# Modular and future proof design of the energy storage and conversion system

## A method development using Design Structure Matrix with the test case based on a Damen double ended ferry

by

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# Preface

This master thesis is my final work to finish my study course of the BEng Mechanical Engineering and the pre-master and master study Marine Technology at the Delft University of Technology to enter the maritime world. I am exited to be able to implement all the knowledge I have gained during the years and look forward to keep learning. Although challenging I enjoyed this project and the ability to learn more about alternative fuels and modular design. This thesis would not have been completed without the support of a number of people who I like to thank.

Firstly, I would like to thank my university supervisor Austin Kana for all the help during my graduation. The meetings, brainstorming, help and advice I got during my research helped me in setting and reaching my goals as well as providing me with valuable guidance.

Secondly, I would like to thank Damen Shipyards for the research topic and providing me with support and the opportunity to contribute a part to the NAVAIS project. I would like to thank my supervisor Tim McElroy for his constructive questioning of my approach and goals motivating me to keep connected to the practical vessel system design and to improve my work. In addition I would like to thank all the colleagues at Damen with whom I had brainstorm sessions, got advise and learned a lot from.

My graduation was mainly in a time of working at home and during this time I was mentally motivated and supported by family and friends. A special thanks goes to Klaas without whom my pre-master and master would have been much less enjoyable and to my girlfriend Anne-Mae and my parents for supporting me during my study.

*L. P. Treur*
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# Nomenclature

## 0.1. Abbreviations

| Nomenclature | |
|---|---|
| BTL | Biomass-To-Liquid |
| DF | Dual Fuel |
| DME | Di-methyl Ether |
| DOD | Depth of Discharge |
| DSE | Design Space Exploration |
| DSM | Design Structure Matrix |
| G.A. | General Arrangement |
| GTL | Gas-To-Liquid |
| HFO | Heavy Fuel Oil |
| HT-PEM | High Temperature - Proton Exchange Membrane |
| ICE | Internal Combustion Engine |
| IMO | International Maritime Organisation |
| kW | Kilowatt |
| kWh | Kilowatt hour |
| LHV | Lower Heating Value |
| LBG | Liquefied Bio-Gas |
| LPG | Liquefied Propane Gas |
| LNG | Liquefied Nitrogen Gas |
| LT-PEM | Low Temperature - Proton Exchange Membrane |
| MBSE | Model Based System Engineering |
| MCFC | molten Carbonate Fuel Cell |
| MDF | Marine Diesel Fuel |
| MDO | Marine Diesel Oil |
| MFD | Modular Function Deployment |
| MGO | Marine Gas Oil |
| NAVAIS | New, Advanced and Value-added Innovative Ships |
| POC | Proof of Concept |
| P&ID | Piping and Instrumentation Diagrams |
| QFD | Quality Function Deployment |
| RFLP | Requirement management, Functional Requirement, Logical design, Physical design |
| SE | Systems Engineering |
| SOFC | Solid Oxide Fuel Cell |
| TRL | Technological Readiness Level |
| TTP | Tank To Propeller |
| V&V | Verification and Validation |
| WTP | Well To Propeller |

## 0.2. Terminology

- **Damen** When Damen is used in the thesis it refers to Damen Shipyards Gorinchem which is part of the Damen Shipyards Group.
- **design procedure** The sequence in which the design process activities are deployed[66].
- **design process** A series of transformations taking place to translate user needs into a defined configuration of the functional system of the ship and their assemblies and components[66].
- **Modular engineering** The method where modules are defined such as a part of the propulsion system. This module then can be engineered and approved by class[66].
- **Module** A module is the physical representation of a function, possesses physical and functional attributes, cost attributes, production attributes, etc. which can be linked to form the configuration of a ship that matches the requirements and constraints[66]. *Additional thesis definition: An analyzed and evaluated cluster result of the algorithm which has technical feasibility based on the design approach.*
- **NAVAIS** New, Advanced and Value-added Innovative Ships which is an EU H2020 NAVAIS project[64].
- **Ship design** The combination of details or features defining the configuration of the ship regarding the functional systems and their assemblies and components. Including the properties and locations of all the components on the ship.
- **Classification society** The classification society is the society that inspects and certificates the design in order to register and insure a vessel. Partner in the NAVAIS project is Bureau Veritas marine & Offshore[101] and it is one of the classification societies that establishes and maintains technical standards for the construction and operation of vessels. In the report further referred as class.
- **Subsystem** A part of a total system which has items or modules forming a unified whole.
- **Product platform** A structured coherent collection of resources that include systems and template hierarchies.
- **Requirement** A design specification which is needed or wanted[74] based on the system, client, vessel or class specification.
- **Functionality** The ability to perform a task or function[68] meaning a definition of system limits and specifications.
- **Cluster** A group of similar things that are close together[73]. *Definition used in the thesis: A grouping solution based on the algorithm result where no evaluation has been done.*

# Abstract

Currently there is an energy transition from fossil fuels towards zero emission fuels within the maritime sector. In addition to this, improvements are made in system design with regard to standardization which allow for variation. The combination of these two improvements is found in the EU H2020 NAVAIS project which focuses on customer tailored vessels in combination with a standardized and modularized approach. In this research the focus is on the inland and coastal passenger/road ferries operating near to zero emissions where the test case is the Damen 9819 E3 double ended ferry. The specific objective is to use modularity to help support the development of zero-emission propulsion methods for a ferry. Where the specific objective is to apply this for the energy storage and conversion system. The objective is fulfilled by answering the main question of this research: “How can the energy carrier and conversion system of a ferry be made environmentally friendly and modular and how does the inclusion of low emission and modularity objectives impact the power supply and total design of the ferry?”

