line_bilge_b, line_keel_CL, line_maindeck_CL, Mid_hull_line_F, Mid_hull_line_A.

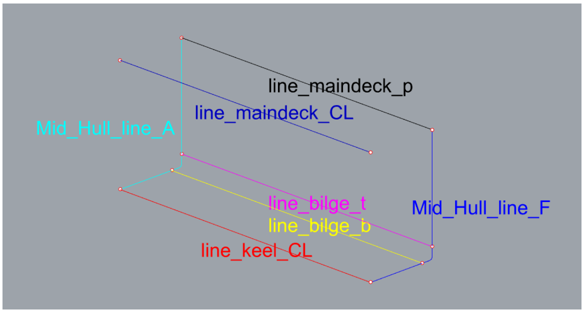


Figure 5.4: MidHull curves

- **AftHull Shell**
  1. Length
  2. Beam
  3. Height
  4. Bilge continuity
  5. Parametric description of the curves: line_bilge_t, line_bilge_b, line_keel_CL, line_maindeck_CL, line_trans1_p, , line_trans2_p Mid_hull_line_F, Mid_hull_line_A.

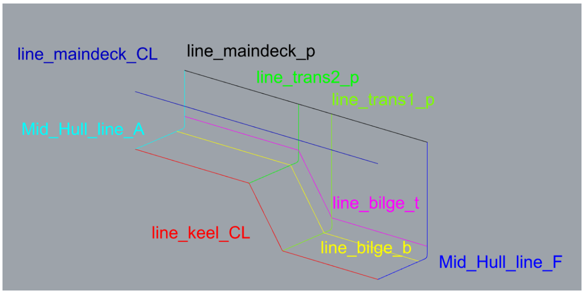


Figure 5.5: AftHull curves

5

- **Connection Shell**
  1. Length
  2. Beam
  3. Height
  4. Bilge continuity
  5. Parametric description of the curves:

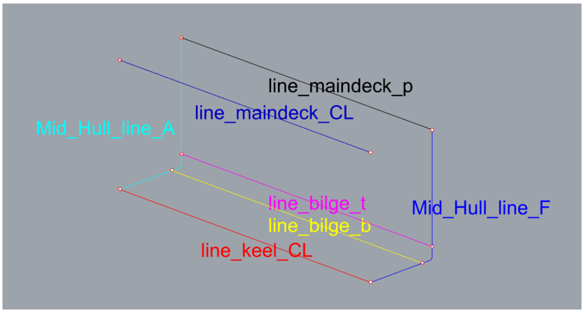


Figure 5.6: Connection curves

5.2.2. HULL BLOCKS MATHEMATICAL EXPRESSION AND INPUT

The main dimensions (L.O.A, L.O.B, Mould_Depth) are defined by the user and input as parameters. The main dimensions are the main drivers for generating different models in Rhinoceros-GH. A set of equations is provided in Equation 5.1 for generating a geometric model. The most important input is the length parameter, the *"shell"* object is defined by the percentage of the L.O.A. The *Width* and *Height* values are directly adapting the LOB and mold depth. Following is a short description of equations in addition to main dimensions. The *Bilge* parameter is to define the continuity between two bilge curves, *line_bilge_t* and *line_bilge_b*. The values of bilge indicate the blending curve is built by maintaining the position at the end of the curvature from parent lines. This will result in a very different bilge shape in the model. The *"GeometricModel"* is a set of different coefficients to define the shape of the curve and will affect the modeling result. The reason for creating this *"shell"* model is to go through stability estimation and buoyancy check.

$$Length_i = L.O.A * f1_i(var1_i), \quad \sum var1_i = 1, \quad \forall var_i \geqslant 0.001 \tag{5.1}$$

$$Width_i = L.O.B \tag{5.2}$$

$$Height_i = Mould\_Depth \tag{5.3}$$

$$Bilge_i = var4_i, \quad \forall var4_i \in (0,1,2), \quad var4_i = var4_{i-1} \tag{5.4}$$

$$GeometricModel_i = f5_i(IndependentVariables_i) \tag{5.5}$$

5.2.3. RESULT OF SHELL GENERATOR

Three ship hulls with different configurations are provided. These hulls are generated with the basic MMG shell function. The first one is a conventional ship using reference vessel-*BOKA Sherpa* ("BOKA SHERPA", 2020)'s specification. This model contains two shell objects, *Shell_ForeHull* and *Shell_AftHull*.

The second hull is a reproduction of the reference vessel-*BOKA Da VINCI* ("BOKA DA VINCI", 2020). This model consists of four shell objects: *Shell_ForeHull, Shell_Connection, Shell_MidHull*, and *Shell_AftHull*. It can be identified by the bulb-like bow shape and a gradually changing stern shape.

The third model is a demonstration of replacing the bulb-like bow with an inverted bow using the same hull of *BOKA Da VINCI*. By modifying the input parameters, it is proved that the model can generate different ship hulls based on the users' inputs.

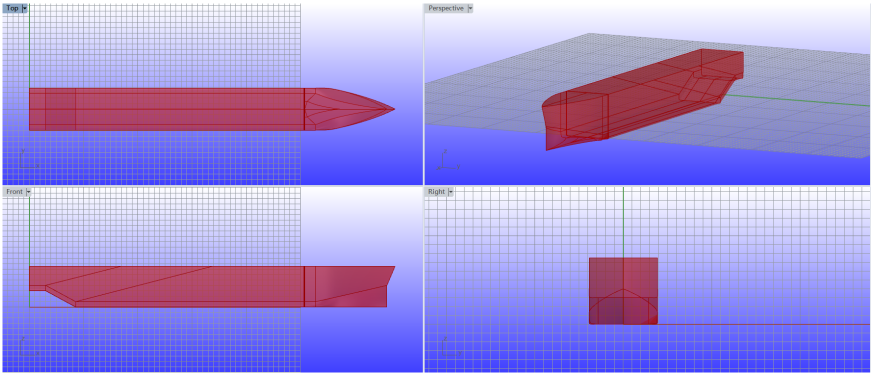


Figure 5.7: Conventional Ship model (stern+connection(thin)+bow)

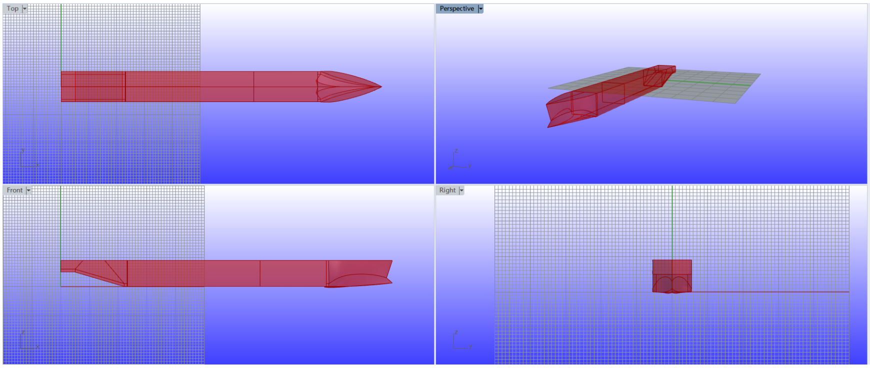


Figure 5.8: Bulb-like Ship model (stern+connection(compartment)+bow)

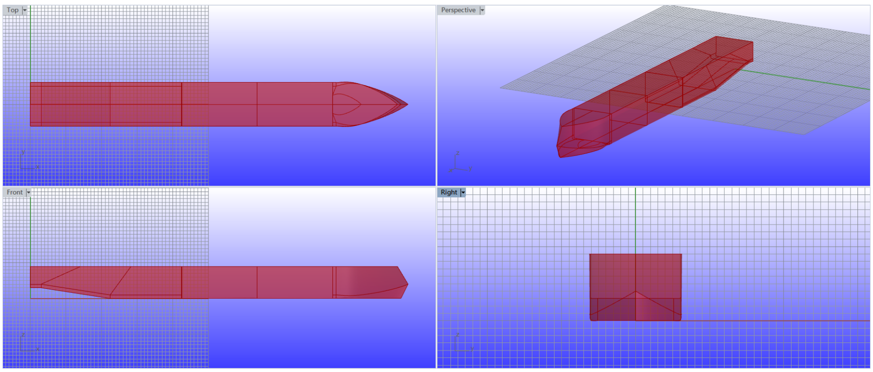


Figure 5.9: Inverted Ship model (stern+connection(compartment)+bow)

5.3. SUPERSTRUCTURE SHAPE

The superstructure is designed as a movable object generated according to the user-defined longitudinal length, floor height, and deformation ratio at the x-axis. It is aimed to create a full breath structure that changing the shape according to the deck line. The concept for building this object is following these steps:

1. Extract the deck line from the *shell* object.
2. Create the aft- and fore boundary of the superstructure.
3. Sweep along the deck line from aft to the fore boundary to form the floor of the superstructure.
4. Move the floor along the deck line to the desired position. In this step, users can check whether a kink appears. The continuity check can also be done at the same time.
5. Extrude the floor with the assigned deck height. (The floor and ceiling shapes can be adjusted independently)

In the program, all the extruding work and deformation work are done simultaneously. The user is asked to decide the number of decks beforehand. Generated superstructure objects can still be moved afterward and the shape will keep changing according to the shape of the deck line. The program will keep tracking the total floor area and display it in a separated monitor object. The rest area on the main deck will then be assigned as the working deck.

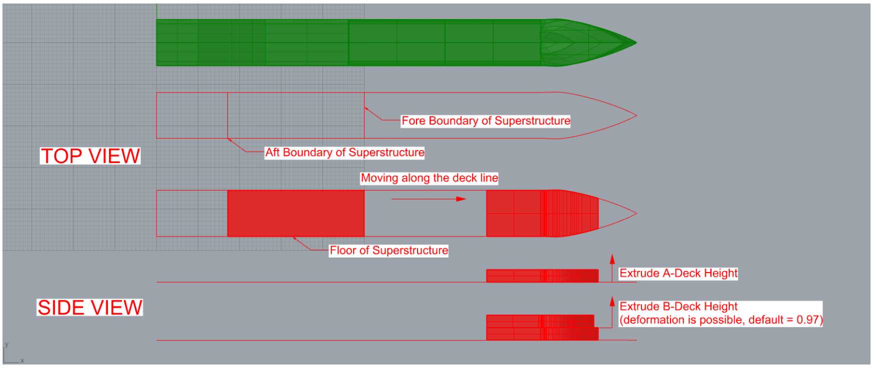


Figure 5.10: Model Fore Hull Result

Finally, the building concept of float structure HLP is explained. With this framework, the user is provided with a tool to generate a basic ship hull model with hull shape and superstructure and estimate the primary hydrostatic performance and estimate the weight of the hull. The sections are also able to mark the main watertight bulkhead position. If assigned with a self-defined deck, the user can start to process the first version of the general arrangement. In the next section, the building concept of the second type of KBE system, the layout generator will be introduced. These two systems are expected to work independently in order to show the possibility of a parallel working process in the design work.

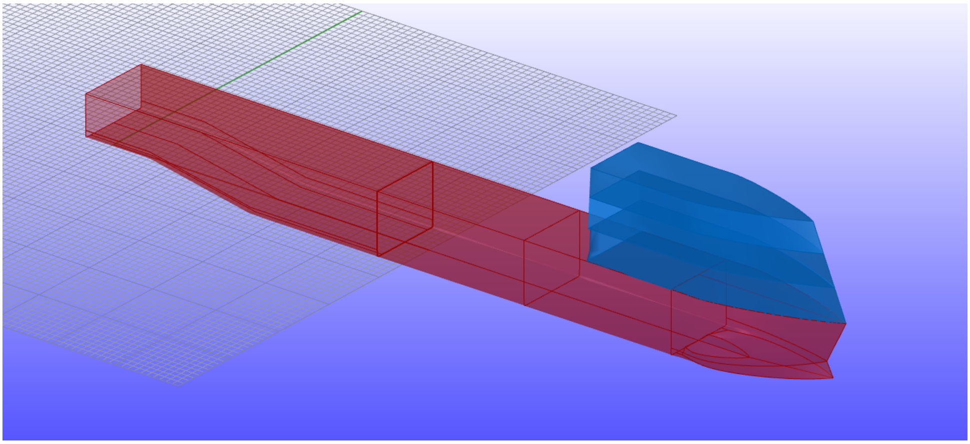


Figure 5.11: Model Float Structure HLP Result

5.4. LAYOUT GENERATOR

This is the second part of the modeling process which is aimed to provide a clear view into how the layout generator is built. There are two types of layout generator, one uses the building block as basic assemblies and another use modules to generate a layout for a whole compartment. These two concepts are similar but have different levels of limitation from the boundary box mentioned in the hull shape generation part.

5.4.1. HULL ASSEMBLIES COUNDARY BOX

Hull assemblies are the parts forming the hull object. They can be boxes, cylinders, and other geometries in the CAD system. In order to minimize the interaction with the shell object, an internal boundary is required to specify the actual functional space within the hull, namely the compartment except for wing and bottom tanks. The wing and bottom tanks are chosen to be the objects defining the boundary is an assumption made after going through a number of reference vessels and the block division plan according to the author's working experience. The default function of the bottom tank is assigned to be bottom ballast tanks. As for the wing tank, there is no default function as it can be either thin as a steel plate or spacious as a walkway according to the user's input. Examples from three different vessels are provided in Figure 5.12.

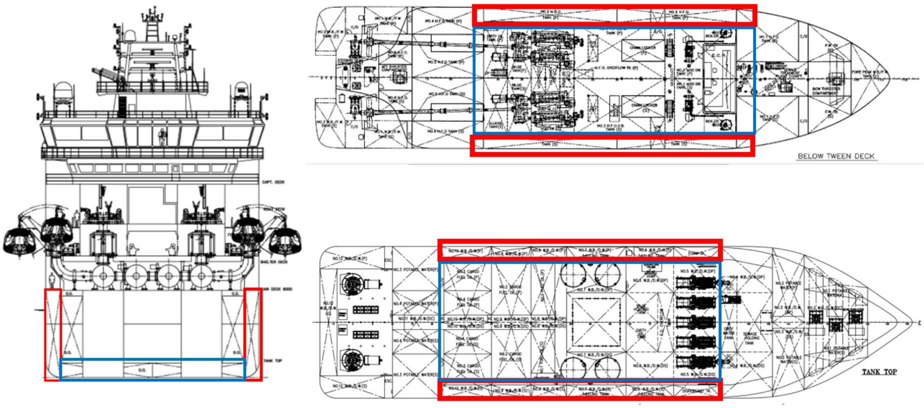


Figure 5.12: Examples of Wing (red) and Bottom (blue) tank layout in three different vessel (“BOKA DA VINCI”, 2020, “BOKA SHERPA”, 2020, “FOCAL 532 90M RDSV”, 2017)

A procedure for creating this internal boundary is illustrated in Figure 5.13. Details for each step:

1. Project *line_bilge_t* to the center surface to create a reference line *line_bilge_CL*
2. Extrude *line_bilge_t* to *line_bilge_CL* to generate the tank top deck.
3. Close the openings to form a *ClosedBrep* to represent the bottom tank. The top surface of the bottom tank is the bottom boundary of the wing tank surface.
4. Extrude the side shell to defined length to generate the wing tank.
5. Mirror the two *ClosedBrep* objects according to the centerline to create symmetric tanks on the starboard side.
6. Take all the corners of the inner space to create the boundary box.
7. This boundary box’s dimension is adjustable afterward by changing the width of the wing tank.

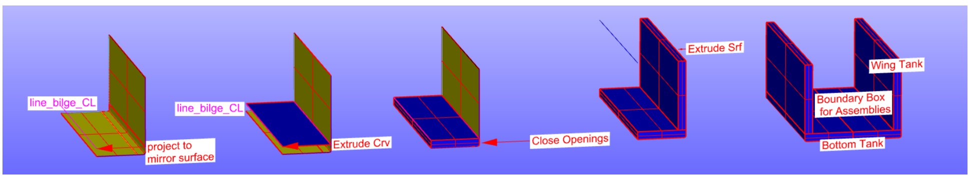


Figure 5.13: Assembly boundary box construction concept

The boundary box will separate the shell generator and internal layout generator into individual systems. The advantage for making this boundary is to make hull design and internal system design can be parallel processing. A result of this concept is generated according to the main dimension of reference vessel *BOKA Da Vinci* as shown in Figure 5.14. The three main sections with different functions can be identified from the model. The boundary of the functional compartment is the bulkhead shared with *Shell_ForeHull*. This boundary box concept is applicable to *MidHull*, *AftHull*, and *connection*. The *ForeHull* is an exception for this concept due to tolerance problems at the peak section which can lead to a fatal fail in modeling results. Thus it will be discussed independently in the next section.

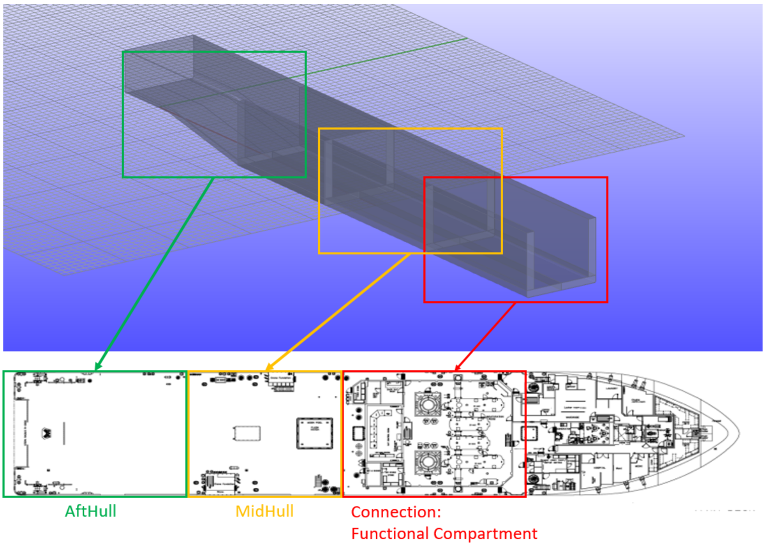


Figure 5.14: Assembly boundary box construction result

5.4.2. Model Assembly configuration concept

The first type of layout generator uses the boundary box as the assembly of the hull section. The first set of objects are the boundary boxes and building blocks mentioned in section 3.2. The most representative section layout for explaining this concept is *MidHull*. From the functions assigned to this HLP listed in subsection 4.3.2, it is assumed that *MidHull* is a section built with "box-like" assemblies as F.O.T, L.O.T, F.W.T, liquid cargo tank, and an optional tunnel passage to connect bow and stern. In Figure 5.15, the procedure to generate an internal layout for a similar tank is provided:

1. Create the floor of each assembly
2. Extrude it with the defined height
3. Close all openings and check all the blocks are "Close-Brep"
4. (Optional) Create the cross-section of the tunnel passage
5. (Optional) Extrude the section along the section to generate a box
6. (Optional) Use *BooleanDifference* to create the tunnel.

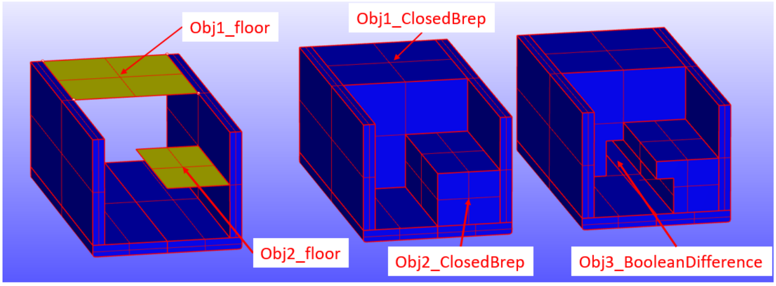


Figure 5.15: Assembly boundary box internal construction concept

Example results of a *MidHull* and an *AftHull* are provided in Figure 5.16. An explanation for creating the tunnel passage with *BooleanDifference* is that the system is coded to keep recording the enclosed volume of all the tanks in this section. The red box and green box in the *AftHull* are both assigned to be propulsion room as a reserved function for installing either direct drive from the propulsion machinery or azimuth thrusters. The *connection* HLP are assigned either functional compartment or cargo hold, thus the internal layout is basically a box that filled all the space enclosed by the boundary box.

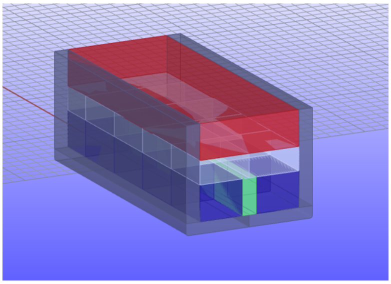


Figure 5.16: Assembly Boundary box Internal Construction Example-MidHull

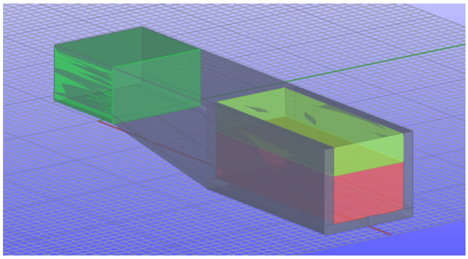


Figure 5.17: Assembly Boundary box Internal Construction Example-AftHull

FOREHULL ASSEMBLIES

The *Shell_ForeHull* is the section with the most diverse shape. Even in this research, the number of characteristic curves has been considerably reduced, the model is still unstable due to the curves' continuity at the joint. The consequence is that making a box-like object within the shell is a time-consuming process and often gives unstable modeling result. Thus the shell of the *forehull* is chosen to be the boundary box to enclose all necessary compartments.

In Figure 5.18shows an example of how this concept is deployed.

1. Create the boundary to separate the fore- and aft section of the ForeHull section. This boundary is different from the curve *"line_trans2_p"* to define the shape as mentioned earlier in the hull shape generating part.
2. Define the deck height of the **"1st-deck"**.
3. Use "BooleanSplit" to Split the *"closedBrep"*
4. Check all four breps are "closed-brep". This is important for a fail-created brep will invert the "BooleanSplit" result and switch the defined engine room and bow thruster room. *shell_forehull*

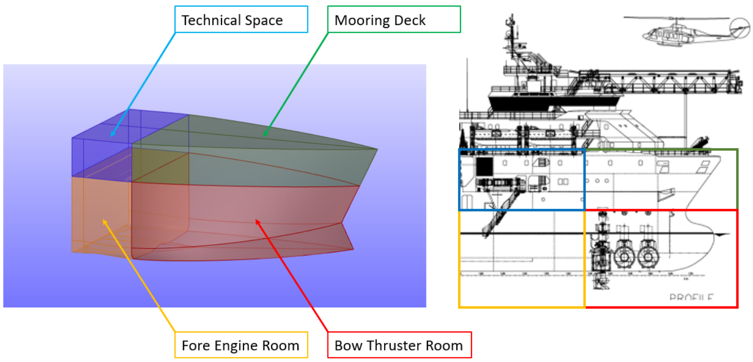


Figure 5.18: Model Fore Hull Result

5.4.3. WORKING DECK AND MODULAR COMPARTMENT LAYOUT GENERATOR

This is the second type of layout generator. It is designed to enable generating objects at the requested position. A simple description of the process is "create-scale-move-extrude". A schematic draw is provided in Figure 5.19. The target plane is divided into three sections: Port-side, centerline and starboard-side. It can be subdivided into the forepart and aft part for certain objects that can only be placed closed to the superstructure (a conditioned deck) or need to be placed at the stern (a stern roller). The reference point for moving objects on the target plane is defined by the section it belongs to. This setting is to reduce the user confusion about which value should be assigned to y-direction [2]. The logic for building the input data is following the order of centerline, port-side, starboard-side to make it easier to be placed. [3] Other objects are settled according to their relationship matrix.

[2]In Rhinoceros setting, the longitudinal length (x-axis) use the real distance. While using y-direction, it assigned port-side to be (0.5) and starboard-side to be (-0.5).

[3]User is free to create a separate input file with different numbers and sizes of objects. In the default sheet, each vessel is given ten(10) slots for working deck objects, one (1) slot for engine, one(1) slot for Generator set, one(1) slot for bow thrusters, one(1) slot for shaft & azimuth thruster.

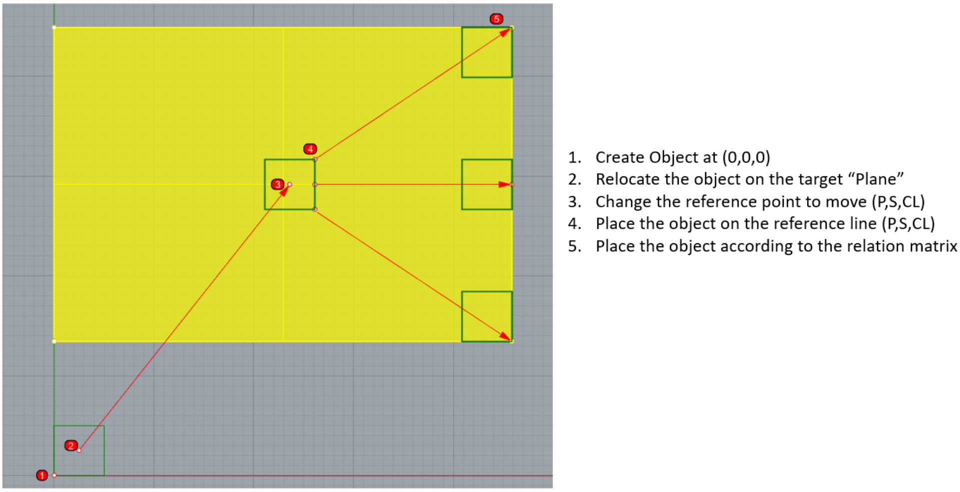


Figure 5.19: Layout Generation Concept

5

MAIN MACHINERY ROOM

This category includes the main engine room, propulsion room, and bow thruster room. They share a common characteristic that the object should be place symmetric to the centerline to assure balance on both sides. An example is shown in Figure 5.20 Bow thrusters are placed along the centerline of the bow thruster room and create an open on the hull to represent the bow thruster tunnel. Objects in the engine room is simultaneously generated on a surface with the same shape as the engine room floor outside the hull to ensure the user has a better view of the layout. The blue box is an indication of the chosen object in the model. It gives the user freedom to move on the x-y surface and indicates the collision with other objects.

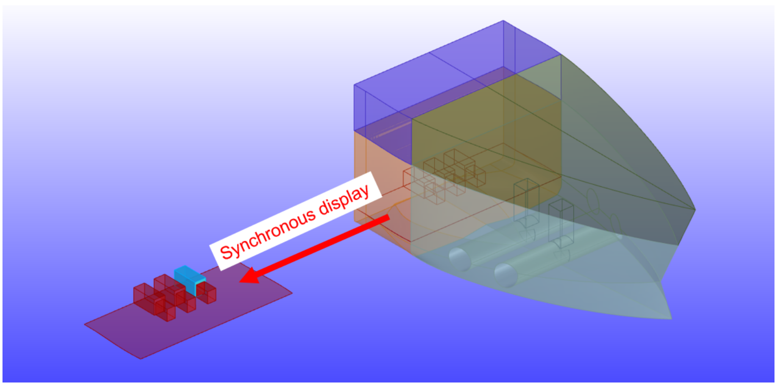


Figure 5.20: Layout generator result: Main Engine Room & Bow Thruster Room

Functional compartment

Functional compartments are basically assigned to the connection section. It contains a layout that has the possibility to interact with the hull, special operational layout, or compartment that doesn't fit in the storage tank category. There can be various types of layouts according to the users' requests. A default boundary is a box object. Users can assign different floor levels within the box thus creating a target plane to place modules and run through an optimization program to decide the layout generation default. An example layout of a diving support vessel is provided in Figure 5.21. A target plane is set on the tank top deck of the connection section. Three-floor areas are placed on this plane to indicate the diving support facility, the diving control room, and storage room. Then another target plane is assigned to the diving facility area. Moonpool(shown as a column to illustrate the required clean space above and below) and saturation vessels (shown as four cylinders) are placed accordingly to the layout scenario. By creating different layout configurations within the box, it is expected to provide all kinds of different indoor facilities built within the hull.

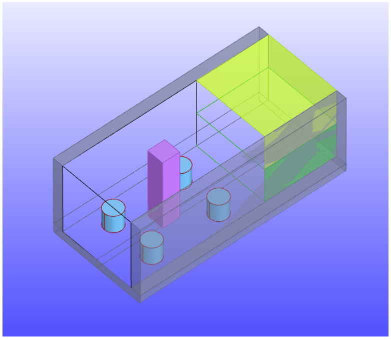


Figure 5.21: Layout generator result: Functional compartment-Diving Support Room

Working Deck Layout

The working deck layout is one of the most important part in this research. Due to the diversity of OSV, the equipment list can be totally different even if two vessels fall in the same ship type. Thus, scenarios have been built customized according to the essential equipment for each type of vessel:

1. **GSV:** containerized laboratory, towed array sonar, seabed driling Rigger, ROV system
2. **DSV:** ROV system, TMS, ROV garage, Wet diving bell
3. **CLV:** carousel, carosel handling crane, tensioner, stern roller.
4. **CSV:** Anchor handling winch, towing winch, shark jaw, guide pin and stern roller

The order for placing each object follows the rules is the same as the rule discussed at the beginning of this section, "center-port-starboard". The built-in python layout generator places the object at the required place with a default position of each object. At this point, it only provides one set of scenario but remains the ability to improve in the future. Example scenario for each vessel is provided in Figure 5.22.

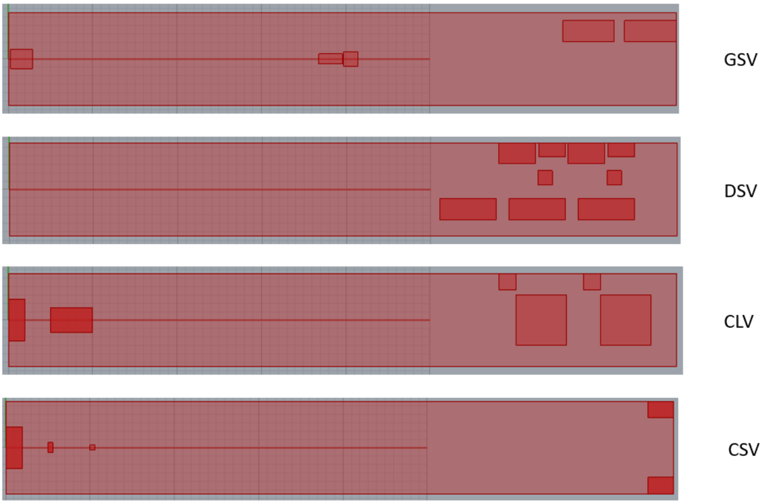


Figure 5.22: Layout generator result: Working Deck

5.5. Conclusion of Part III

In this chapter, the full process to build the MMG is provided. The development of the system is trying to keep as simple as possible thus the concept of naming convention, object properties description, and intake of data has been integrated in the development. Following the OOP structure, the procedure of constructing this framework is clear, "point-curve-surface-box" for the floating structure HLP in the hull shell generation and "shape-scale-place-arrange" for the modules HLP in the layout. It turns out to be a decent modeling tool that is able to reproduce previous design results if a formalized and standardized database is provided. In Figure 5.23, a full model trying to fit all the features of a DSV in the reference ship database is generated. A conceptual CLV is provided in Figure 5.24 as a supplement to show that this frame work is able to generate vessels with different configurations. The Rhinoceros-Grasshopper combination shows the possibility that users can see the modification made in the input sheet are directly reflected in the model. Small modification in the model is also possible for the parameters for building each section remained open to access from the grasshopper interface.

The framework development contains a lot of assumptions in making all the decisions since there is lack of a standardized design database input. Most of the information comes from the ship owners' and operators' brochures, shipyards' advertisements, and specification sheets of vessels on the second-hand market. Mining information from all the fragment information is a challenge for there is always a missing puzzle that makes the information set incomplete. Another reason making the model not fully up-to-date is the slow development of grasshopper comparing to the annually updated Rhinoceros software. The Python framework embedded in the grasshopper stop receiving updated since 2007 which makes it hard to keep up with the latest CAD development.

Finally, the MMG system has proved to provide a decent modeling result that is ready for testing. In the next chapter, a procedure for building a power estimation, weight estimation, and ship coefficient collection function module in grasshopper will be provided. Results for reproducing several reference ships will be discussed in order to validate the modeling result.

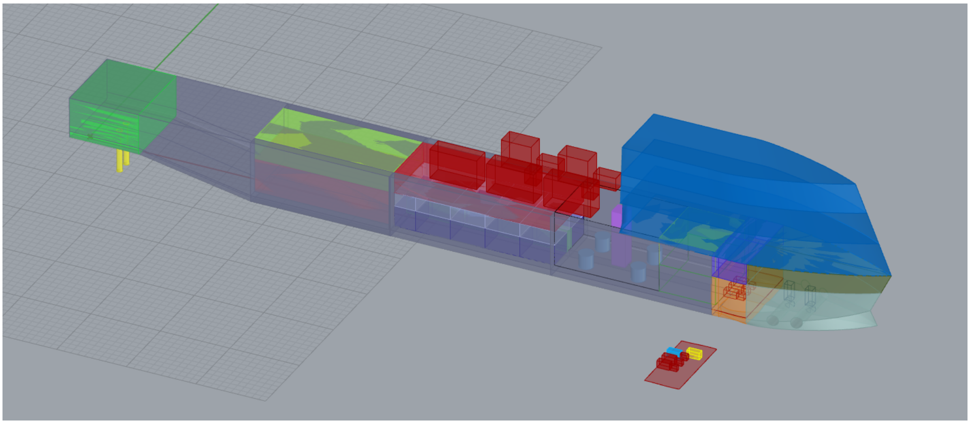


Figure 5.23: Assemblies result-reference DSV

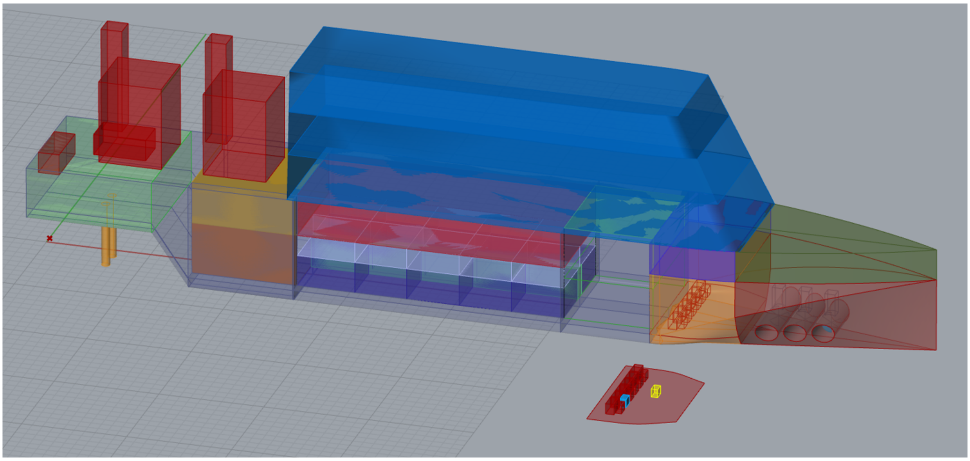


Figure 5.24: Assemblies result-Conceptual CLV

6

Evaluation of the Results

In this chapter, the verification and validation of the MMG modeling results will be discussed. The content consists of three parts: Equations for verification, generating different ship hulls, and generate different operational layouts on a chosen ship hull. This progress is created to imitate the product platform developing process mentioned in section 2.7. It is aimed to perform an OSV product family design process from choosing the modular platform to mount different task-related modules on the working deck. Each combination of modular platform and task-related module set is an individual product in the OSV product family.

6.1. Geometrical model evaluation

- **Initial stability**

  From the Definition (Papanikolaou, 2014), metacentric height (GM) can be calculated by applying the following equations:

$$GM = KM - KG \tag{6.1}$$

$$KM = KB + BM \tag{6.2}$$

$$BM = \frac{I}{V} \tag{6.3}$$

$$KG = \frac{W_{Hull} \cdot Z_{C.O.V} + W_{WorkingDeck} \cdot Z_{deck}}{W_{Hull} + W_{WorkingDeck}} \tag{6.4}$$

where
GM : metacentric height
KM : distance from the keel to the metacenter.
KB : distance from the keel to the center of buoyancy.
BM : distance from the center of buoyancy and to the metacenter.
I : second moment of area of the waterplane (m^4)
V : volume of displacement (m^3)

C.O.V : Center of volume The required value of KB, I, and V can be retrieved from the Rhinoceros function for finding volume and surface properties.