In the approach for the system design a transition is made from a more conventional design spiral to a Systems Engineering approach using the V-cycle or the RFLP approach. In this approach the design is approached by the elaboration of the Requirements, Functionalities, Logical design and the Physical design. Based on the main vessel requirements, research requirements are defined as well which are the systems ability to be: future proof, modular, fulfilling the energy and power requirements, the ability to be refitted and technical feasibility. From these requirements the main functionalities of the energy storage and conversion system are defined and are used for the determination of feasible energy carrier and conversion systems. As a result of the vessel requirements and functionalities the feasible system options are: a conventional diesel generator using MGO, a dual fuel engine using MGO and LNG and a LT-PEM fuel cell using hydrogen.

After the determination of the requirements, functionalities and the feasible energy storage and conversion systems, a platform approach is defined in which a number of approaches and design methods are included. The combination of a number of approaches combined is called a platform approach and for this research includes: Firstly, the top-down approach to allow for modular design while allowing for the inclusion and implementation of alternative energy types while following the RFLP approach. Secondly, the common-core approach is used to decrease the complexity and size of the modules in order to increase the technical feasibility, reduce the over-design and include the ability for parallel development for the system modules. And the design approaches combined in the platform approach are practically applied by using a design support tool which is the Design Structure Matrix. The DSM uses a matrix setup and in this thesis a clustering algorithm in order to find modules. A second level of evaluation is applied to assess the results of the algorithm after the clustering resulting in potential modules.

After the determination of the design approach for the method, the practical elaboration is started. Following the main guideline of the RFLP approach in combination with the top-down approach the first step is the functional decomposition of the energy storage and conversion system. For this the decomposition is performed to a level of sub-function while following the Axiomatic design descriptions being: transform, transport, store, exchange and control. In addition to these descriptions also ‘provide’ and ‘convert’ are included in order to design a systematic decomposition of the functions. For this the top level functional descriptions are the different energy conversion system descriptions which are to provide: battery power, electrical power using a fuel cell and mechanical power by using a combustion engine. The next step is the logical decomposition where a one-to-one relation between the functional requirements and a logical or technical solution is desired. In this way the functionalities are connected to the technical solutions to a level of sub-functions connected to sub-systems. The combination of top-down and bottom-up design is used meaning that a technical solution design is based on the functionalities and technical drawings. To evaluate both the decompositions they are connected in a DSM and the connection between functions and technical solutions is evaluated. This to ensure the quality of the decomposition and find mistakes or mismatches.

The DSM and specifically the clustering algorithm has the goal to find modules based on minimizing interactions between modules. This is done based on the logical or technical decomposition where only the sub-systems are included in the matrix. The interactions between the sub-systems are defined using a binary definition. The clustering algorithm is used where random groups of sub-systems, named clusters or potential modules, are formed which then are evaluated based on the interactions and parameters to control the size and interactions between the clusters. Simulated annealing is used to optimize the solutions in combination of multiple runs for the defined system configurations. In this way interchangeable modules can be defined which can be used for the diesel generator, dual fuel and fuel cell configuration. The multiple solutions are merged into combined potential modules after which the results are evaluated. The evaluation is done based on the number of interactions, the technical feasibility and physical evaluation of the modules and finally based on the ability to standardize the interactions of the module. These steps result in a suggestion of modules which are interchangeable and are based on a minimization of interactions between or outside the modules. While leaving the ability to extend the method to allow for new alternative fuel systems.

To be able to use the method, a methodological implementation of the modules for the energy carrier and conversion system is designed. This method is described by two levels of decision making where the first one is the usage of the DSM and clustering algorithm. The second level is the analysis of the results and the refinement and evaluation of the clustering results. Two examples are elaborated in order to make the results more practical and visual for a change in design while using the described method and approach.

Finally the results and the method are evaluated in the chapter of verification and validation of the results. Due to the results of this research being a method, it is not possible to validate and verify in a standard way as there are no physical results. Therefore the validation of the method is done by proving the internal consistency of the method and the verification is performed by proving the internal consistency and validation of the results. This results in the acceptance of the usefulness of the method beyond the elaborated examples.

# Contents

# 1

# Introduction

## 1.1. Problem background

This project aims to support the EU H2020 NAVAIS project, further referred to as NAVAIS project, by researching modular engineering approaches towards zero emission energy carriers for ferries within Damen Shipyards[65][71]. The problem and approach of this thesis are not bound to the ferry as ship type. However, the reference vessel is a series build vessel in which a design optimization can have significantly more effect and can work better than a one-off build vessel. Therefore the vessel is used as a reference for the research and to develop a solution.