The KG value is estimated by taking the weights of the hull and working deck layout into account. For achieving a more practical GM value, the value 2.5m from literature (Wawrzyński, 2018) is suggested by a ship designer is chosen to be the goal of the design value. This standard is higher than the minimum requirement of 0.15 m suggested by DNV-GL ("RULES FOR CLASSIFICATION Ships Part 5 Ship typesChapter 10 Vessels for special operations", 2020).

- **Ship weight estimation**
  Weight estimation will be approached from two aspects. The first one is from the theoretical aspect adapting the empirical and semi-empirical methods introduced in Watson's publication (Watson, 1998).

$$W_{si} = K_{si} \cdot E^{1.36} \tag{6.5}$$
$$W_s = W_{si}[1 + 0.05(C_b{}' - 0.70)] \tag{6.6}$$
$$C_b{}' = C_b + (1 - C_b)\frac{(0.8D - T)}{3T} \tag{6.7}$$
$$W_{machinery} = 12(\frac{MCR}{RPM})^{0.84} \tag{6.8}$$
$$W_{remainder} = K_{remainder} \cdot MCR^{0.70} \tag{6.9}$$
$$W_{electric} = 0.72(MCR)^{0.78} \tag{6.10}$$
$$\sum W_{Hull} = W_s + W_{machinery} + W_{remainder} \tag{6.11}$$
$$+ W_{electric} + W_{WorkingDeck} \tag{6.12}$$
$$DeckLoading = W_{WorkingDeck} / A_{WorkingDeck} \tag{6.13}$$

where:
W_{si} : steel-weight at $C_b{}' = 0.70$ as plotted/lifted from graph.
W_s : steel-weight for actual $C_b{}'$ at 0.8D
$K_{remainder}$: 0.19 (frigate)

Coefficient K is chosen to be 0.045 from Table 6.1 provided in Watson's book. The value of E is chosen to be 1300, as it can fit to both offshore support vessel and research vessel requirements. In addition to the two types mentioned above, the coefficient for estimating the weight of a tug is also provided due to the fact that CSV can be categorized as a type of tug. The result gives a rough steel weight for the whole ship including the superstructure. The sum of the estimated weights will give an estimation of the primary dead weight. The result is a rough calculation to show the MMG is able to run a weight estimation and give users a sense of how heavy the vessel is. It can not be directly referring to the real weight of the vessel.

Table 6.1: Table of value K and value E (Watson, 1998)

Type	K_{si} Mean value	Range	Range of E
Offshore Supply	0.045	±0.005	800 - 1300
Research Ship	0.045	±0.002	1300 - 1500
Tugs	0.044	±0.002	350 - 450

The second approach is estimating the wet volume from the modeling result. It takes the displacement defined by assigned draft then multiplies by the density of seawater. The proposed method is to examine the difference between the two values calculated from different approaches. It will indicate how much additional payload can be taken on board. In addition to the difference between the two weight values, the deck loading is also taking into consideration to ensure a feasible result. [1].

- **Power estimation**
  Installed power estimation is based on the empirical methods introduced by Klein Woud and Stapersma (Woud and Stapersma, 2018). It is a series of equations to derive the brake power from the effective power. The result will indicate the required installed power to meet the designed ship speed, maximum ship speed and bollard pull for tug boats.

$$C_T = \frac{R_T}{\frac{\rho}{2} \cdot {v_S}^2 \cdot S} \tag{6.14}$$

$$R_T = C_T \cdot \frac{R_T}{\frac{\rho}{2} \cdot {v_S}^2 \cdot S} \tag{6.15}$$

$$P_E{}^{def} = R_T \cdot V_s \tag{6.16}$$

$$= T \cdot V_s \tag{6.17}$$

$$P_B = \frac{P_E}{\eta_D \cdot \eta_{TRM}} \cdot EM \cdot SM \tag{6.18}$$

$$\tag{6.19}$$

where:
R_T : total resistance
ρ : density of sea water
v_s : ship speed
C_T : 0.001 - 0.005 (Birk, 2019)
T : Thrust
EM : 0.85
SM : 1.1

[1]DNV-GL suggest a 7 t/m^2 loading on the main deck

6

6.2. GEOMETRICAL MODEL VALIDATION

In this section, models generated based on two reference vessels will be examined. It is a validation process to show whether the MMG is able to generate different ship models. The goal is to generate two different ship models of different sizes. This stage is to explain the design process initiating from deciding the main dimensions of the modular platform.

BOKA DA VINCI

The first one is *BOKA DA VINCI*. She is a 12,565-ton diving support vessel equipped with both surface and saturation diving facility certified by DNV-GL. The most important feature is the modularized saturation diving facility. The modular facility is integrated with the ship structure. The facility includes two moonpools at the bottom level and a set of saturation vessels. In addition to the diving facility, the large capacity for fuel and water enables her to perform missions with a longer duration [2]. From the system break down, the vessel needs to provide saturation and surface diving function, ROV support, carrying deck cargo, and basic hotel and ship service. Thus *connection*, *MidHull*, *AftHull*, *ForeHull*, Superstructure are chosen to form this vessel.

By running the MMG, a reproduction of the vessel is generated. The characteristics of the vessel and the comparison with the reference vessel are provided in Table 6.2. From the table, the difference in displacement is less than 2 percent. As a model generated with only the main dimension, the result can be considered satisfied. The total installed power is difficult to estimate for most of the energy consumption remain unknown at the moment. While the estimation of the required power for propulsion is highly matched. The forecastle floor is overestimated for around 200 m^2 conditioned deck area is included. The crew number is underestimated for some accommodation compartment located under the main deck. The superstructure area is distributed to crews,7 m^2 per person according to MLC rules for vessels over 10,000 tons.

A detailed input for the MMG is provided in Table 6.3. In this stage, one can see that the MMG first takes in the percentage of the vessel's LOA to decide the main sections. Secondly, unique parameters for each section are provided to create the interior configuration for each section. The working deck configuration is also created on the working deck surface. The weight information of the working deck will be sent back to the analysis program section to improve the estimation of GM. The visualization of the model is provided in Figure 6.1.

[2] In the specification sheet, this vessel can perform missions with a maximum duration of 45 days.

Table 6.2: Vessels Characteristics (BOKA DA VINCI)

		GSV-BOKA Da Vinci	
		MMG	Reference
General			
LOA	(m)	115.4	115.4
Beam	(m)	22.2	22.2
Height	(m)	11.8	11.8
Depth	(m)	9	9
Draft	(m)	7.035	7.035
Displacement	(ton)	12689	12565
Propulsion Power Estimatior	(kw)	6302	6000
Bow Thruster	(set)	2	2
Forecastle deck space	(m^2)	501 (conditioned deck included)	235
Cargo main deck space	(m^2)	1120	1120
Fuel oil	(m^3)	1424	1440
Fresh water	(m^3)	1068	1160
Performance			
Speed (MCR)	(kn)	13	13
Saturation diving support		Yes	Yes
MoonPool		Yes	Yes
HeliDeck		Yes	Yes
ACCOMMODATION			
Crew		91 (minimum)	123
Working Deck			
Main Crane		Yes	Yes
Auxiliary Crane		Yes	Yes

6

Table 6.3: Technical Specification-BOKA DA VINCI

Technical specification								
Important features			**AftHull (0.38)**			**MidHull(0.17)**		
LWL	(m)	115.4	Fore_trans	(m)	2	Side_Tank_Width	(m)	1.2
GM	(m)	3.93	Aft_trans	(m)	6	Passage_Width	(m)	0.001
C_B	(m)	0.51	trans_height	(m)	6	Passage_Height	(m)	3
W_{si}	(ton)	766673	Type		Pod	2nd_Deck_Height	(m)	3
P_E	(kw)	6302	num. propulsor		2	3rd_Deck_Height	(m)	4
\eta_p		0.6	Shaft_diameter	(m)	0.8	#1 Tank Length	(m)	18
\eta_trm		0.96	shaft_length	(m)	4	#2 Tank Length	(m)	1
Sea margin	(%)	110				#3 Tank Length	(m)	0
Engine Margin	(%)	85				#4 Tank Length	(m)	0
K		0.05						
E		1300						
Connection(0.1)			**ForeHull (0.35)**			**ForeHull_BowThrusterRoom**		
DivingRoomLength	(m)	13.527	lock_pos	(m)	2	n_propeller		2
FunctionTank_Height	(m)	0	Shape_Control	(m)	15	Shaft_diameter		1.5
nvessel		4	ShapeControl_bilge_y		-2	ME_floor		1
PressureVessel_Radius	(m)	1	ShapeControl_bilge_z		3	num_Genset		3
PressureVessel_Height	(m)	3	ShapeControl_bottom_y		-3	**SuperStructire**		
nmoonpool			fore_BP_x_mover_top		0	S.S.Deck_height		3
MoonPool_length	(m)	2.2	fore_BP_x_mover_mid		-2	Position		0.57
MoonPool_width	(m)	2.2	fore_BP_z_mover_mid		2	Length_max		0.388
			fore_BP_x_mover_bottom		0	**SuperStructure_Helideck**		
			fore_BP_z_mover_bottom		1.2	Deck No.		2
			1st_WT_Bulk		10	Helideck Radius		11
			1st_Deck_height		3			

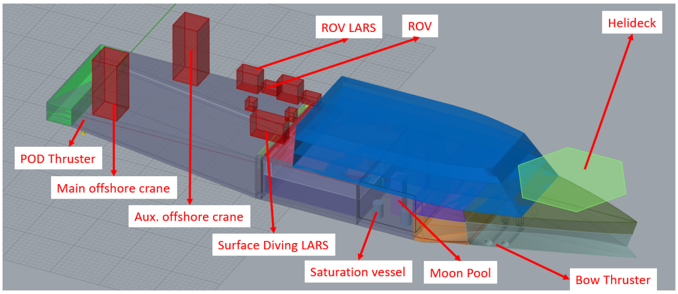


Figure 6.1: Reference vessel modeling result-BOKA DA VIN CI

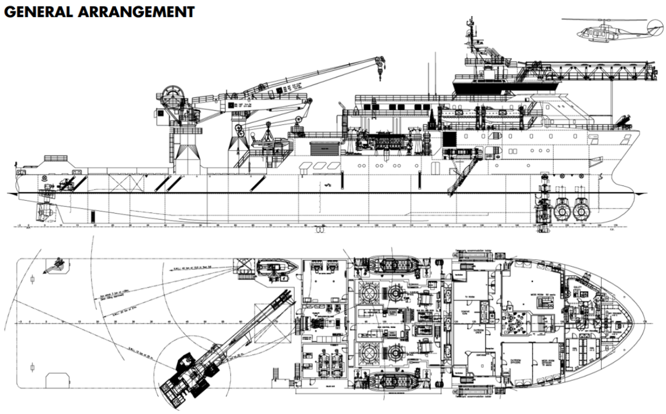


Figure 6.2: Reference Vessel-BOKA DA VIN CI

BOKA SOVEREIGN

The second vessel is *BOKA SOVEREIGN*. She is a medium-sized sea-going tug boat and also provided anchor handling service. This vessel is chosen to be validated to show that the MMG can handle smaller vessels and provided a satisfied bollard pull power estimation. From the system breakdown, this vessel provides towing and anchor handling surface, higher speed requirement, a direct drive from the fore engine room. Thus *AftHull*, *ForeHull*, *ForeHull*, superstructure are chosen to form this vessel.
The input for the model is provided in Table 6.4 The DWT of this vessel is not provided, thus the most important feature in this table is the estimation of bollard pull power. It is estimate at the design bollard pull force, 195 t, at 0.1 knots. The freshwater tank does not meet the requirement for the most voids in the stern section are categorized as the fuel tanks. The real tank arrangement is not available from the datasheet thus there could be hidden voids for freshwater storage. Except for this defect, the other numerical results highly correspond to the reference vessel.

A detailed MMG system input is provided in Table 6.5. The visualization of the model is provided in Figure 6.3. One important point here is the absence of the *connection* section results in that the fore engine compartment in *ForeHull* and the main propulsion in *AftHull* are directly connected. This connection is created in purpose to represent a direct driving configuration.

Table 6.4: Vessels Characteristics (BOKA SOVEREIGN)

		GSV-BOKA SOVEREIGN	
		MMG	Reference
General			
LOA	(m)	67.4	67.4
Beam	(m)	15.5	15.5
Height	(m)	7.5	7.5
Depth	(m)	7.44	7.44
Draft	(m)	6.2	6.2
GT	(m^2)	2,239	2,263
Power Estimation (bollard)	(kw)	12,052	12,000
Bollard Pull		22431	
Bow Thruster	(set)	2	2
Cargo main deck space	(m^2)	383	344
Fuel oil	(m^3)	2740	2740
Fresh water	(m^3)	129	216
Performance			
Speed (100% MCR)	(kn)	17	17
Tugger Winches		Yes	Yes
Stern Roller		Yes	Yes
Towing Pins		Yes	Yes
Shark Jaws		Yes	Yes
ACCOMMODATION			
Crew		36	36

Table 6.5: Technical Specification-BOKA SOVEREIGN

Technical specification					
Specification			**AftHull (0.65)**		
LWL	(m)	66	Fore_trans	(m)	2
GM	(m)	2.04	Aft_trans	(m)	6
C_B	(m)	0.56	trans_height	(m)	6
W_{si}	(ton)	126113	Type		SHAFT
P_E	(kw)	(Bollard) 22781 @ 0.1 knot (Max) 6444 @17 knot	num. propulsor		2
\eta_p (bollard pull)		0.6 (1)	Shaft_diameter		0.8
\eta_trm		0.96	shaft_length		40
Sea margin (bollard pull)	(%)	110 (100)			
Engine Margin (bollard pull)	(%)	85 (100)			
K		0.044			
E		350			
ForeHull (0.35)			**ForeHull_BowThrusterRoom**		
lock_pos	(m)	2	n_propeller		2
Shape_Control	(m)	18	Shaft_diameter		1.4
ShapeControl_bilge_y		-3	ME_floor		1
ShapeControl_bilge_z		2.2	num_Genset		5
ShapeControl_bottom_y		-3	**SuperStructire**		
fore_BP_x_mover_top		0	S.S.Deck_height		3.3
fore_BP_x_mover_mid		-1.5	Position		0.66
fore_BP_z_mover_mid		4.5	Length_max		0.5
fore_BP_x_mover_bottom		-1.5			
fore_BP_z_mover_bottom		0			
1st_WT_Bulk		4			
1st_Deck_height		3			

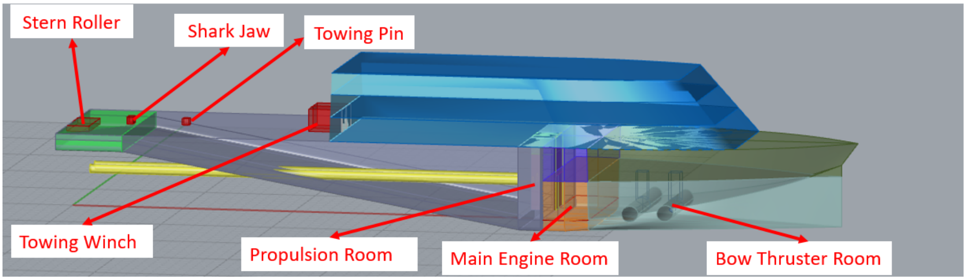


Figure 6.3: Reference vessel modeling result-BOKA SOVEREIGN

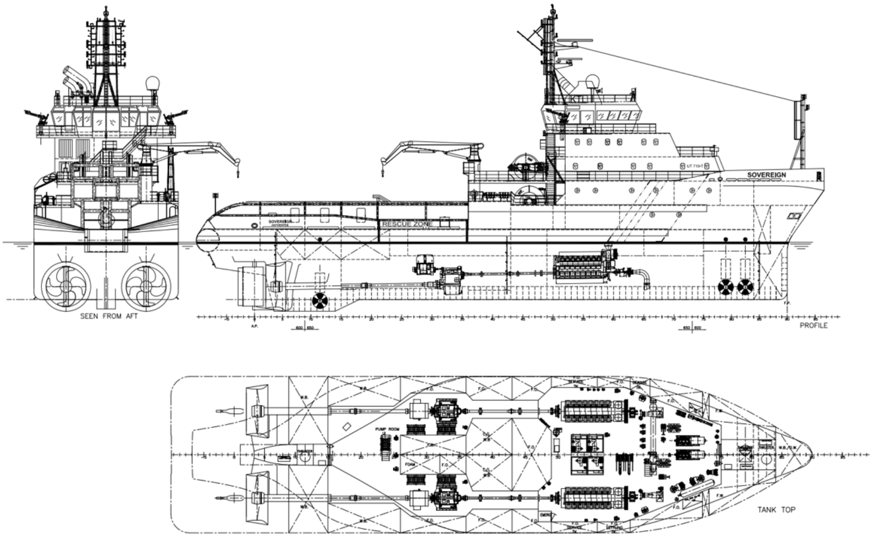


Figure 6.4: Reference Vessel-BOKA SOVEREIGN

6.3. MODULAR PLATFORM

The second part of the modular platform development is performed. This is to show the impact of different operational configurations installed on the working deck.A possitive GM is the main indication .

In the real cases, payloads on the working deck will elevate the position of COG. The value of GM will correspondingly decrease as the result. In this section, a process showing that *BOKA Da Vinci*'s Hull is chosen to be the base of a OSV modular product family. It is now carrying different operational configurations to perform various operations including cable laying, Geo-physical/technical survey, and platform supply.

6.3.1. CSV LAYOUT

The CSV configuration is adapted from *BOKA SOVEREIGN*. It consists of a set of anchor handling winch, a towing winch guide pin, shark jaw, and roller. The configuration is to fulfill the requirement to handle the anchoring of wind farm foundation and deploy buoys as amrks on the sea. The anchor handling winch provide continuous pulling force to keep the anchoring falling at a constant speed. The guide pin and the shark jaw on the deck keep the chain at the central position to prevent it sweeping on the deck. The empty area on the deck are reserved storage area for spare ahcnors and buoys. It can also take deck cargo when necessary. The proposed equipment list is provided in Table 6.6. The GM is estimated as 4.69 m. Estimations of the equipment weights come from ship outfitting providers. The deck loading is 0.19 ton/m^2. It can take at least 10 offshore anchors with nominal weight 30,000 kg from Fendercare marine®. The rest of the deck area can be used for carrying deck cargoes. The modeling result is visualized in Figure 6.5.

Table 6.6: Modular Platform - CSV

Technical specification_CSV			
Specification			**Layout**
GM	(m)	4.69	Anchor Handling Winch
Deck Capacity	(ton)	3,087	Guide Pin
SuperStructure_Helideck			Towing Winch
Deck No.		2	Shark Jaw
Helideck Radius		11	Stern Roller

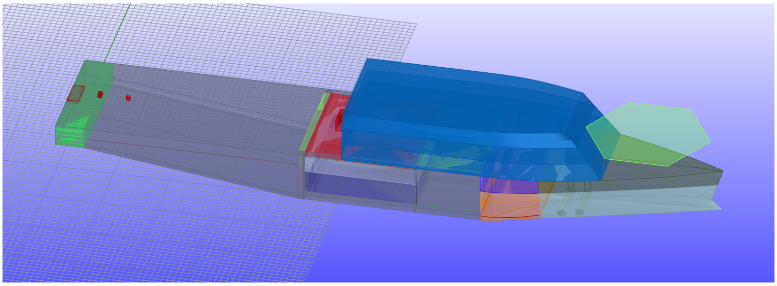


Figure 6.5: Modular Platform CSV

6.3.2. GSV LAYOUT

The GSV configuration is the type of vessel that lacks reference. The proposed equipment list is provided in Table 6.7. Estimations of the equipment weight are either adapting from other vessels or direct calculate the weight from the box and mild steel density. The equipment including a towed array sonar (TELEDYNE MARINE®-BENTHOS) and its LARS (estimated), sea drill rigs (MARUM®-MeBo70 drill rig) and containerized lab (GeoTech®). The GM is estimated to be 5.4 m. The spare area on the working deck can be used to carry cargoes and samples from the seafloor. The modeling result is visualized in Figure 6.6.

Table 6.7: Modular Platform - GSV

Technical specification_GSV			
Specification			**Layout**
GM	(m)	5.4	Towed Array Sonar
Deck Capacity	(ton)	3,266	Towed Arrary Sonar LARS
SuperStructure_Helideck			Containerized Lab
Deck No.		2	Sea Drill Rig
Helideck Radius		11	

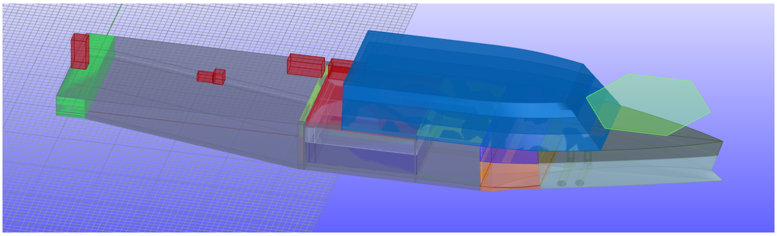


Figure 6.6: Modular Platform GSV

6.3.3. CLV LAYOUT

CLV is the heaviest configuration among all configurations. The proposed equipment list is provided in Table 6.8. A cable storage facility is necessary for transporting cables to the designated location. There is usually a auxiliary crane on the side of the storage to lift the end of the wire in order to feed it into the tensioner. The wire will be stretched in the tensioner then attached to the trencher. After lowering the trencher to the seabed, the cable laying work is performed by ship movement or a automated trencher operation. The proposed equipment list is provided in Table 6.8. A full cable laying facility is adapted from a commercial charting company (Drammen Offshore Leasing®). Deep dig-it from Van Oord® is adapted to be the trencher model. The GM is estimated as 2.44 m. The modeling result is visualized in Figure 6.7.

Table 6.8: Modular Platform-CLV

Technical specification_CLV			
Specification			**Layout**
GM	(m)	2.44	Carrousel (with wire)
Deck Capacity	(ton)	623	Crane
SuperStructure_Helideck			Tensioner
Deck No.		2	Roller
Helideck Radius		11	Trencher

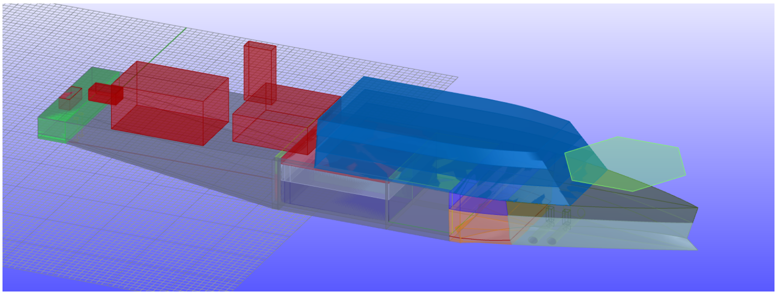


Figure 6.7: Modular Platform CLV

6.3.4. MPV LAYOUT

The MPV vessel adapts the configuration of a DAMEN-designed service operations vessel ("Bibby Wavemaster 1", 2017). It is designed to provide all kinds of offshore support operations including the crew transportation and offshore fleet supplement. The proposed equipment list is provided in Table 6.9. Walk-2-Walk module is adapting the Ampelmann® A-type specification. Crane is adapting the specification of the same crane from the DSV model. Three deck cargoes with the maximum loading are also provided. The GM is calculated as 4.7m. Deck loading is 2.39 ton/m^2. The spare deck area is reserved for more deck cargoes. The modeling result is visualized in Figure 6.8.

Table 6.9: Modular Platform - MPV

Technical specification_MPV			
Specification			**Layout**
GM	(m)	4.7	W2W
Deck Capacity	(ton)	3,098	Crane
SuperStructure_Helideck			DeckCargo
Deck No.		0	
Helideck Radius		11	

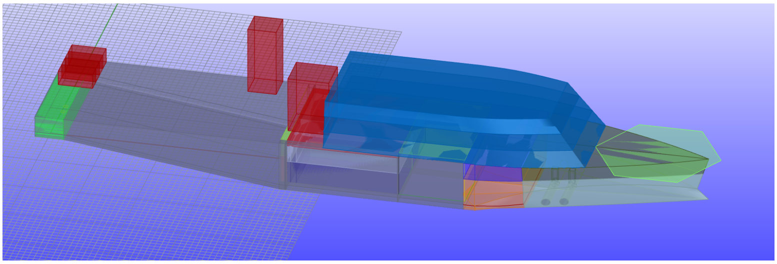


Figure 6.8: Modular Platform MPV

6.4. Discussion based on the proposed design framework

The proposed framework is proved to generate reasonable design results. The benefit is that the platform design and configuration design can be processed separately. Users are able to access the design result with the visualization in the CAD software. The framework consists of two stages: the chosen of ship hull and the selection of request operation configuration.

In the first stage, ship designers can choose the required section blocks in the database if provided. The choosing process is based on the SBSD process to decompose the ship functions. With the utilization of ship hull HLPs, it is expected to generate dozens of ship hulls by putting different ship blocks together. Furthermore, the framework is designed for general offshore structures, thus it has the potential to generate different kinds of offshore structures like drilling platforms, barges, and multi-hull vessels.

The second stage is the choosing process of the operation configuration. The switch between different configurations can be done with just a click. Users are expected to be able to choose from different main engine room layouts, drive chain scenarios, functional compartments, loading plans, helicopter deck types, and working deck layouts. New configurations can be easily integrated with the framework by transforming the latest innovation into a provided data structure.

In addition to the parametric model development, the self-designed analysis system assists users to view the design result from a naval architecture aspect. Important information as displacement, C_b, GM, deck area, deck loading can be read from the monitor block. A primary estimation of installed power can be accessed from the power estimation block. Users are able to create an analysis tool in the grasshopper interface easily by installing the required plug-ins or developing their own tools.

To sum up, the framework provides a different approach to the ship design process. Naval architects from different departments can be freed from repetitive design work if the design project is based on a previous design case with a small modification. They can invest more time to explore the optimization of the ship hull or the innovations in the function configurations.

7

Thesis Conclusions

7.1. Thesis Conclusions

The final output of the present research work is a MMG designed for offshore windfarm service OSVs. It is proved to generate various modular vessel platforms to reproduce models of reference vessels. Furthermore, the modular platform which is chosen to be the base of a modular product family has been developed to form a whole offshore service fleet by switching the working deck configuration. The general idea of this research is to find the HLPs for each subsystems. The present research provides three types of HLPs and their application involved in the design of a OSV product family. They are HLP-Shell to represent the assemblies of the modular platform, HLP-Boundary box to represent the assemblies of ship sections, and HLP modules to generate functional layout installed in different compartment to make them functional parts. All HLPs have their own attributes and operations stored in a class-structured database that can be reused, resized and rearranged to form a new product in the product family. This chapter contains the research conclusions and recommendations for further researches.

The main advantage for applying the tool developed in this research it to accelerate the design process at the preliminary design stage. The MMG developed in this research enables a rapid generation of a prototype design including primary design results including GM , displacement, propulsion power. With these basic information indicating the modular platform performance, customers are able to quickly make a decision for the platform and pass the work to the operation-related modules design.Following sections will provide the answer to each sub objectives included in this research.

- **Offshore support vessel**

  What is the current state-of-the-art of OSVs for wind farms? What are their limitations?

  Currently, the offshore market is dominated by the conventional oil industry (Rex, 2018). This lead to the fact that most OSVs are designed to better support these extremely large mass platforms and their affiliated facilities (Edwards, 2011). When the offshore market gradually shifts to wind farm development and maintenance, the current fleet seems not to be an optimal solution while running at low energy and cost-efficiency. Offshore wind power requires a fast and flexible supporting fleet to perform precise works on site. These works including the pre-construction investigation, installation, maintenance, and operation.

- **Modularity**

  What are the potential advantages of modularity for improving the design process? -What are its limitations?

  Modularity or more specifically, modularization has three main advantages as the reduction of complexity, Utilization of similarities, and creation of variants. The first two advantages enable speeding up the gaining of problem knowledge and delaying the usage of committed costs. The creation of variants ensures the modules can be reassembled to generate a sufficient number of variants.

  The limitations of modularization can be examined from two aspects. The type of modularity and the product architecture involved in the design. Different modularity types have been proved to optimize an industrial product from a certain aspect. Since ships are products that have a higher level of complexity than other industrial products, there is still no consensus on the optimization direction for this product. Thus modularization done from a single aspect can hardly reach the best design result. The second limitation is about the product architecture involving in the design process. From the cargo ship industry, ship design can be accessed from two aspects. Large ship blocks such as bow, midship and stern are suitable for modular (top-down) architecture. Local configuration design is more suitable for integral architecture. There are still doubts whether the same experience can be directly transferred to offshore support vessels for offshore wind farms.

  What is the state-of-art modularity concept applied in ship designs especially for OSV?

  The OSV platform can be roughly divided into a platform and a functional system. Both of them can be decomposed further into several sub-systems by the similarities from system aspect, structural aspect, and mission aspect (Erikstad and Levander, 2012). This lead to a certain system decomposition process named

"SBSD". In the research, decomposed functions are related to pre-designed modules. Modules are designed to have their own characteristics but are required to maintain minimum interactions with other modules. The encapsulation of function forms the basic data structure for processing configuration design. In this research, the similar function decomposition and encapsulation process are adapted but the output is a structural diagram created for OOP.

- **Knowledge based engineering(KBE)**

What are the KBE principles and how can they be applied to support modularity design?

KBE is a type of engineering methodology to capture, formalize and reuse previous design results and turn them into the base of developing new products and variants. A KBE system is formed by a KB system and a CAD application. The KB system processes the stored knowledge, or standardized information, to explore innovative and valuable combinations for generating new design results. The CAD application takes over the design results outputted from the KB system and visualizes the design result in the user interface to give users an intuitive and direct overview of the design. The standardization of formation in the first stage is done in two steps, which are the parsing of data and the reconstructing of knowledge modules.

This process in the digital world has many similarities to the modularity design process. The modularity design can be briefly expressed as a process to decompose the existed product into lesser parts and then reassemble them to form new products. A hypothesis for applying the modularity concept in data processing has been suggested in the literature by claiming that modules can be a carrier of information. Thus the connection between the two topics has the potential to be further studied.

What are the KBE design experiences in other engineering fields to support this modularity design concept?

KBE has been widely applied in the aerospace industry. It has been proved to be valuable for assisting the design of Boeing's airplane products. An example from the literature explains that the airplane can be expressed as a combination of fuselage, wings, and engines. Each part has there own properties and function but they don't act as an airplane if working independently. These parts act as the modules performing certain functions and finally coming together to form an airplane product.

- **Automated layout generation algorithms**

  How to build a trustworthy automated layout algorithm to demonstrate this modularity-KBE system?

  In this research, the Rhinoceros-Grasshopper combination is chosen to be the platform for building this framework. The advantage of this combination is the extensive possibility of implementing various powerful programming tools in this developer environment. The official forum also provides a large variety of open sources for exploring the possibilities of the system and importing them in the annual update.

  In addition to the software-wise support, the literature developed in the aerospace industry has provided a clear procedure for developing a product design algorithm. Though it can not be transferred directly from the aerospace industry, the experiences and developed tools are valuable references in building this modularity-KBE system.

  How to use an OSV layout on the market to validate the design result?

  OSV is a complete and well-developed product family in the offshore industry. In this research, OSVs designed for supporting the construction and operating of the offshore wind farm are chosen to be the main research target. Products are examined from their operations, performances, hull shapes, and general arrangement in order to capture more critical data from the scattered information. Finally, the output from design results is going to be validated by comparing with the provided information from the reference vessel.

Recall the main objective of this research:

Develop an automatic General Arrangement generation framework that is able to combine modularity principles with a KBE system to assist in designing a new OSV family for wind farms.

The developed KBE-like MMG framework has met most of the requirements for this main objective. The defect of this framework for making it not being called a KBE framework is due to the missing data-based optimization parts.

The proposed MMG system is developed in three stages. The first stage is to perform an SBSD based decomposition of the OSV system and link them with corresponded modules. The second stage is to determine the main components in this OSV design framework, namely the choosing process of HLPs. In this stage, it is decided to create three sub-KBE-like systems in order to create a relative practical modeling framework.

The three subsystems are the ship hull subsystem, the section interior configuration subsystem, and the working deck subsystem. Three different categories of HLPs are chosen for each subsystem. The *shell* HLP is the base for generating different hull shapes. The compartment HLP is the basic component to form the sectional function configurations. The *task-related module* HLP forms different working deck configurations to enable the OSV product to perform different operations. The final stage is the CAD application development and validation of the design results. The output of this framework is a model saved in a 3dm file and a performance estimation in comparison with the reference vessel.

The MMG has been proved to be able to reproduce vessels from different scales and with different operational configurations.

7.2. Recommendations for Future Research

The MMG is proved to generate acceptable models for the OSV product families involving in different stages in the life cycle of offshore wind farms. However, this is still in the early-stage development of this topic. For future researchers who are also interested in this topic and willing to improve the MMG framework, the ideas for further developments are listed as follows:

Design Perspective

- In the literature review phase, there are fully developed KBE applications involving in the ship design process. However, most of them are focus on local structural design or layout design but seldom enlarge their scope to the full vessel. The MMG developed in this research has the potential to import the structural design application to the MMG. A similar design pattern and workflow can be found in Koning and his teams' work (Koning, 2010).

- The hull shape developed in the MMG is extremely rough compared to the real hull design. There is a chance to improve the hull design by adding more section control lines in the MMG to improve the generated hull.

- The compartment layout HLP is created as a platform for all kinds of functional layouts. There is an idea inspired by the control volume in the thermodynamic field. That is to treat each compartment as an independent control boundary, thus the input and output from the compartment can be defined and categorized. The input and output properties can be either solid as the electricity and piping network or purely energy density of the whole compartment. With this data structure, there is a potential to explore new sectional configurations.

Analysis tools

7

- A complete KBE contains an internal analysis and an external analysis chain. Modeling results in this research are checked by a self-developed analysis tool but missing the external analyzing process. A self-developed external analysis tool or a further validation process in the existed analysis software as ANSYS® is preferable and necessary.

Database and optimization engine

- As mentioned in the conclusion section, a well-structured database and the optimization framework based on the database are missing in this research. It results in the fact that the framework developed in this research can not be named as a KBE framework. An optimization engine to process reasoning and decision making in the automatic generation will be a big complementary to the whole application.

Epilogue-personal reflection

It is a ten-month most impressive and precious experience ever in my life. Not only because the outbreak of the COVID-19 pandemic but also the impact on my life style.

The first three months of my research, I was trying to read as much literature as I can to figure out each single topic in my research. It was a difficult work especially when I have some mistaken stereotype of them. In addition to the development of the research methodology, I also invested time to gathering vessel information for building my own database.

From the fourth to sixth month, I made the decision to take the course in the Aerospace department to learn more about KBE and its application. I was looking for a chance to apply one of the well-developed KBE tool in my research by joining a group project in this course. Unfortunately, it turns out to be more difficult than I thought to process my thesis along with the KBE assignment. Also, the application for including a commercial KBE software failed at the last moment. Thus, I started to looking for another platform to develop my MMG. Rhino and grasshopper appeared to be the most feasible option on my list. From this experience, I learn that Plan B is a must for every well-planned schedule.

Started from the fifth month, I started to build the first MMG prototype. The difference in processing data between grasshopper and python did cause a lot of problem for there was less flexibility to access the input data sheet. Aside from the software problem, the complexity of the OSV systems was one of the tough questions that I need to figure out. Fortunately, the block division plan and the dry dock schedule of a semi-submersible carrier hanging on my wall gave me inspiration. Among all blocks, the design of engine room block become the definitive concept for building the whole MMG application.The engine room floor including the sludge tank and engine support is the base for mounting all machinery in the engine room. The engine room is a module for a ship section. Multiple sections are combining together to form a vessel product. The topdown structure of "OSV-Section-block-layout-component" is then setup. At the end of the seventh month, the MMG can finally provide models with "closed-brep" property that enables the analysis work.