### Zero emission propulsion system

Currently there is an energy transition from fossil fuels, such as diesel, to more environmental friendly and zero-emissions fuels. This is especially relevant for ferries as travel distance is shorter and energy storage is therefore potentially more manageable. Previous research has examined potential fuels of the future based on market developments and on technical feasibility [103] [106]. However, most vessels are still designed and built to be diesel driven. An important aspect during the energy transition for the designs becomes the ability to be future proof. As new possibilities are being developed it is possible that newly designed vessels could become obsolete faster due to their type of propulsion method. Currently when implementing alternative propulsion systems this is a complicated and costly task. Where it is possible to select different sizes, brands or types in the use of diesel engines this is not possible in the case with alternative fuels. Alternative fuels require different storage and conversion systems limiting the possibilities to interchange systems without changing most of the machinery in the vessel. Besides this, there are significant differences in design, size, power density and emissions. [106] [97]. Currently, there is no optimal alternative propulsion method defined as new methods continue to be developed. This means that commercially available and future available possibilities can be used to find a more optimal solution.

Previous preliminary research has been done to determine the feasibility of zero-emission energy systems for double ended ferries where design parameters are created for vessel concepts using the zero-emission systems. Technical output of the tool which was developed was energy system mass and volume, used energy per trip, vessel length and displacement. The result of the previous research is technical feasibility, economical effects and energy efficiencies[81] [99]. However, as a next step a more specific approach towards alternative propulsion is necessary as there is no optimal design method to be able to continue in the energy transition. Besides this, customers are requesting a future proof vessel which means that the course of the development and the specific implementation possibilities have to be determined. As for now, multiple alternative fuels are expected to be feasible solutions based on the previous research but the research deals with the energy types as future developed solution and does not address uncertainty in the development.

### From standardization to modular design

In addition to the energy transition and the research into zero-emission energy types there is another process within Damen. Already for years Damen builds vessels in series and continuously works on standardizing vessel types in order to decrease the product-lead time and costs and to increase quality. Vessels are designed

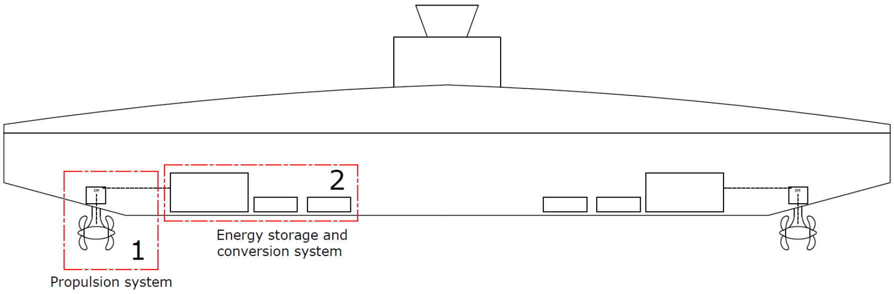


Figure 1.1: Simple systematic overview of a ferry

similar using standard approaches in order to decrease development and engineering costs. This process is continuously being developed over the history of Damen in order to compete with other shipbuilders. Vessel types and hulls are already similar, however the systems within the vessel are less standardized within the ship type but also across the different ship types. This means that the engineering of the systems within the vessels is more similar to unique designs than series or similar designs. Hence, the problem is that there is the continuing goal of Damen to standardize in order to increase delivery speed and reduce costs but full standardization gives no room for change. This results in problems as customers do want adaptions to fit to their specific needs and also nowadays regarding being future proof with the new energy types and uncertainties. In order to standardize the systems within the vessel and remain to have flexibility, the system can be grouped by modules which can be combined into a feasible system. The grouping into modules or modularization is a foundation to reduce project lead-time and costs due to rapid product configuration, purchasing, logistics and manufacturing with a guaranteed quality [56]. This approach reduces the engineering and the detailed design of systems and is the next step in standardizing. Modularity has a significant amount of theory supporting it but has also a significant amount of complexity in it which causes it not to be commonly used yet. Specifically for this research it means that using modularity the vessels can be designed cheaper and faster with a high quality. In a similar European Union's Horizon 2020 research project[24], modular design is a central aspect. In this project the problem within the design of vessel according to Jürgenhake: "There is a dominant belief that complete optimisation is the only way to design a ship. This is a result of today's extremely specified tender processes, which lead to one-off ships due to all the requirements vessel owners include in their tenders." and according to Seidenberg: "The maritime industry also has a strong focus on initial price". These two problems point out why it is important to investigate modular design as there is much to gain with regard to design costs and life cycle costs when designing modular.[24][66][64]

A continuation in the design process towards a modular zero-emission design is by working towards the practical design of the system. For this the approach is to divide the propulsion system and the alternative fuels in parts. The alternative fuel approach is focused on the propulsion system part which is currently the diesel engine and the storage tanks. This part can be called a sub-system which consists of modules and is a part of a total system which has items or modules forming a unified whole[108]. According to the NAVAIS project a module is the physical representation of a function, possesses physical and functional attributes, cost attributes, production attributes, etc.[66] These modules can be linked to form the configuration of a ship that matches the requirements and constraints. This also implies a certain interconnection flexibility when one or more modularity types are used [41]. Within these modules, adaptions can be made for the propulsion system to fit to the requirements of the vessel without changing the whole system. Using this approach it is possible to purely focus on the alternative propulsion methods.

The propulsion system is shown in a schematic overview of a ferry in Figure 1.1. The propulsion system here is defined from the electric motor to the propeller and is framed by the first box. The energy storage and conversion system is shown in the second box. These boxes are two sub-systems consisting of modules within the vessel. The energy storage and conversion system is variable. Where the original ferry system has diesel as fuel and diesel generators other energy types and conversion systems can be implemented.