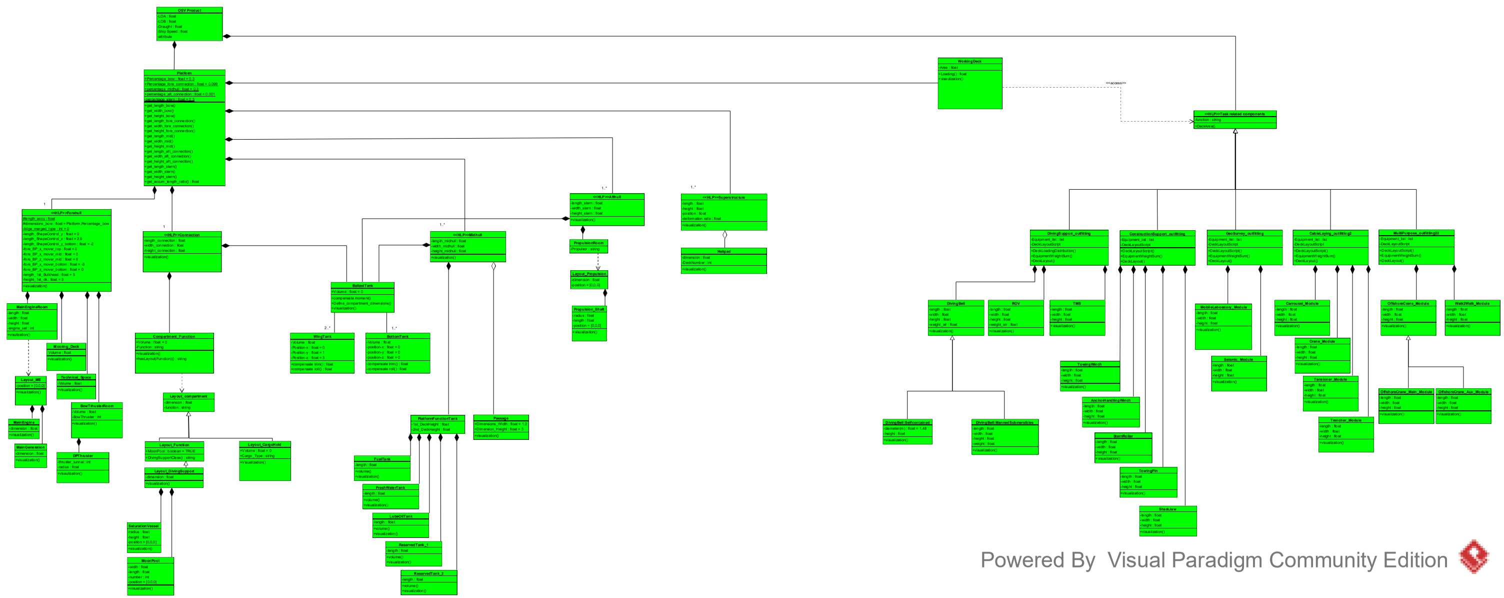
The next two month, the research processed to the next stage. Since the analysis tools provided on the forum are based on architecture application, thus they are weak to deal with floating structure. Thus I start to build the analysis tool to retrieve ship coefficient from the model thus to enable the estimation of ship hull weight and installed power. Thanks for the input from my friends who work in a ship design company in Sweden to provide me some critical values in the design of OSV products in order for me to validate the exported models.

The biggest points throughout the whole research work is the missing of a trustworthy database. The lacking of database do impact the whole schedule since there are thousands of OSV products on the market. To build a acceptable reference vessel database, information of 200 vessels are recorded in the database for building this model. This is excluding the effort searching for detail information for equipment and layout on the working deck, in the engine room, in the bow thruster room and in the main propulsion room. From this challenge, I learned to accept the truth that all the models are wrong and put more focus on generating a practical model but not a accurate model. The reality has more details that need to be taken into account. That gives the fact that ship design is never a work that can be done by a single person, working as a team is the best solution for everyone in the naval architect industry.

Personally speaking, the MMG is designed to be a useful tool for prototyping OSV products by assembling different parts capturing from previous design cases. These design cases provide solutions for different design problems that can be accessed in the future when similar problems appear.By doing so, the time for redeveloping an repetitive solution can be saved for developing new conceptual designs.

APPENDICES

I. OOP-OSV CLASS STRUCTURE DIAGRAM

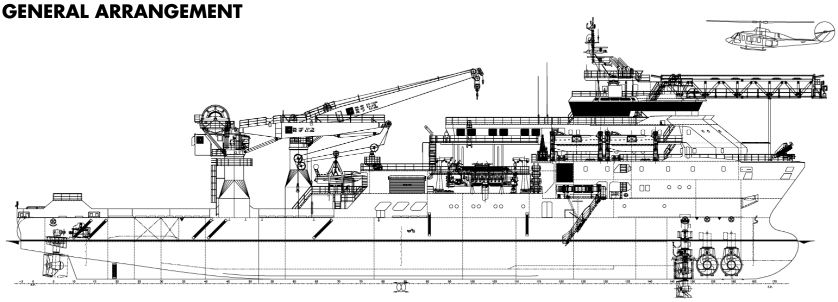


II. GA of DSV-BOKA Da Vinci

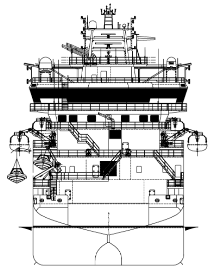
Boskalis

BOKA DA VINCI
DIVE SUPPORT VESSEL

GENERAL ARRANGEMENT

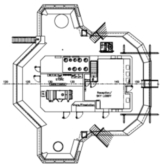


PROFILE

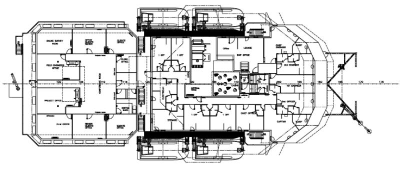


AFT VIEW

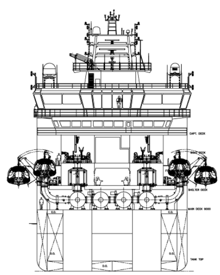
SIDE VIEW



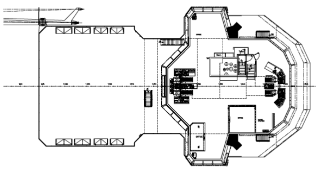
TOP OF WHEELHOUSE



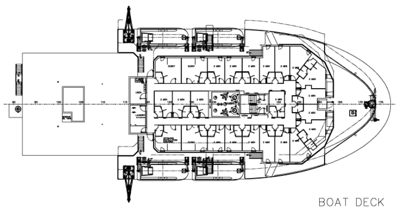
CAPT. DECK



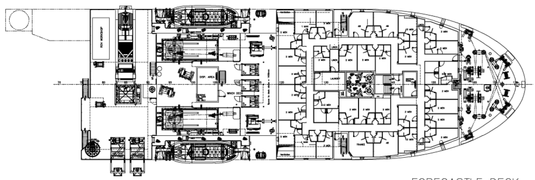
TRANSVERSE SECTION
SATURATION SYSTEM



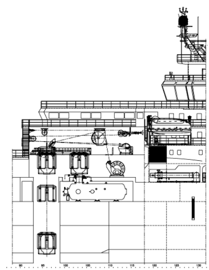
BRIDGE DECK



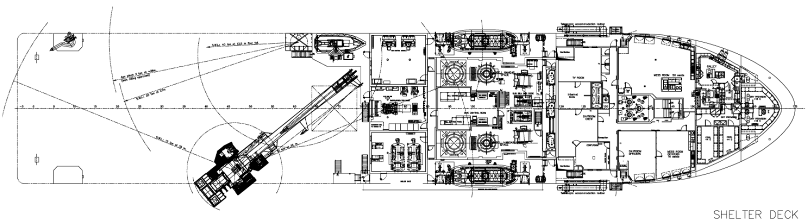
BOAT DECK



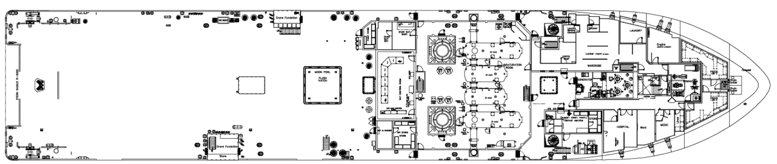
FORECASTLE DECK



LONGITUDINAL SECTION
SATURATION SYSTEM



SHELTER DECK



MAIN DECK

TOP VIEW DECK LEVEL

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III. GA of CSV-BOKA Sovereign

Boskalis

EQUIPMENT SHEET

SOVEREIGN
OFFSHORE VESSELS / ANCHOR HANDLING TUG (AHT)

CONSTRUCTION / CLASSIFICATION

Year of construction	2003
Classification	Bureau Veritas I ✠ HULL ✠ MACH Tug, Fire-fighting 1 Offshore support vessel (Supply), Unrestricted navigation ✠ AUT-UMS, MON-SHAFT, INWATERSURVEY, ✠ DYNAPOS AM/AT R
IMO no.	9262742
Call sign	ORQW
Flag	Belgian
Port of registry	Antwerp
Trading area	Worldwide / unrestricted

PROPULSION AND MAIN SYSTEMS

Main engines	2 x Wärtsillä 16V 32 LND 16,500 bhp / 12,000 kW driving two controllable pitch propellers in fixed nozzles
Propulsion	2 x 6,000 kW @ 750 rpm
Steering gear	Tenfjord SR 662 Ulstein independently / synchronized controlled twin high lift rudders
Bow thruster	2 x electrically driven 588 kW each
Stern thruster	1 x electrically driven 660 kW
Fire fighting	FiFi 1-2 x Skum SFP 250 x 350 pumps each delivering 1,200 cbm/h through combined water / foam monitors, situated port and starboard with remote control

MAIN DATA

Length overall	67.40 m
Breadth moulded	15.50 m
Depth moulded	7.50 m
Max draught	7.44 m
Design draught	6.20 m
Gross tonnage	2,263 GT
Bollard pull ahead	178 t
Speed max	17 kn
Speed economic	12 kn
Deck area	344 m²
Max deck cargo	700 t

FEATURES

Accommodation	31 berths, 13 x single cabins and 9 x double cabins all with private facilities, 1 x hospital, 1 x ships office, 1 x deck office, 1 x survey office
Bunker capacity:	Fuel m^3: 1,482 cbm MGO Fresh water m^3: 420 cbm FW
Chain lockers	(2#) of 112 m^3 each
Positioning	Dynamic positioning class II, K-POS 21

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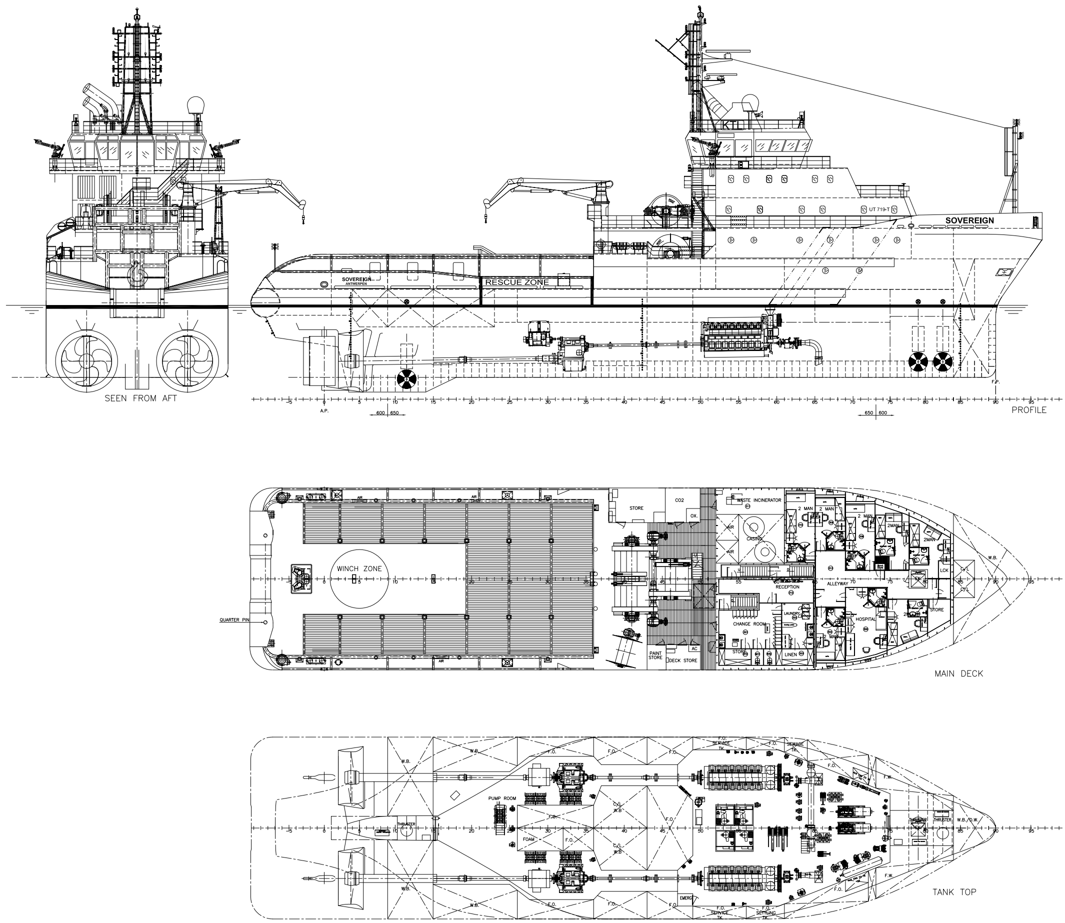
DECK EQUIPMENT

Towing and anchor handling winches	Brattvaag Triple drum Brattvaag: power 300 t (1st layer), brake holding load 450 t (1st layer) (2#) AH drum wire capacity 1,200 m dia. 76 mm (1#) towing drum wire capacity 1,500 m dia. 76 mm
Rope reels	2 x powered rope reels
Forward winch	Hydraulic anchoring windlass with 2 cable lifters of 38 mm chains, 2 mooring drums and two warping ends, 2 x spek anchors
Capstan winches	2 x 10 t hydraulic capstans aft

DECK EQUIPMENT

Tugger winches	2 x 10 t hydraulic tugger winches
Stern roller	(1#) SWL 500T, l 4.5 m x b 2.5 m
Crane	Palfinger Marine 1 x deck crane SWL 3 t @ 15 m 1 crane for rescue boat, 1 t
Towing pins	KARMOY 1 set of KARM towing pins, 300 t
Stopper pins	KARMOY 2 KARM forks SWL 600 t
Gypsy wheels	(2#) non-declutchable cable lifters for 3.25 inch chain



GENERAL ARRANGEMENT PLAN

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IV. GA OF CLV-NDURANCE

EQUIPMENT SHEET

NDURANCE
CABLE LAYING VESSEL

CONSTRUCTION/CLASSIFICATION

Built by	Samsung C&T corporation ZPMC - Shanghai Zhenhua Heavy Industries Co.Ltd
Year of construction	2013
Classification	Lloyd's Register, offshore multifunctional accommodation barge, bottom strengthened for loading and unloading aground

FEATURES

- Completely new ship and turntable design.
- Diesel electric propulsion system.
- Accommodation on fore ship, total for 98 persons
- Two engine rooms.
- Beaching capability.
- Corridor under accommodation to handle projects at the bow.
- 6 point mooring system.
- Launch & recovery trencher with a-frame (SS5)

MAIN DATA

Dynamic positioning system	DP-2
Length overall	99.00 m
Breadth	30.00 m
Moulded depth	7.00 m
Design draught	4.8 m
Displacement	12,285 t
Turntable capacity	5,000 t
Outer diameter	26 m
Inner diameter	3-6 m (adjustable)
Product cable size	50-300 mm
Cable speed range	0-1000 m/h
MBR cable highway	4.50 m
Cable tensioners	15 t
Crane	25 t SWL at 25 m
Cable handling area	35 m x 30 m
Max. sailing speed	11.5 kn
Total installed power	7,500 kW
Main engines	7,280 kW
Azimuth thrusters	2 x 1,250 kW + 2 x 1,000 kW
Bow thruster	1 x 550 kW

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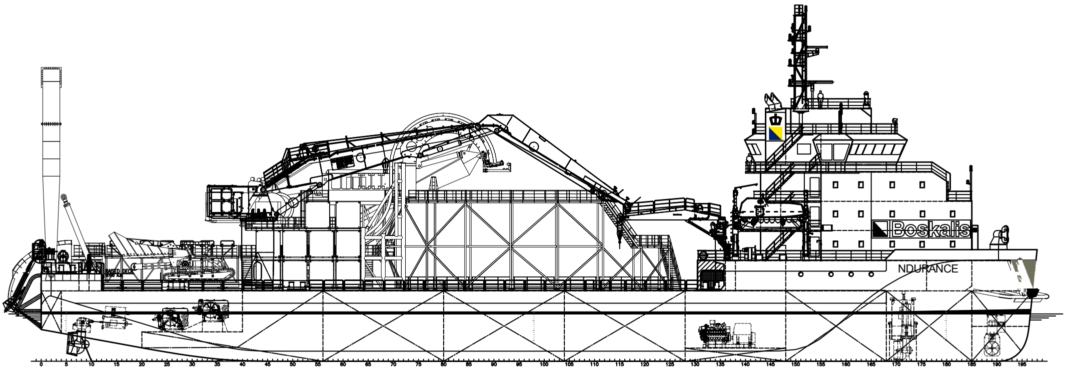
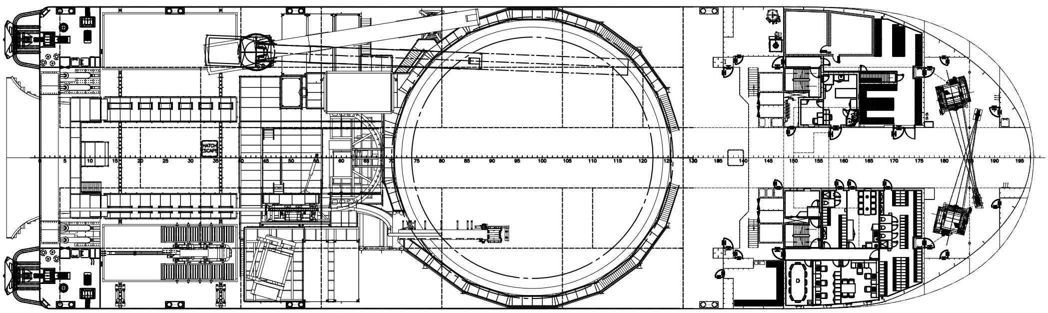
NDURANCE

CABLE LAYING VESSEL



SIDE VIEW



TOP VIEW DECK LEVEL

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V. GA of MPV-Bibby Wavemaster 1

TECHNICAL DATA SHEET

BIBBY
MARINE LIMITED

BIBBY WAVEMASTER 1

GENERAL

Yard number	553016
Delivery date	September 2017
Basic functions	Offshore transfers for special personnel and equipment by means of an motion comp. access system and heave comp. offshore rated crane on a stable DP-2 platform
Classification	DNV-GL Maritime, notation; ✠ 1A1, Offshore Service Vessel, COMF(C2, V-2), DYNPOS(AUTR), Clean, SF, E0, DK(+), SPS, NAUT(OSV-A), BWM(E), Recyclable, BIS, HELDK, Crane
Flag	UK MCA, SPS 2008 Code
Owner	Bibby Marine Services Ltd

DIMENSIONS

Length o.a.	89.65 m
Length loadline (IMO)	84.95 m
Beam mld.	20.00 m
Depth mld.	8.00 m
Draught summer (base / u.s. keel)	4.80 m / 6.30 m at foreship
Deadweight at summer draught	2260 t
Cargo weather deck area	425 m² (11 slots for 20ft cont.)
Covered / conditioned	390 m²
Warehouse areas	(6 slots for 20ft cont.; level floors)
Deck load (at 1 m above deck)	600 t

TANK CAPACITIES (APPROX.)

Ballast water	1130 m³
Fuel oil (service + cargo)	545 m³ + 345 m³
Fresh water (serv./potable + cargo)	180 m³ + 430 m³
Waste water (holding/black/grey)	129 m³

PERFORMANCES (APPROX.)

Speed (at summer draught)	13.0 kn
Economical speed	12.0 kn
ERN*	99,99,98,97

PROPULSION SYSTEM

Main engines	Diesel-electric, 690 V, 60 Hz
Propulsion power	2x elec. motors of approx. 2150 kW each
Azimuthing thrusters	2x FP propellers in nozzles
Bow thrusters	2x 860 kW fixed + 1x 860 kW retractable

AUXILIARY EQUIPMENT

Networks	690 V, 440 V and 230 V - 60 Hz
Main generator sets	4 pcs. – total installed electric power 6434 ekW
Emerg. generator set	1 pcs. – 238 ekW

DECK LAYOUT

Offshore crane	Knuckle boom crane 2t AHC/5t max swl.
Access system	Continuous access from warehouses to WTS/OSS provided by 6 station multi stop elevator and linked Uptime W2W 3D motion compensated gangway with height adjustable pedestal.
Daughter craft vessel	Tuco Marine Pro zero 11m windfarm service boat.
Helicopter deck capacity	D-factor 21 m, take-off weight 12 ton.
CTV landing facilities	1 fixed steel landing structure at stern. 1 removable aluminum structure, can be fitted as per GA at SB or PS position. CTV refuelling station at SB side.
Anchor mooring winch	Foredeck; 2x electric/hydraulic, with rope drum and warping head. Aft deck; 2x capstan 5t pull each.

LIFE SAVING EQUIPMENT

Life boats	2 x 45 persons
Life rafts	Numbers are per regulations

FACILITIES AND ACCOMMODATION

Crew/ special personnel	Total 90 persons on board. 60 single or large double cabins for crew and Special Personnel provided with internet, telephone and video entertainment (VOD and satellite TV).
Other spaces	6 offices, 5 meeting/conference rooms for Charterer's use. 2 recreation-dayrooms, reception room, hospital, drying rooms (M/F), changing rooms (M/F), wellness area (gym and sauna).

NAUTICAL AND COMMUNICATION EQUIPMENT

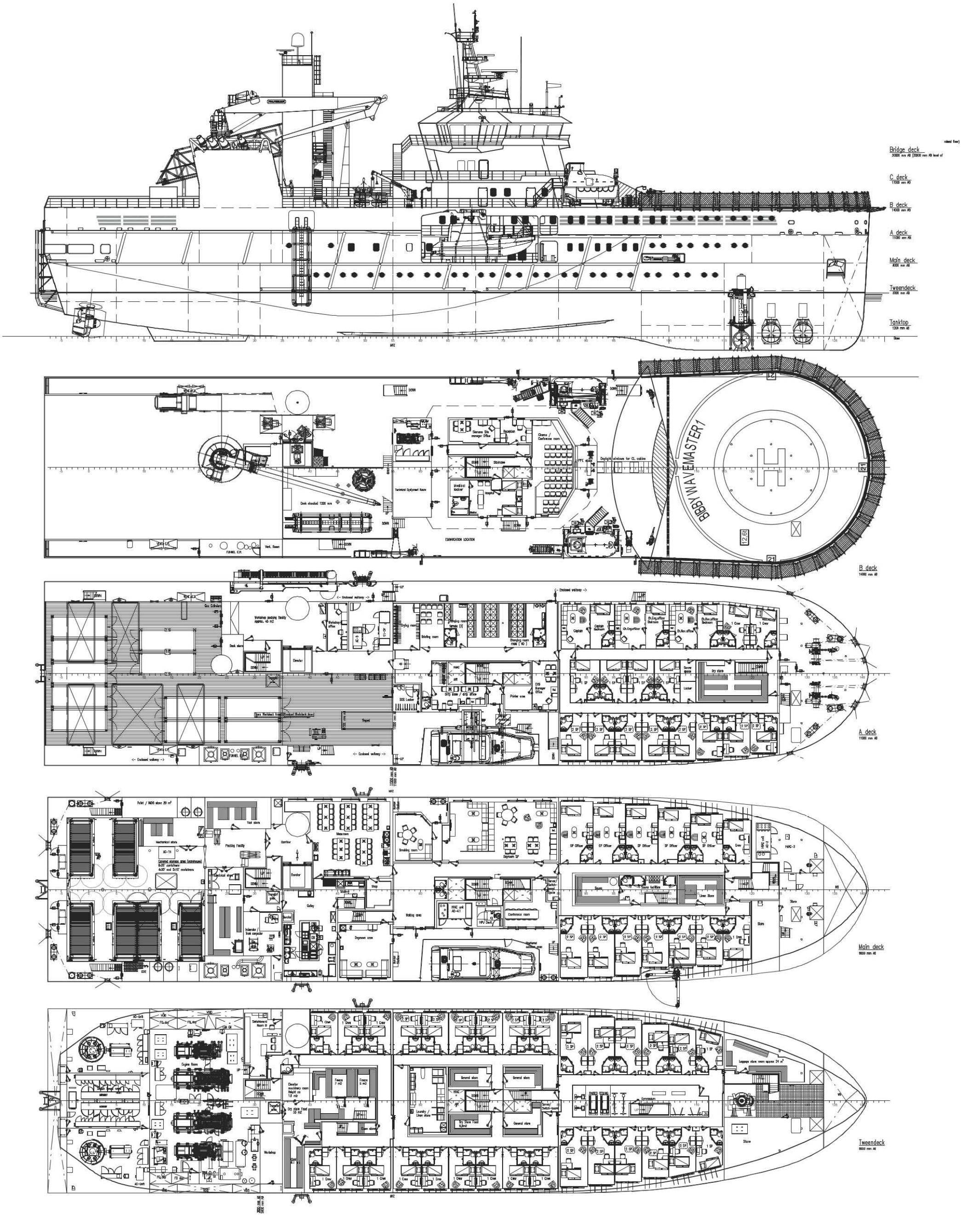
Nautical	Radar X-band + S-band, ECDIS, Conning, GMDSS Area 1, 2 and 3
DP – system	DP-2 with Radar scan, Laser and DGPS reference systems

TECHNICAL DATA SHEET

BIBBY
MARINE LIMITED

BIBBY WAVEMASTER 1

SERVICE OPERATION VESSEL WITH WALK TO WORK GANGWAY SYSTEM



Rev 4. November 2017 Specifications subject to change.

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VI. REFERENCE VESSEL DATABASE

Table 1: Example of reference vessel database

Type	Vessel	Year(new/re)	Class	Operator/Designer	L	B	D	DWT	GT	Crew	
					Spec	(m)	(m)	(T)	(m^3)	(p.p.)	-2*URL
OSV	(pending)	2022	unknown	Ørsted	84.4	19.5				87	http://www.g-tec.eu/en/fleet/omalius
Multi	Multi-Purpose Drilling Vessel		DNV-GL	G-tec	83.45	18	5.55			51	
DSV	SX121	N/N		Concept	130	14	7	7000		130	https://ulstein.com/vessel-design/sx121-diving
OSV	IHC OSV T3000-20	N/N	DNV-GL	IHC	97.12	20	9			88	https://www.royalihc.com/en/products/offshore/offshore-support/offshore-support-vessels
RSV	Toisa Pegasus	2008		Toisa Ltd.	131.7	22	9.5	8200		64	https://www.royalihc.com/en/products/offshore/offshore-support/offshore-support-vessels
RSV	SEVEN ATLANTIC	2009		Subsea 7	144.79	26	7	8700		150	https://www.royalihc.com/en/products/offshore/offshore-support/offshore-support-vessels
RSV	Well Enhancer	2009	DNV-GL	Helix Energy Solutions Group	132	22	11	6.25	9.383	122	https://www.helixesg.com/what-we-do/our-assets/well-enhancer/
ISV	Apollo	2018	ABS	DEME	89.32	42	8			92	https://www.deme-group.com/technologies/apollo
FPV	Flintstone	N/N	LR	DEME	154.6	32.2	7.74		20000		https://www.deme-group.com/technologies/flintstone#
ISV	Goliath	N/N	ABS	DEME	59.5	32.2	5				https://www.deme-group.com/technologies/goliath
ISV	Innovation	N/N	DNV-GL	DEME	147.5	42	11			100	https://www.deme-group.com/technologies/innovation
MCV	Living Stone	2017		DEME	161	32.2					https://www.deme-group.com/technologies/living-stone
ISV	Neptune	N/N	ABS	DEME	60.25	38	6		6000	60	https://www.deme-group.com/technologies/neptune
ISV	Orion	2019	DNV-GL	DEME	216.5	49	16.8				https://www.deme-group.com/technologies/orion
FPV	Rollingstone	N/N	ABS	DEME	139	32	6.6		12000		https://www.deme-group.com/technologies/rollingstone
ISV	Sea Challenger	N/N	DNV-GL	DEME	132.41	39	9		21100	60	https://www.deme-group.com/technologies/sea-challenger
ISV	Sea Installer	N/N	DNV-GL	DEME	132.41	39	9		21100	60	https://www.deme-group.com/technologies/sea-installer
FPV	Seahorse	N/N	LR	DEME	162	38	6.34				https://www.deme-group.com/technologies/seahorse
ISV	Thor	N/N	DNV-GL	DEME	70	40	8.46		10000		https://www.deme-group.com/technologies/thor
OSV	ESVAGT FROUDE	2015		ESVAGT	83.7	17.6	6.5				https://www.esvagt.com/fleet/wind-service-operations-vessels/esvagt-froude/
OSV	ESVAGT FARADAY	2015		ESVAGT	83.7	17.6	6.5				https://fastrescueboat.dk/fleet/wind-service-operations-vessels/esvagt-faraday/
OSV	ESVAGT DANA	2018	DNV-GL	ESVAGT	88.4	15				75	https://fastrescueboat.dk/fleet/wind-service-operations-vessels/esvagt-dana/
OSV	ESVAGT ALBERT BETZ	2021		ESVAGT	70.5	16.6					https://fastrescueboat.dk/fleet/wind-service-operations-vessels/esvagt-albert-betz/
OSV	ESVAGT NJORD	2016		ESVAGT	83.7	17.6	6.5				https://fastrescueboat.dk/fleet/wind-service-operations-vessels/njord/
OSV	ESVAGT MERCATOR	2017		ESVAGT	58.5	16.6	5.5		2901		https://fastrescueboat.dk/fleet/wind-service-operations-vessels/esvagt-mercator/
CCV	ESVAGT ALPHA	1971	BV	ESVAGT	68.5	12	4.6	829.7			https://www.esvagt.com/fleet/crew-change-vessels/esvagt-alpha/
CCV	ESVAGT BETA	2008	BV	ESVAGT	76.6	14.6	5.93	1157	2360		https://www.esvagt.com/fleet/crew-change-vessels/esvagt-beta/
MSV	Quest Horizon	2013	ABS	Horizon Geosciences	65	16.2	4.7	1569		58	https://horizon-geosciences.com/vessels/quest-horizon/
MSV	HORIZON NOMAD	2013	ABS	Horizon Geosciences	60	13.3	5			52	https://horizon-geosciences.com/vessels/horizon-nomad/
MSV	HORIZON GEOBAY	1999	ABS	Horizon Geosciences	87	15.6	6.91	2451		66	https://horizon-geosciences.com/vessels/horizon-geobay/
MSV	HORIZON SURVEYOR	2002	ABS	Horizon Geosciences	40.2	10	3.8	480		28	https://horizon-geosciences.com/vessels/horizon-surveyor/
SEP	HORIZON 27	2007		Horizon Geosciences	18.3	12.2	1				https://horizon-geosciences.com/vessels/h27/
SEP	TERRA SURF			Horizon Geosciences	12	10	1.5				https://horizon-geosciences.com/vessels/terra-surf/
Multi	KOMMANDOR STUART	2006	DNV-GL	FURGO	60	12	5.4			38	https://horizon-geosciences.com/vessels/kommandor-stuart/
GSV	Fugro Gauss	1980	DNV-GL	FURGO	68.87	13.09	5.2		1684	30	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
GSV	Fugro Supporter	1994	LR	FURGO	75.4	12.5	5.3		2065	47	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
GSV	Fugro Discovery	1997	DNV-GL	FURGO	70	12.6	6		2018	34	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
GSV	Fugro Meridian	1997	LR	FURGO	72.5	13.8	6.8		2255	26	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
GSV	Fugro Enterprise	2007	ABS	FURGO	51.8	12.2	3.4		874	26	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
GSV	Fugro Mercator	2007	BV	FURGO	42.35	10.34	1.4		360	18	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
GSV	Fugro Synergy	2009	DNV-GL	FURGO	103.7	19.7	6.5		3775	84	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed2
GSV	Fugro Searcher	2010	DNV-GL	FURGO	65.2	14	5.3		1940	42	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
GSV	Fugro Equinox	2011	BV	FURGO	60	16	4.85		1642	35	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
GSV	Fugro Equator	2012	DNV-GL	FURGO	65.65	14	4.2		1917	42	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
GSV	Fugro Brasilis	2013	DNV-GL	FURGO	66.65	14	4.2		1929	42	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
GSV	Fugro Helmert	2013	DNV-GL	FURGO	41.53	10	3.4		498	20	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
GSV	Fugro Frontier	2014	BV	FURGO	53.7	12.5	3.1		1400	31	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
GSV	Fugro Pioneer	2014	BV	FURGO	53.7	12.5	3.1		1322	34	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
GSV	Fugro Proteus	2014	DNV-GL	FURGO	53.7	12.5	3.35		1308	34	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
GSV	Kobi Ruegg	2015	ABS	FURGO	58.8	12.5	4.57		1340	38	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
GSV	Fugro Venturer	2017	GL	FURGO	71.5	15.4	5.6		2455	34	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
RSV	Fugro Etive	2007	DNV-GL	FURGO	92.95	19.7	7.7		4926	100	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/subsea-vessels
RSV	Fugro Aquarius	2015	LR	FURGO	82.6	84.7	18		4144	60	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/subsea-vessels
RSV	Atlantis Dweller		DNV-GL	FURGO	69.2	16.2	4.75	1004	3346	70	https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/subsea-vessels
MSV	RV Ventus	2013	RINA	EGS	49.8	9.6	5.6	1082		100	http://www.egssurvey.com/vessels.html
MSV	GEO ENERGY	2004	CR	EGS	72.2	16	7	1047	2151	42	http://www.egssurvey.com/vessels.html
MSV	GREATSHIP RACHNA	2012	LR	EGS	78	17	6.3		3306	50	http://www.egssurvey.com/vessels.html
MSV	R.V. EGS SURVEYOR	2010	BKI	EGS	47.15	8.8	5.2		622	38	http://www.egssurvey.com/vessels.html
MSV	R.V. RIDLEY THOMAS	2006	ABS	EGS	61.1	12	4.4		1241	36	http://www.egssurvey.com/vessels.html
MSV	R.V. BOLD EXPLORER	1989	RINA	EGS	68.28	13.11	4.5		1914	44	http://www.egssurvey.com/vessels.html
MSV	R.V. GEO RESOLUTION	1989	LR	EGS	68.3	13.1	4.59		1913	45	http://www.egssurvey.com/vessels.html
MDV	Omalius	2015		DEME	83.45	18	5.55				https://www.deme-group.com/technologies/omalius
OCV	EDDA FREYA	2016	DNV-GL	DEEPOCEAN	149.8	27	12			140	https://deepoceangroup.com/asset/edda-freya/
IMR	EDDA FLORA	2008	DNV-GL	DEEPOCEAN	95	20	8			70	https://deepoceangroup.com/asset/edda-flora/
IMR	EDDA FAUNA	2008	DNV-GL	DEEPOCEAN	108.7	23	7.8			90	https://deepoceangroup.com/asset/edda-fauna/
OCV	HAVILA PHOENIX	2009	DNV-GL	DEEPOCEAN	127.4	23	6.25			140	https://deepoceangroup.com/asset/havila-phoenix/
MCV	MAERSK CONNECTOR	2016	LR	DEEPOCEAN	138.35	27.45	6.25		9300	90	https://deepoceangroup.com/asset/maersk-connector/
OCV	MAERSK FORZA	2008	DNV-GL	DEEPOCEAN	107.6	22	7.15		7732	120	https://deepoceangroup.com/asset/rem-forza/
OCV	NORMAND JARSTEIN	2014	DNV-GL	DEEPOCEAN	117.35	22	9		8377	110	https://deepoceangroup.com/asset/vessels-normand-jarstein/
MCV	NORMAND OCEAN	2014	DK	DEEPOCEAN	107.6	22	9		7300	90	https://deepoceangroup.com/asset/rem-ocean/
RSV	POLAR ONYX	2014	DNV-GL	DEEPOCEAN	130	25	10			130	https://deepoceangroup.com/asset/polar-onyx/
OCV	VOLANTIS	2007		DEEPOCEAN	106.6	22	7.3	5200			https://deepoceangroup.com/asset/volantis/
RSV	ARBOL GRANDE	2003	DNV-GL	DEEPOCEAN	94.28	20	7				https://deepoceangroup.com/asset/arbol-grande/
MSV	DINA STAR	2013	DNV-GL	DEEPOCEAN	93.8	20	8	4900	4950	72	https://deepoceangroup.com/asset/dina-star/
OCV	ST-268 OCV	N/N		Skipsteknisk	166	34	14			150	https://www.skipsteknisk.no/st-design/offshore/ocv/st-268-ocv/86/260/
OCV	ST-266 OCV	N/N		Skipsteknisk	158.2	32	14			150	https://www.skipsteknisk.no/st-design/offshore/ocv/st-266-ocv/86/55/
MCV	NDURANCE	2013	LR	Boskalis	99	30	7			98	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/cable-laying-multipurpose-vessels.html
MCV	NDEAVOR	2013	LR	Boskalis	90	30	7			98	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/cable-laying-multipurpose-vessels.html
MCV	Spirit	N/N	BV	Boskalis	90	28	6.5			60	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/cable-laying-multipurpose-vessels.html
FPV	Rockpiper	2011	BV	Boskalis	158.6	36	13.5			60	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/fallpipe-vessels.html
FPV	Seahorse	1999	LR	Boskalis	162	38	6.34				https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/fallpipe-vessels.html
RSV	Constructor	2010	LR	Boskalis	76	18	6.1		3000	70	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/diving-support-vessels.html
RSV	BOKA ATLANTIS	2011	DNV-GL	Boskalis	115.4	22.2	9		8691	120	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/diving-support-vessels.html
RSV	SMIT KAMARA	2005	ABS	Boskalis	70.9	16	7			63	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/diving-support-vessels.html
RSV	EDT PROTEA	2006	DNV-GL	Boskalis	91.2	14.8	6.83	2091		88	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/diving-support-vessels.html
RSV	BOKA DA VINCI	2011	DNV-GL	Boskalis	115.4	22.2	9		5662	120	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/diving-support-vessels.html
AHTS	BOKA ALPINE	2006	BV	Boskalis	75.05	18	8	3568	3239	36	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html
AHTS	BOKA SUMMIT	2007	BV	Boskalis	75.05	18	8	3568	3239	36	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html
AHTS	BOKA SHERPA	2007	LR	Boskalis	75.05	18	8	3568	3239	36	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html
AHTS	BOKA EXPEDITION	2007	LR	Boskalis	75.05	18	8	3568	3239	36	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html
AHTS	BOKA PEGASUS	2013	BV	Boskalis	91	21.95	8	3681	7534	60	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html
AHTS	BOKA PERSEUS	2015	DNV-GL	Boskalis	91	22	8			60	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html
AHTS	PRINCESS	2002	BV	Boskalis	67.4	15.5	7.5			27	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html
AHTS	SOVEREIGN	2003	BV	Boskalis	67.4	15.5	7.5			27	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html
AHTS	UNION LYNX	1999	BV	Boskalis	73.5	16.4	8	2900	2590	24	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html
AHTS	SAPPHIRE	2001	BV	Boskalis	35.75	11	4.8		498	10	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html
AHTS	FAIRMOUNT GLACIER	2007	LR	Boskalis	75.05	18	8	3568	3239	36	https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html
CLV	Nexus		LR		122.68	27.45	5.82	8398		90	