When approaching the problem at a modular level, references to approaches in other industries are available[35]. Modular building is already applied in industries such as the car industry. Using the modu-

Figure 1.2: 9819 E3 Damen ferry

lar approach it is possible to develop and build a basic module and vary other parts to personalise the car. Next to this it allows for the change, repair or replacing of components or systems without changing the rest of the system design[35]. Modular shipbuilding is applied within the shipbuilding industry but at a lower level as series are significantly smaller. Besides this, personalizing changes for the client can have such an impact on the vessel that system changes are required. This means that the current process is engineering-to-order [65]. These changes are at system level which means that modular engineering can play a significant role in this process. Modular engineering is the method where modules are defined and the module then can be engineered and approved by class. The total design then is a combination of modules that are already approved by class and can be fit together [41]. This way the engineering time can be reduced significantly[66][87].

## 1.2. EU H2020 NAVAIS project

A European project was initiated to maintain world leadership in complex, value-added and highly specialised vessels called the EU H2020 NAVAIS project [66]. NAVAIS stands for New, Advanced and Value-added Innovative Ships and focuses on a new business case that merges customer tailored vessel solutions with standardised and modularised approach. The focus within NAVAIS is on two types of vessels which are the urban, inland and coastal passenger/road ferries operating near to zero emissions and a new multi-use workboat concept for various offshore tasks. However, the focus of this thesis is on the urban, inland and coastal passenger/road ferries. The focus for these clean fuels will be on energy types with less green house gas emissions and hybrid powering options. Within the NAVAIS project the challenge is to balance requirements for more specialised and customised vessels with the minimum amount of design, development, production and service efforts. Based on the specified vessel type as a coastal passenger/road ferry a case study vessel is chosen for the NAVAIS project. A model rendering of the ferry is shown in Figure 1.2. This vessel is the 9819 E3 Damen ferry which is a low impact modular E-400 passenger/120 cars road ferry with automated contact/battery charging[41].

The overall concept of NAVAIS is to review the current solutions for design and production of the vessels and to define their limitations and to develop a solution.

## 1.3. Design methods

The two processes within Damen for the energy transition towards zero-emission energy carriers and the process regarding standardization require a clear approach which allows for both. As elaborated in Chapter 1.1 this combination is somewhat in conflict with each other when using the standard design approach using the Design Spiral. The focus of this thesis based on the NAVAIS project is to balance requirements with the minimal amount of design, development, production and service efforts. This goal of NAVAIS is similar to the goal of Damen and shows the connection of the Damen vision and approach to the NAVAIS project. Within Damen and NAVAIS the total goal is regarding the total vessel where the focus of this research is regarding the energy carrier and conversion system. However, this does not change the idea and the approach for this

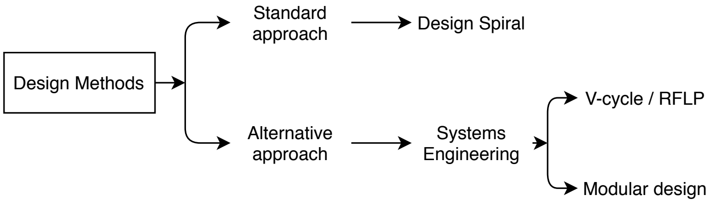


Figure 1.3: Design method approach

research. In order to change and optimize the approach which allows for the standardization and modularization first the current design process has to be elaborated. The design and engineering of the energy carrier and conversion system is part of the total systems engineering (SE) which will therefore be the basis of the approach. The new approach is in search for an approach which facilitates the two focus points of a modular design and a zero emission goal that is most suited. Figure 1.3 shows the alternative design approach which is used in this thesis with the use of alternative methods which will be elaborated in this chapter.

### 1.3.1. Standard design approach

In a standard design of a Damen vessel there are multiple phases[41]. These phases follow a point-based design approach where the different vessel or system calculations are done. As elaborated in the phases the steps consist of loose actions that have to be executed at each step meaning also a significant amount of work. The phases specifically are:

- **Concept design phase** starts with the mission requirements and includes the ship type, deadweight or payload, the type of propulsion, service speed and area, endurance at sea, position keeping and class society and notation.
- The **preliminary design phase** determines the main hull conditions and the form coefficients to estimate OPEX and CAPEX. This is based on the hull geometry, the arrangement and compartmentation, the first estimate of the propulsive power and the ships lightweight.
- The **contract design phase** determines the ships characteristics and main equipment. Included in this is the general arrangement, the technical specification on functional level and diagrams of main piping systems.
- The **basic design phase** makes the hull geometry ready for model tests and makes class drawings, hydrodynamic calculations and a component selection based on the functional requirements.
- The **detail design phase** provides information for the manufacture, assembly and testing of the vessel.

The point based approach is derived from the design spiral. Within ship design there are always the standard calculations and actions that have to be done to reach a technical feasible vessel. These actions are defined in the approach of the design spiral from J. Evans[38][107]. This spiral is shown in Figure 1.4. The design spiral includes all the steps that need to be taken to reach the final design. As shown in the figure, the design consists of the first three phases described above in the Damen approach. After these phases the detail design phase can start and the vessel can be produced. The design spiral was developed for the approach on how to estimate or calculate and balance ship design parameter values[50].

The advantages of the design spiral are that it is an iterative design process that works towards a feasible design. Besides this it works best at variants of existing ships. The design spiral is a point-based design which means that the start can be at a point from which the previous data is known[50]. Experienced naval architects are able to complete the spiral in only a few iterations. However according to Hopman [50], there are multiple weaknesses in this approach.