VII. Reference Equipment List

Table 2: Reference modularized equipment list

	component_class	instance_name	Length(ra	Width	Height	density	number	Area	Volume	Weight	reference	remark
PSV1	PSV_W2W	A-Type-ampelmann	7.2	6.3	10	0	1	0	0	39000	https://www.ampelmann.nl/systems/a-type	
PSV2	PSV_Crane	Crane Type CCL 40T	5	5	12	0	1	0	0	140000	https://www.macgregor.com/contentassets/f461d06a964a4d3bb2af0a2452702385/cr anes_cargo.pdf	
PSV3	PSV_Cargo_DK	20ft Container-Alconet	6.05	2.5	2.6	0	4	0	0	30480	https://www.alconet-containers.com/container/20ft-shipping-container-a-quality/	
CSV1	CSV_Winch_AH	AnchorHandlingWinch	3	2	2	7850	1	6	0	94200	https://www.damenmc.com/en/products/winches/anchor-handling-winches	estimated
CSV2	CSV_Winch_TW	TowingWinch	3	2	2	7850	1	6	0	94200	https://www.damenmc.com/en/products/winches/anchor-handling-winches	estimated
CSV3	CSV_Pin	GuidePin	0.6	1.2	0.6	7850	2	0.72	0	3391.2	http://www.hiseamarine.com/hydraulic-towing-pin-with-shark-jaw-5467.html	
CSV4	CSV_SharkJaw	SharkJaw	0.6	0.6	0.6	7850	1	0.36	0	1695.6	http://www.hiseamarine.com/hydraulic-towing-pin-with-shark-jaw-5467.html	
CSV5	CSV_Stern_Roller	SternRoller	2	5	-0.5	1000	1	10	1000	20000	estimated	
CLV1	CLV_Carosal_1	Carosal_lay	13.7	13.7	5	1000	1	36	1000	2180000	https://www.drammenyard.no/wp-content/uploads/Equipment-for-rent.pdf	
CLV3	CLV_Crane_1	Crane	5	2	10	7850	1	4	1000	350000	https://issuu.com/marinemegastore.com/docs/tts-marine-cranes-as-tts-lmg-cargo-cranes-tailor-m?fbclid=IwAR1UgH1CfmT_471-fdybjDpr4g80aOCUgcK4urjKszZ7qIh6uKZpwYXnYyo	
CLV4	CLV_Tensioner_1	Tensioner	5	3	2	1000	2	15	1000	12000	https://www.drammenyard.no/wp-content/uploads/Equipment-for-rent.pdf	
CLV5	CLV_Roller_1	Roller	2	5	-2	1000	1	10	1000	20000		estimated
CLV6	CLV_Trencher	Trenchrer	16.8	10.5	8.1	0	1	0	0	125000	https://www.vanoord.com/en/updates/deep-dig-it-trencher-buries-cables-more-5-metres-below-seabed-connect-offshore-wind-farms/	
DSV1	DSV_ROV	NEXXUS	3.2	1.7	1.9	460	2	5.44	0	4754.56	https://www.oceaneering.com/brochures/nexxus/	
DSV2	DSV_THS_Unit	TMS Type 4a	1.7	1.7	2.02	2213	2	2.89	0	12919.05	https://f-e-t.com/wp-content/uploads/2019/10/tms-type-4.pdf	
DSV3	DSV_THS_Garage	GarageTMS_TypeB	4.3	2.5	4	116	2	10.75	0	4988	https://f-e-t.com/subsea/vehicles/tether-management-systems/	
DSV4	DSV_WetDivingBell	DivingBell	6.75	2.5	4.3	156	1	16.875	0	11319.75	https://www.royalihc.com/-/media/royalihc/about-us/business-units/ihc-hytech/02_Datasheets/08_Handling_Systems/Wet%20bell%20%20diver%20handlin g%20system	
DSV5	DSV_Crane_main	Crane Type CCL 140T	5	5	12	0	1	0	0	350000	https://issuu.com/marinemegastore.com/docs/tts-marine-cranes-as-tts-lmg-cargo-cranes-tailor-m?fbclid=IwAR1UgH1CfmT_471-fdybjDpr4g80aOCUgcK4urjKszZ7qIh6uKZpwYXnYyo	
DSV6	DSV_Crane_aux	Crane Type CCL 40T	5	5	12	0	1	0	0	140000	https://www.macgregor.com/contentassets/f461d06a964a4d3bb2af0a2452702385/cr anes_cargo.pdf	
GSV1	GSV_TWS	Towed array sonar-TELE	2.75	1.22	1.37	0	1	3.355	0	900	http://www.teledynemarine.com/towed-systems	
GSV2	GSV_TWS_LARS	TWS_LARS	1.7	1.7	2.02	2213	1	2.89	0	12919.05	http://www.teledynemarine.com/towed-systems	
GSV3	GSV_SDR	SeabedDrilingRigger	2.6	2.3	5.6	0	1	5.98	0	10000		estimated
GSV4	GSV_Lab	Containerised_Labs	6.1	2.5	2.6	0	2	15.25	0	5500	https://www.marum.de/en/Infrastructure/Sea-floor-drill-rig-MARUM-MeBo70.html	
GSV5	GSV_ROV	NEXXUS	3.2	1.7	1.9	460	2	5.44	0	4754.56	https://www.oceaneering.com/brochures/nexxus/	

VIII. GRASSHOPPER SCRIPT OVERVIEW

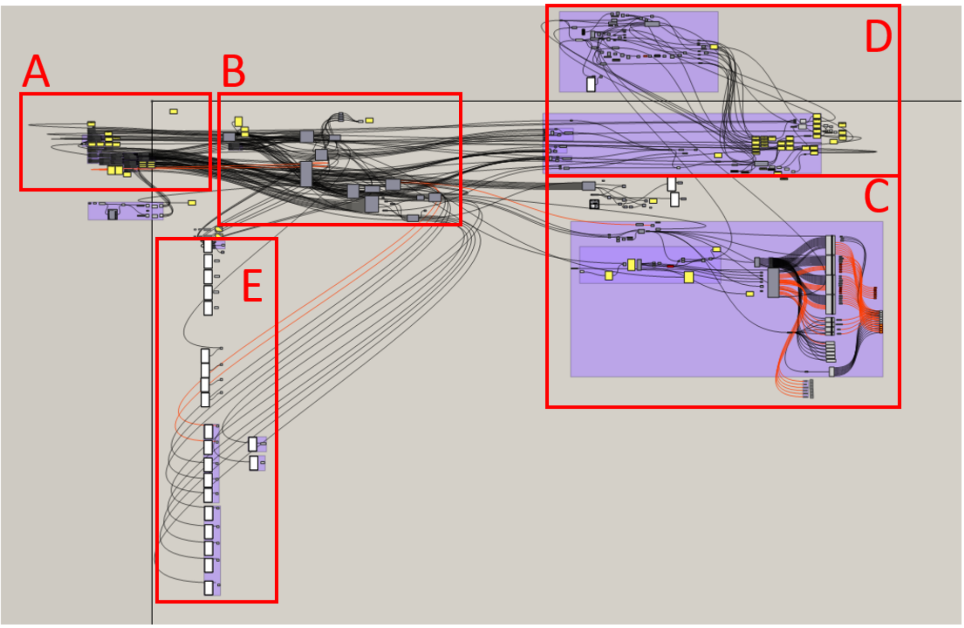

Figure 1: Grasshopper Script Overview-Main sections

This additional section provides a walkthrough of the MMG script. There is no requirement for installation. With Rhinoceros 6 or higher version, the grasshopper is included in the software. If user is using Rhino 5 or earlier version, please download Grasshopper from McNeel official website (https://www.rhino3d.com/download/Grasshopper/1.0/wip/rc/). The grasshopper script has been tested in the Rhinoceros6 environment without incompatible problem. As for early version of rhinoceros, users may encounter some problem when running model with different tolerance. Before start the GH script, change the environment tolerance to **0.001 m** in the Rhinoceros console. This is very important for generating models properly.

There are two different way to import vessel data.One is import it directly from the excel datasheet. Another one is to adjust parameters in the grasshopper interface with numerical slider. When adjusting parameters with sliders, disable the estimation section to prevent computer crash from running out of RAM.
From Figure 1, one can see that the GH script is divided into 5 main sections as following:

- **A:** Main parameter
- **B:** Shell generator and boundary box configuration generator
- **C:** Working deck layout generator
- **D:** Analysis section
- **E:** Visualization section

VIII.1. SECTION A: MAIN PARAMETER

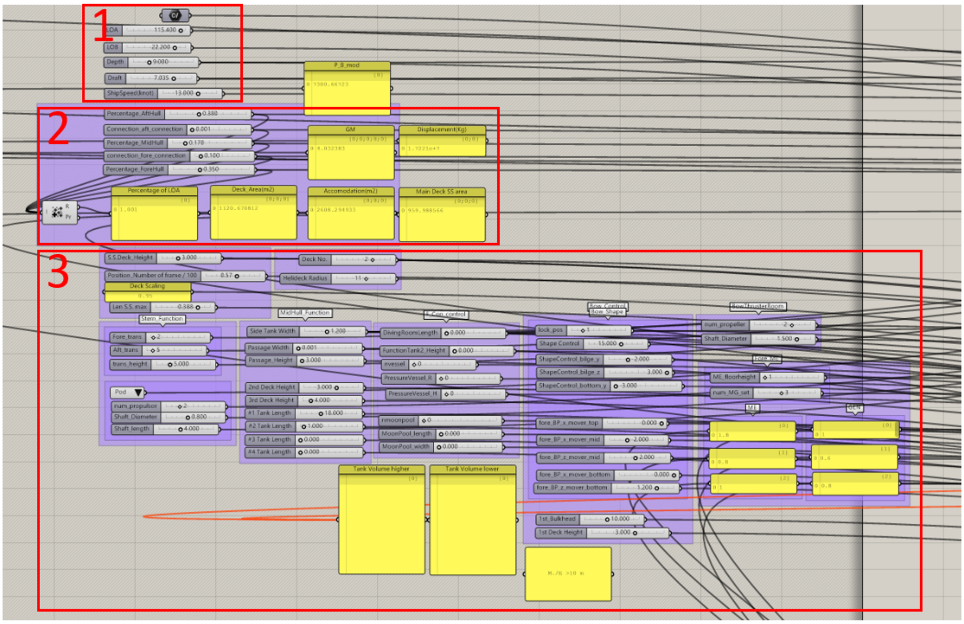

Figure 2: Section A: Main parameter

- **A-1: Main parameter input** Choose from a existed data sheet (.csv) or directly through entering main parameters.
- **A-2: Proportion of each section** Adjust the proportion of each section. Change the value to 0.001 if there is an unnecessary section.
- **A-3: Detail parameters** Detail settings for each section. Parameters for boundary box configuration are included in corresponded section. For example, the type of main thrusters can be switched between shaft or pod in the AftHull section.

VIII.2. SECTION B: SHELL GENERATOR AND BOUNDARY BOX CONFIGURATION GENERATOR

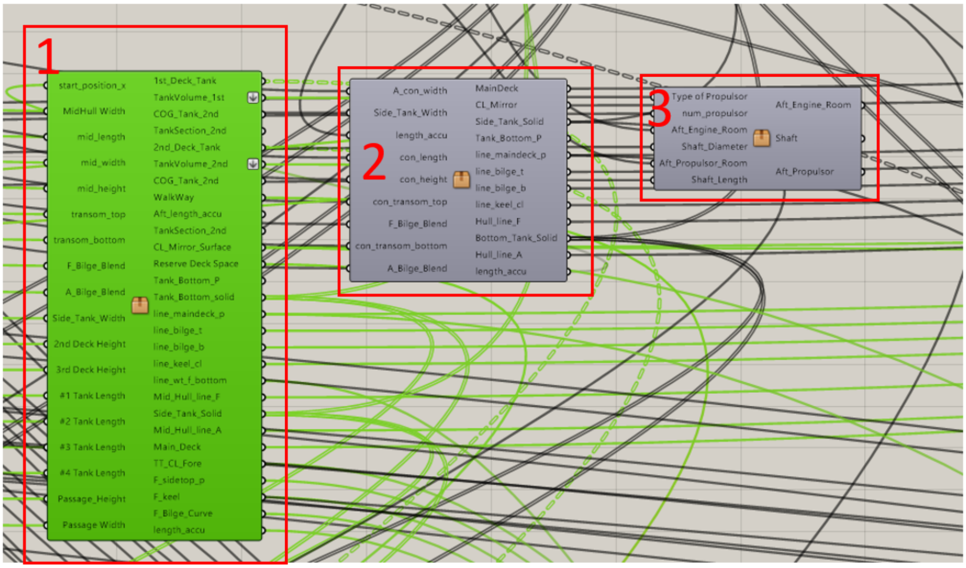

Figure 3: Section B: Shell generator and boundary box configuration generator

- **B-1: MidHull Shell section generator** This is the basic shell generator block. Different shells as ForHull and AftHull are variants derived from this generator.
- **B-2: Connection Shell section generator** This is the connection shell generator. In the MMG, three main configurations are installed:a Diving support,a Two-deck cargo tank ,and a bulk cargo hold.
- **B-3: Boundary Box Configuration generator** This is an example of boundary box configuration generator. They are placed direct after the shell generator showing they are part of shell assemblies.

VIII.3. Section C: Working deck layout generator

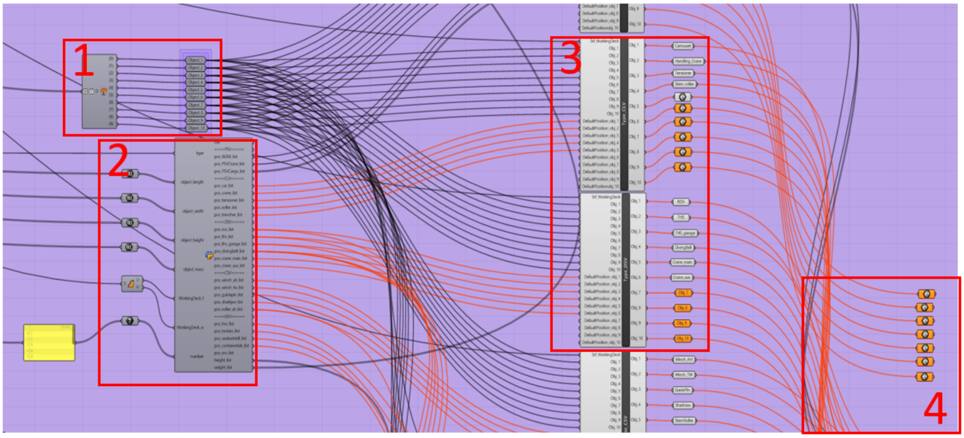

Figure 4: Section C: Working deck layout generator

- **C-1: Working deck equipment Input** Working deck equipment list input from the data sheet. Default number of input is set to 10. It can be extended if more components are addign to the equipment list.
- **C-2: Layout configuration script generator** In this Python block, scripts for working deck layout are installed. The output from this block is a list of anchoring point on the working deck surface.
- **C-3: Equipment Placer** In this section, equipment input in the **C-1** block will be placed at the designed position output from **C-2**.
- **C-4: Working deck visualization section** In this section, the working deck configuration is visualized in default red blocks.