- Firstly, the spiral does not specify the level of detail and the order to analyse as this is dependent on the ship type.
- Secondly, it defines how to design and not on what is required in the design.
- Thirdly, it only deals with the combination of components or elements to form a connected whole and not the optimisation.

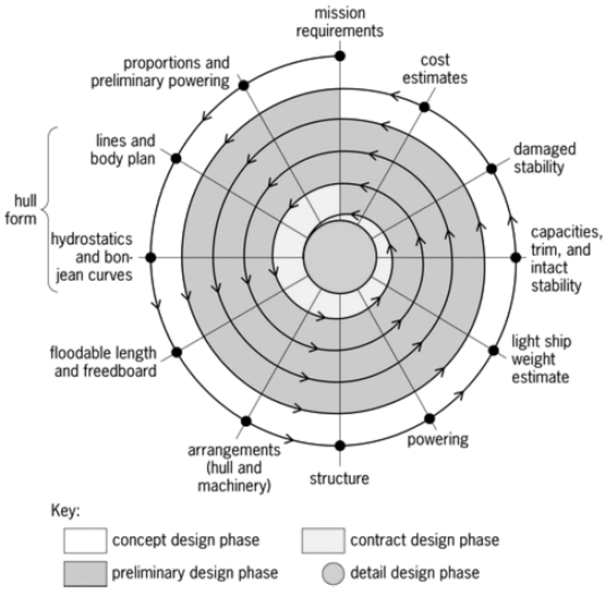


Figure 1.4: Design Spiral Evans [38]

Especially the second and third weakness have significant influence when designing a vessel with an alternative propulsion system. As competition is increasing, designs need to be innovative, cheaper and the designing time needs to be shorter. Therefore another approach is required in the designing of future proof innovative vessels. Making it more specific, the design points show that the first estimate of the propulsive power is defined in the preliminary design phase and the main equipment is determined in the preliminary design phase. This means that in the case of alternative fuels the weight of the systems will only be known at this point. If the size of the vessel is already set this may have to change depending on the energy carrier and conversion system after which the power requirement again changes. This process hence sees a significant amount of iteration in the case of designing a new type of system. This example using the design spiral also shows that the innovation towards zero-emission fuels cannot be based on standard design as the amount of iterations would make the design unique instead of standard. This uniqueness of the design would also increase the costs of the design and therefore loses the advantage which was gained through standardization.

### 1.3.2. Systems Engineering

An approach that addresses the limitations other than the point based design spiral is found in Systems Engineering. This method is based on a system thinking approach to understand and/or solve problems and on systems science which provides the theories and methodologies for applying the approach to solve systems. The system thinking views problems as part of a larger system and encourages looking for similarities or commonalities between systems from different domains. The approach is based on the complete system and the basic function where the function cannot be understood by understanding the parts themselves[50]. System thinking proposes a shift in thinking for interdependencies and feedback loops between different elements. This moves the short-term thinking to a more long-term big picture thinking. SE focuses on defining the customer needs and the required functionalities at the start of the design. Besides this, it considers both the business and the technical needs of all the customer[82]. Within SE the principal stages in the system life cycle are also defined and are shown in Figure 1.5. Rather than a simplistic approach, system thinking requires to look at when and how to (re-)design a product architecture and to find a balance in the short-term and long-term goals and requirements. This focuses on collective intelligence and perspectives. The figure is based on a general SE approach and names requirements as operational deficiencies. An operational deficiency is an unfulfilled requirement which means that for this report the two terms are interchangeable. A more detailed figure of the concept design is shown in Figure 1.6. This approach divides the requirements in two parts. First the operational requirements for the vessel and secondly the technological opportunities which include the desire to innovate and improve current designs. The usage of the two requirement types enable the definition of the vessel requirements and secondly allows for the implementation of alternative

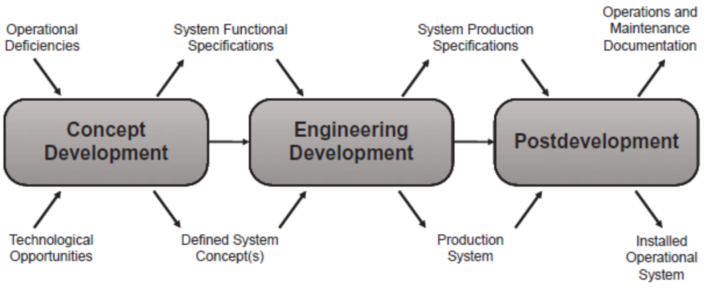


Figure 1.5: Principal stages in a system life cycle[54]

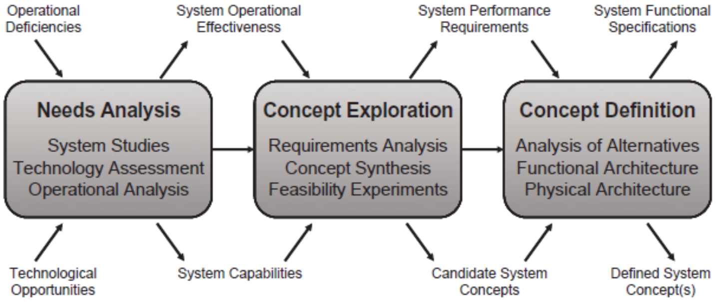


Figure 1.6: Concept design development phases[54]

fuels.

The method specifically combines the problems or shortcomings with opportunities or solutions. The problems or shortcomings can be translated into functional requirements and the opportunities or solutions into defined systems. For this research it means that using SE it is possible to start with the definitions of the requirements that have to be met for the system. These can also be requirements which yet cannot be solved. On the other hand there is the definition of the opportunities or solution possibilities. This means that both the technical available systems and functional requirements are defined and these can be optimally matched in a systematic way while considering the overall life cycle.

The system engineering process consists of the operational requirements, the functional analysis, the system analysis and trade-off strategy and the system test and evaluation strategy. This system engineering approach being used by NASA in 2007[83] and the International Council on Systems Engineering which was established in 1990[82] shows that the approach is not new but is increasingly used to manage complexity and change while reducing the risk in the design. This approach is the basis of the V-cycle approach is presented visually in 1.7. The practical SE process is based on the RFLP approach that stands for Requirement management, Functional analysis, Logical design and Physical design. The goal of this approach is to progress throughout the process as independently as possible to allocate elements of logical design model elements into a physical design. This procedure is the basis for the ability to design modular for the defined platform-based ferries. The literature research includes the first three steps in the process towards the engineering. These steps are:

1. Define the customer conditions and requirements
2. Define product conditions and their requirements which can be defined as functionalities
3. Define the system requirements and the design

### 1.3.3. Modular design

The second design approach is the modular design for the energy storage and conversion system as continuation of the standardization. As there is no optimal alternative propulsion method defined, flexibility is required in the design and adaption of the design. This flexibility is difficult due to the complex implementation and therefore it is difficult to be able to reach a future proof design. Modular design can be used based

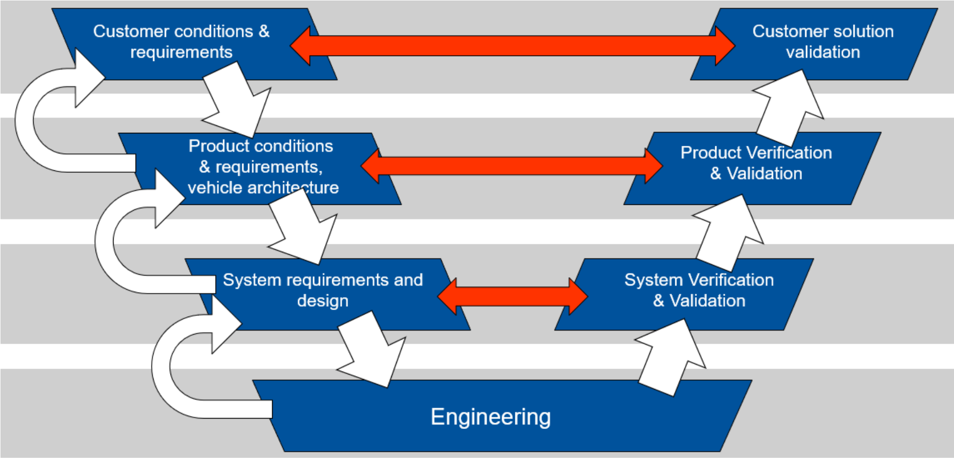


Figure 1.7: V-cycle product development process[85]

on the RFLP approach which makes the two methods complementary. The elaboration of modular design itself is done in Chapter 4.

### 1.3.4. Design method overview

To give a clear overview of the design method and the approach in this research, Figure 1.8 shows the three main reasons that are in conflict in a modular design approach and the reasons for the V-cycle approach. The V-cycle approach is a specific approach within system engineering which is used for the design and engineering of the energy carrier and conversion system. The V-cycle specific approach is based on operational requirements and technical opportunities and can therefore be utilized to facilitate for the two focus points of a modular design and zero emission propulsion system. Instead of focusing only on optimization this way it is possible to implement innovation.

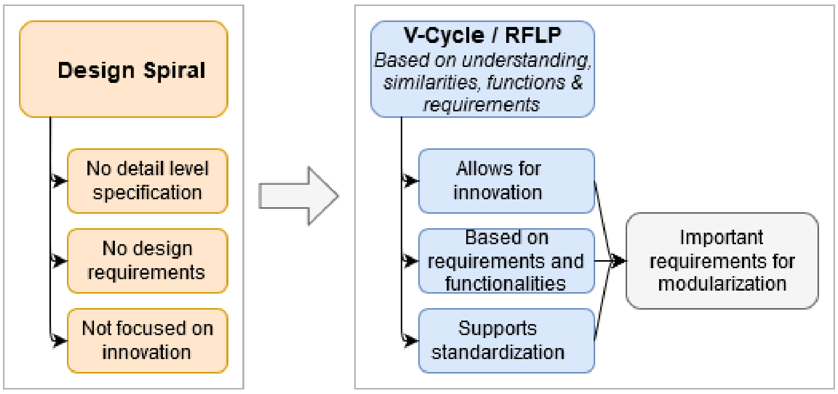


Figure 1.8: The design method from a design spiral approach towards the V-cycle approach

#### Downsides of the RFLP approach

The downsides of using the RFLP approach are first of all that this approach is named the expert approach. This is due to The fact that system knowledge is required if the starting point is functionalities instead of system requirements. Specifically it means that the user of the approach is required to know the different capabilities or applicability's of systems, system combinations and system developments which have to be combined in the functionalities. Besides this, there is a practical difficulty or downside of the approach according to M. Lansiaux. Meyer Werft implemented the RFLP approach up to a component level which resulted in the problem that they were not able to manage it and therefore the use of the approach failed. It therefore is important to be able to define the different system levels and to be able to manage it.