VIII.4. Section D: Analysis section

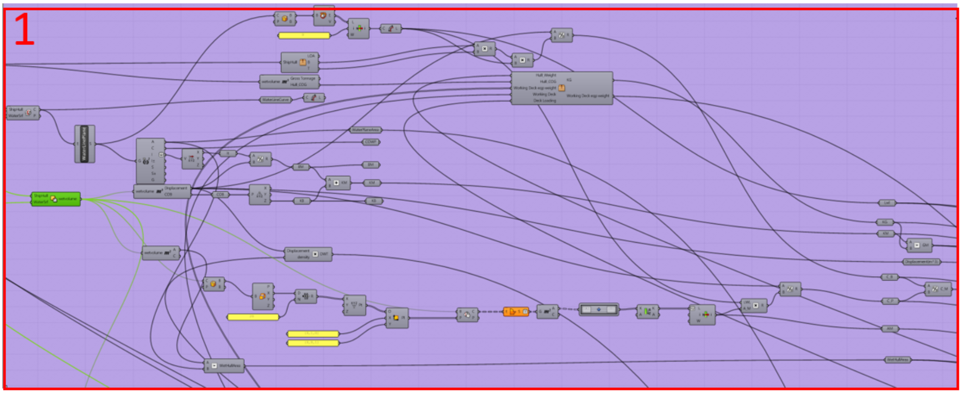

Figure 5: Section D: Analysis section-Hull coefficient

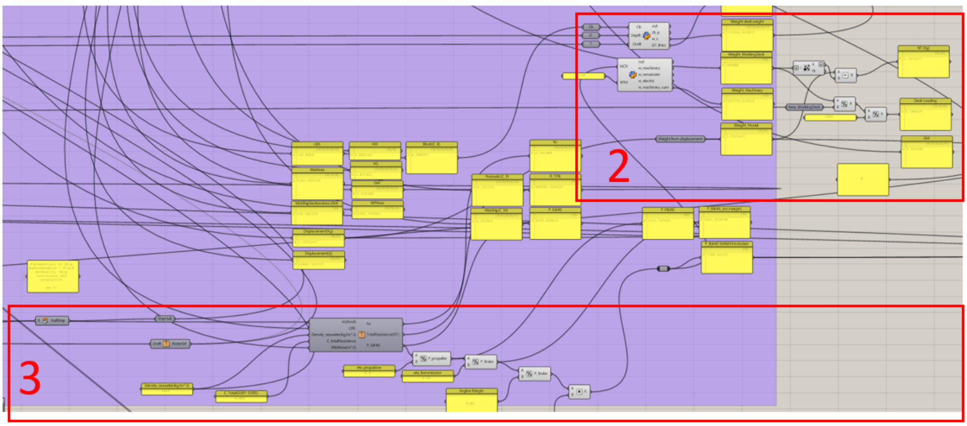

Figure 6: Section D: Analysis section-Performance estimation

- **D-1: Ship Hull Coefficient** This is the function for retrieving hull coefficient from the shell entity and the wet volume defined by the designed draft.
- **D-2: Weight estimation** This Python block takes the weight data from the working deck and adds it to the estimated hull weight to check the feasibility.
- **D-3: Installed Power installation** This section follows the empirical equations for estimating installed power. When estimating bollard pull power, enter the bollard pull force and reduce the speed to 0.1 knot in the main parameter section (section A).

VIII.5. SECTION E: VISUALIZATION SECTION

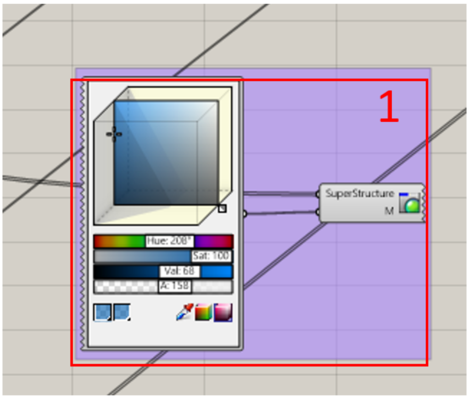

Figure 7: Section E: Visualization section

- **E-1:** In this section, the visualization block takes in objects generated in each section and assigned them with selected color and texture. The result will be presented in the Rhinoceros drawing window.

Bibliography

Alexander, C. (1964). *Notes on the synthesis of form*. Harvard University Press.

Anderson, D., & Pine, J. (1997). *Agile product development for mass customization*. McGrawHill.

Apollo. (2020). https://www.deme-group.com/technologies/apollo

Arbol grande. (2020). https://deepoceangroup.com/asset/arbol-grande/

Bibby wavemaster 1. (2017).

Birk, L. (2019). *Fundamentals of ship hydrodynamics : Fluid mechanics, ship resistance and propulsion*. John Wiley Sons Ltd.

Boka alpine. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html

Boka atlantis. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/diving-support-vessels.html

Boka da vinci. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/diving-support-vessels.html

Boka expedition. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html

Boka pegasus. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html

Boka perseus. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html

Boka sherpa. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html

Boka summit. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html

Cable-laying vessel nexus. (2015).

Charisi, N. (2019). *Parametric modelling methodbased on knowledge basedengineering* (Master's thesis).

Choi, M. (2018). *Modularadaptable ship design for handlinguncertainty in the future operatingcontext* (Doctoral dissertation). Norwegian University of Science and Technology.

Choi, M., Erikstad, S. O., & Chung, H. (2018). *Operation platform design for modular adaptable ships: Towards the configure-to-orderstrategy* (Vol. 163). SINTEF. https://doi.org/10.1016

Constructor. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/diving-support-vessels.html

Cooper, S., Fan, I., & Li, G. Achievingcompetitive advantage through knowledge basedengineering -a best practice guide. In: *White paper forthe department of trade and industry*. 2001.

Cooper, S., Fan, I.-S., & University, G. L. (2001). Achieving competitiveadvantage throughknowledge-basedengineering.

de Roo, R. (2019). *Modulate the kampong* (Master's thesis). Delft University of Technology.

Devaraja, H. V. (2018). *Knowledge based engineering* (tech. rep.). Infosys.

Dina star. (2020). https://deepoceangroup.com/asset/dina-star/

Edda fauna. (2020). https://deepoceangroup.com/asset/edda-fauna/

Edda flora. (2020). https://deepoceangroup.com/asset/edda-flora/

Edda freya. (2020). https://deepoceangroup.com/asset/edda-freya/

Edt protea. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/diving-support-vessels.html

Edwards, I. (2011). Overcoming challenges for the offshore wind industry and learning from the oil and gas industry.

Egs ventus. (2020). http://www.egssurvey.com/vessels.html

Elgård, P., & Miller, T. D. Designing product families. In: *Design for integration in manufacturing*. 1998.

Erikstad, S. O., & Levander, K. (2012). System based design of offshore support vessels.

Esvagt albert betz. (2020). https://fastrescueboat.dk/fleet/wind-service-operations-vessels/esvagt-albert-betz/

Esvagt alpha. (2020). https://www.esvagt.com/fleet/crew-change-vessels/esvagt-alpha/

Esvagt beta. (2020). https://www.esvagt.com/fleet/crew-change-vessels/esvagt-beta/

Esvagt dana. (2020). https://fastrescueboat.dk/fleet/wind-service-operations-vessels/esvagt-dana/

Esvagt faraday. (2020). https://fastrescueboat.dk/fleet/wind-service-operations-vessels/esvagt-faraday/

Esvagt froude. (2020). https://www.esvagt.com/fleet/wind-service-operations-vessels/esvagt-froude/

Esvagt mercator. (2020). https://fastrescueboat.dk/fleet/wind-service-operations-vessels/esvagt-mercator/

Esvagt njord. (2020). https://fastrescueboat.dk/fleet/wind-service-operations-vessels/njord/

EVANS, J. H. (1959). Basic design concepts. *Journal of the American Society for Naval Engineers*, *71*(4), 671–678. https://doi.org/https://doi.org/10.1111/j.1559-3584.1959.tb01836.x

Fairmount glacier. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html

Flintstone. (2020). https://www.deme-group.com/technologies/flintstone#

Focal 532 90m rdsv. (2017).

Fuchs, C., & Golenhofen, F. J. (2019). *Masteringdisruption andinnovationin productmanagement*. Springer.

Fugro brasilis. (2020). https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1

Fugro discovery. (2020). https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1

Fugro enterprise. (2020). https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
Fugro equator. (2020). https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
Fugro equinox. (2020). https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
Fugro etive. (2020). https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/subsea-vessels
Fugro frontier. (2020). https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
Fugro gauss. (2020). https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
Fugro geophysical survey. (2015).
Fugro helmert. (2020). https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
Fugro mercator. (2020). https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
Fugro pioneer. (2020). https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
Fugro proteus. (2020). https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
Fugro searcher. (2020). https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
Fugro supporter. (2020). https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
Fugro synergy. (2020).
Fugro venturer. (2020). https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1
Fujimoto, T. (2013). *Coping with complex artifacts* (Y. Publishing, Ed.). Yuhikaku Publishing.
Furgo. (2020a). Fugro synergy.
Furgo. (2020b). Fugrompsv atlantis dweller.
Furgo. (2020c). M.v. fugro equator.
Furgo. (2020d). M.v. fugro meridian.
Gale, P. A. (2003). Ship design and construction. In T. Lamb (Ed.). Society of Naval Architects; Marine Engineers (SNAME).
Geo energy. (2020). http://www.egssurvey.com/vessels.html
Geotek customisedcontainer laboratories. (2021).
Goliath. (2020). https://www.deme-group.com/technologies/goliath
Government, T. S. The future of the ocean economy- offshore wind. In: 2014.
Greatship rachna. (2020). http://www.egssurvey.com/vessels.html
Havila phoenix. (2020). https://deepoceangroup.com/asset/havila-phoenix/
Ho, A., Mbistrova, A., & Corbetta, G. (2015). The european offshore wind industry - key trends and statistics 2015.
Horizon 27. (2020). https://horizon-geosciences.com/vessels/h27/

Horizon geobay. (2020). https://horizon-geosciences.com/vessels/horizon-geobay/

Horizon nomad. (2020). https://horizon-geosciences.com/vessels/horizon-nomad/

Horizon surveyor. (2020). https://horizon-geosciences.com/vessels/horizon-surveyor/

Huang, W. (2019). Offshore windfarm growth could offer a lifeline to the osv market. https://www.rivieramm.com/opinion/opinion/offshore-wind-farm-growth-could-offer-a-lifeline-to-the-osv-market-56041

Ihc osv t3000-20. (2020). https://www.royalihc.com/en/products/offshore/offshore-support/offshore-support-vessels

IMCA. (2021). Equipment damage – dropped rov/tether management system (tms).

Innovation. (2020). https://www.deme-group.com/technologies/innovation

Institute, I. T. R. (2021). Thousand wind turbines project.

J., A., R, D., W, S., J, V., M., F., A, M., & C, G. The impact of evolutionary acquisition on naval ship design. In: *Transactions society of navalarchitects and marine engineers (sname)*. 2003.

Kana, A. A. (2019a). Design approaches:set based design.

Kana, A. A. (2019b). Design tools: Quality function deployment (qfd).

Kobi ruegg. (2020). https://www.fugro.com/about-fugro/our-expertise/vessels-and-jack-up-barges/survey-vessels#tabbed1

Kommandor stuart. (2020). https://horizon-geosciences.com/vessels/kommandor-stuart/

Koning, J. H. (2010). *Development of a kbe application tosupport aerodynamic design and analysis* (Master's thesis). Delft University of Technology.

Lamb, T. (2004). *Ship design and construction*. Society of Naval Architects; MarineEngineers (SNAME).

Lee, J., Zhao, F., Dutton, A., Backwell, B., Qiao, L., Lim, S., Lathigaralead, A., & Liang, W. (2020). Global offshorewind report 2020.

Levander, K. (2009). Innovative ship designcan innovative ships be designed in a methodological way?

Lim, S. (2020). Market to watch: Asia pacific to become largest offshore wind market by 2030. https://gwec.net/market-to-watch-asia-pacific-to-become-largest-offshore-wind-market-by-2030/

Living stone. (2020). https://www.deme-group.com/technologies/living-stone

Lizet Ramírez, D. F., & Brindley, G. (2020). Offshore wind in europe key trends and statistics 2019.

M.v. fugro gauss. (2017).

Maersk connector. (2020). https://deepoceangroup.com/asset/maersk-connector/

Maersk forza. (2020). https://deepoceangroup.com/asset/rem-forza/

Ndeavor. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/cable-laying-multipurpose-vessels.html

Ndurance. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/cable-laying-multipurpose-vessels.html

Neptune. (2020). https://www.deme-group.com/technologies/neptune

Normand jarstein. (2020). https://deepoceangroup.com/asset/vessels-normand-jarstein/

Normand ocean. (2020). https://deepoceangroup.com/asset/rem-ocean/

Olivier L. de Weck, E. S. S., & Chang, D. (2004). Product family strategyand platform design optimzation.
Omalius. (2020). https://www.deme-group.com/technologies/omalius
Orion. (2020). https://www.deme-group.com/technologies/orion
Pahl, G., Beitz, W., Feldhusen, J., & Grote, K.-H. (2007). Engineering designa systematic approach. Springer-Verlag London.
Papanikolaou, A. (2014). *Ship design methodologies of preliminary design*. Springer.
Polar onyx. (2020). https://deepoceangroup.com/asset/polar-onyx/
Princess. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html
Quest horizon. (2020). https://horizon-geosciences.com/vessels/quest-horizon/
R.v. bold explorer. (2020). http://www.egssurvey.com/vessels.html
R.v. egs surveyor. (2020). http://www.egssurvey.com/vessels.html
R.v. geo resolution. (2020). http://www.egssurvey.com/vessels.html
R.v. ridley thomas. (2020). http://www.egssurvey.com/vessels.html
R.v. ridley thomas. (2020). http://www.egssurvey.com/vessels.html
Rex, C. (2018). Shipping market review.
Rhino training guides. (2021).
Rocca, G. L. (2011). *Knowledge based engineering techniques to support aircraftdesign and optimization (doctoral dissertation),* (Doctoral dissertation). TU Delft.
Rocca, G. L. (2012). Knowledge based engineering: Between ai and cad. review of a languagebased technology to support engineering design. *Advanced Engineering Informatics*.
Rockpiper. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/fallpipe-vessels.html
Rollingstone. (2020). https://www.deme-group.com/technologies/rollingstone
Rules for classification ships part 5 ship typeschapter 10 vessels for special operations (July 2020). (2020). *DNV-GL*.
Sanches, F. M. (2016). *Parametric modelling of hull form for ship optimization* (Master's thesis). Tecnico Lisboa.
Sanchez, R., & Mahoney, J. T. (1996). Modularity, flexibility, and knowledge managementin product and organization design. *IEEE Engineering Management Review. Reprint fromStrategic Management,*
Sapphire. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html
Schut, E., & van Tooren., M. (2008). Engineering primitives to reuse design processknowledge.
Seahorse. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/fallpipe-vessels.html
Seven atlantic. (2020). https://www.royalihc.com/en/products/offshore/offshore-support/offshore-support-vessels
SIMPSON, T. W. (2004). Product platform design and customization:status and promise. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*.
Smit kamara. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/diving-support-vessels.html

SNAME. (2003). *Ship design and construction, the society of naval architects and marine engineers.*

Sovereign. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html

Spirit. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/cable-laying-multipurpose-vessels.html

St-266 ocv. (2020). https://www.skipsteknisk.no/st-design/offshore/ocv/st-266-ocv/86/55/

St-268 ocv. (2020). https://www.skipsteknisk.no/st-design/offshore/ocv/st-268-ocv/86/260/

T., B., O., H. J., & O., E. S. Representing design knowledge in configuration-based ship design. In: *Compit 2008 - 7th international conference on computer and itapplications in maritime industries,* 2008.

Terra-surf. (2020). https://horizon-geosciences.com/vessels/terra-surf/

Thomas D. Miller, P. E. (1998). *Defining modules, modularity and modularization.*

Toisa pegasus. (2020). https://www.royalihc.com/en/products/offshore/offshore-support/offshore-support-vessels

Tvedt, H. (2012). *Modular approach to offshore vesseldesign and configuration* (Master's thesis).

Ulrich, K., K. Tung. (1991). Fundamentals of product modularity. *Proceedings of the 1991 ASME Winter Annual Meeting Symposium on Issues in Design/Manufacturing Integration.*

Ulrich, K. T. (2008). *Product design and development* (4th ed.). McGraw-Hill/Irwin.

Ulstein. (n.d.). Service operation vessels.

Union lynx. (2020). https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/oceangoing-and-anchor-handling-tugs.html

van der Harst, C. (2013). Ihc supporter® classbetter for less.

Volantis. (2020). https://deepoceangroup.com/asset/volantis/

Watson, D. (1998). *Practical ship design.* Elsevier Science.

Wawrzyński, W. (2018). Area of the unstable solution of rolling equation– jumps of the oscillations amplitude. *Journal of KONES Powertrain and Transport.*

Well enhancer. (2020). https://www.helixesg.com/what-we-do/our-assets/well-enhancer/

Wirz, F. (2014). *Algorithms aided design-parametric strategies using grasshopper®.* Le pensur publisher.

Woud, J. K., & Stapersma, D. (2018). *Design of propulsion and electric power generation systems.* IMarEST.

TU Delft