## 1.4. Problem definition

Currently, there is no optimal zero-emission propulsion method defined for a double ended ferry which can be implemented in a modular way to be able to have a future proof energy storage and conversion system. The technique and working of the propulsion in a vessel is mainly known from the motor to the propeller, section 1 in Figure 1.1. However, in the energy storage and conversion system, section 2 in Figure 1.1, options can vary with regard to the type of energy used and the conversion of this energy as new methods continue to be developed. With a view for the future there is uncertainty within the shipbuilding industry on the course of development for an environmental friendly energy carrier. Specifically this means that an optimal method for converting some kind of energy into electric or mechanical energy is not yet fully developed or known. Vessels with a relative short range start to be designed using more environmentally friendly or zero-emission energy sources. [64] [30]. However, these vessels are engineered separately and no method or tool is available to implement various energy carrier and conversion modules. This way the engineering on system level has to be done separately which is costly. Besides this, it is difficult to compare different energy sources to find the optimal system. Specifically, the problem is that engineering for the propulsion of the vessel is done or at least adapted for every vessel. As the engineering is not modular, the focus is more on selecting a system and optimizing it. This method omits or at least complicates environmental and system optimization.

## 1.5. Objective

The objective for this research is to use modularity to help support the development of zero-emission propulsion methods for a ferry. This way a combination of increase of efficiency in vessel design [65] and a resource-efficient and environmentally-friendly design [64] can be reached. Various energy storage and propulsion system modules can be designed and implemented to improve the design and find a system and environmental optimum. The main question for this research is:

**How can the energy carrier and conversion system of a ferry be made environmentally friendly and modular and how does the inclusion of low emission and modularity objectives impact the power supply and total design of the ferry?**

The first part of the question will be on the possibility to design and develop a modular energy carrier and conversion system using energy friendly to zero-emission fuels. These will be based on current available technology with a high TRL level. The first step in this is to define the system of the ferry after which feasible energy and conversion systems can be defined. Using this data a method is defined and worked out using a number of modular design approaches to combine the modular design and potential environmentally friendly energy types. The second part will be the influence of the alternative modular energy carrier and its conversion on the total design of the ferry. This elaborates and specifies the implication, possibility and method for the chosen energy carrier to fulfill the functionalities and requirements of the vessel. As the main question consists of multiple parts, sub-questions are defined to solve the main question:

*I. What are the vessel and system requirements of the Damen 9819 E3 ferry?*

As elaborated in chapter 1.2 the Systems Engineering and more practically the RFLP approach is used as basis. This means that the start of the research is the requirements of the reference vessel, the Damen 9819 E3 ferry. In this research question the system needs and desires are researched and elaborated for the energy carrier and conversion system which are presented in the model requirements. These requirements are then the basis for the functionalities of the energy carrier and conversion system which are required for the energy types.

*II. What are feasible environmentally friendly energy carrier and conversion possibilities?*

Next to the more standard internal combustion engine in combination with HFO or MGO other options towards zero-emission are available. Based on the general design objective, alternative energy types can be implemented. In addition to this the optimal energy usage of an energy type with regard to the technical feasibility and charging strategies can be defined. This part is based on available research in this field. The research will not be specifically into new energy possibilities but uses commercially available options which will be based on the state of play and the technological readiness of the energy type.[67]

*III. How can the energy storage and conversion system be defined using modules?*

The objective of this question is to define the approach and definition of the different modular design approaches which can be combined in a platform approach. This way the basis of a modular design in combination with alternative energy types is combined in a design approach. The combination of modular driving methods and approaches is used in order to objectively and systematically design the energy storage and conversion system. And in addition to this the technical feasibility and usability of the results and method is increased. Specifically this question elaborates on the different potential modular design approaches which are available and defines the combination of approaches in order to increase the quality of the final design of the modules.

*IV. How can a general interface be defined between the systems for the vessel specification and the propulsion requirements?*

The next step is to use the theoretical approach which is defined in the previous question and use this approach to define potential modules. Specifically, the previously defined functionalities and requirements are combined with the defined modular platform approach. This way the system can be separated into subsystems and these can be combined into modules using the platform approach in order to to be used as interchangeable modules with general interfaces.

*V. How can energy carrier and conversion systems be modular implemented using a method that fulfills the requirements and functionalities of the vessel?*

This objective is first to develop a method to be able to insert requirements for the vessel and then choose or implement various modules for the energy carrier and conversion system. This way various environmentally friendly systems can be implemented, compared and validated. Therefore, the approach is to design a method which includes the platform approach to systematically design a module based system. Where this method allows for modular development and expansion of the solution results in order to design future proof modular energy storage and conversion systems. The reason for a method is that it is more universally applicable than a tool. Where the final goal is to have a method that can potentially be applicable to multiple vessel and system configuration designs.

*VI. How can this method be verified?*

The final objective is to validate the method using different validation techniques. The in- and output can then be checked to be valid and in the right format. Besides this, the objective is to determine if the method is universal and could also work for other vessels. This way it could also be used for possible refits of vessels.

## 1.6. Scope

The scope of the thesis defines the boundaries of this project.

- The focus will be on a new system design for the energy storage and conversion system. The basis of the system design is on the 9819 E3 Damen ferry. Specifications for this vessel are known and based on these basic specifications the research will be executed. The approach of the system design will be such that a design is developed in based on modules that could allow for variance or a refit during the design and in the future life of the vessel using the module defined systems.
- The research is at a requirements and functionality level for the propulsion system. This means that the current technical feasibility and requirements are evaluated and not the future possibilities. This way it is possible to design a general interface for the energy storage and conversion system to modular design and optimize this system.
- The research will not be into all possible available energy types which can be used in the maritime sector. The research will be based on high TRL energy types which are commercially available. This

way the approach towards a physical module can be developed in stead of remaining at a preliminary level of development.

- An energy carrier is a substance which contains energy that later can be converted into other forms. In this thesis the energy carrier is used to define the component of the fuel which carries the chemical energy that can be converted into electric or mechanical energy [7].
- The financial aspect of technology has a significant role when using a top-down approach. However, in this research the focus is on the technical feasibility which means that the financial aspect is addressed in a less significant way.

# 2

# Requirements

The start of the research approach is to define the requirements and customer conditions. These requirements are based on the already existing 9819 E3 ferry. The requirements consist of the goals, purposes, success conditions for the system and the specification of the behaviour of the vessel [48]. A more practical version of this approach for the requirements is used by Vossen et al. [107]. The aspects influencing the requirements of the vessel are:

- The **commercial aspects** that relate to the current market situation in combination with the market perspective. For this project the commercial aspect are the desires of NAVAIS in combination with those of the client.
- The **operational requirements** which cover the operational tasks and their requirements for the vessel which can be seen as the design parameters.
- The **external requirements** describe all the requirements based on rules and regulations of classification societies.
- The final aspect is the **available technology** which includes the available building materials and technology with regard to the equipment which can be used.

Based on the elaborated approach of the thesis in Chapter 1.3.2 two types of requirements are defined. The first one being the vessel requirements and the second type are the research requirements[107]. Figure 2.1 shows the applicable part of the requirements for the vessel.

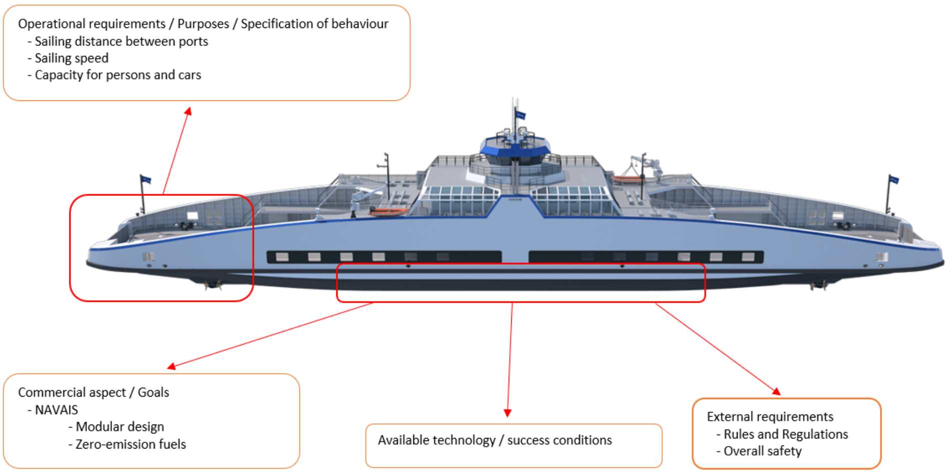


Figure 2.1: Visualization of the requirement specification

- The vessel requirements are factual requirements in order to comply with the basic demands for sailing. These include the operational requirements and the external requirements. These include the resistance at a set sailing speed, efficiencies of components, weight and space 'budget', etc.
- The research requirements, which are the desired requirements, are focused on the desire of Damen and NAVAIS to design a ferry with environmentally friendly or even zero emission energy carriers. And besides this also the modular design aspect of the vessel. These therefore include the commercial requirements and available technology.

However, because the energy carrier and conversion system are not defined in this stage, the requirements will not be on the specific fuel consumption. In addition to this, the external requirements of the classification societies is not defined in the requirements as this is also significantly dependent on the energy carrier and conversion system. Next to this, an amount of data within the research is predefined as the research is based on a case study vessel built for Ontario, Canada. This data is shown in Table 2.1. The route that the vessel sails which corresponds to the environmental condition is shown in Figure 2.2.

Table 2.1: Environmental sailing conditions Ontario, Canada

| | | | |
|---|---|---|---|
| Wind | | | |
| | *Speed* | 15 | km/h |
| | *Direction* | SW 50% -NE 25% | |
| Waves | | | |
| | $H_s$ | 0.45 | nm |
| | *Direction* | SW 20% | |
| Current | | | |
| | *Speed* | <0.2 | kn |
| Water depth | | 20 | m |

Figure 2.2: Sailing route for the 9819 E3 ferry

## 2.1. Main level requirements

The requirements in this report are more specifically defined and are based on main level requirements. These requirements besides the innovation or research requirements are defined within the NAVAIS project. The main level requirements including the innovation or research requirements are shown in Figure 2.3. This figure is adapted from Deliverable 2.2 within the NAVAIS project where the adaption is made towards the energy storage and conversion system. Set and defined requirements are based on these main level requirements. The innovation or research requirements are included in the figure for an overview and are elaborated on in Chapter 2.3.

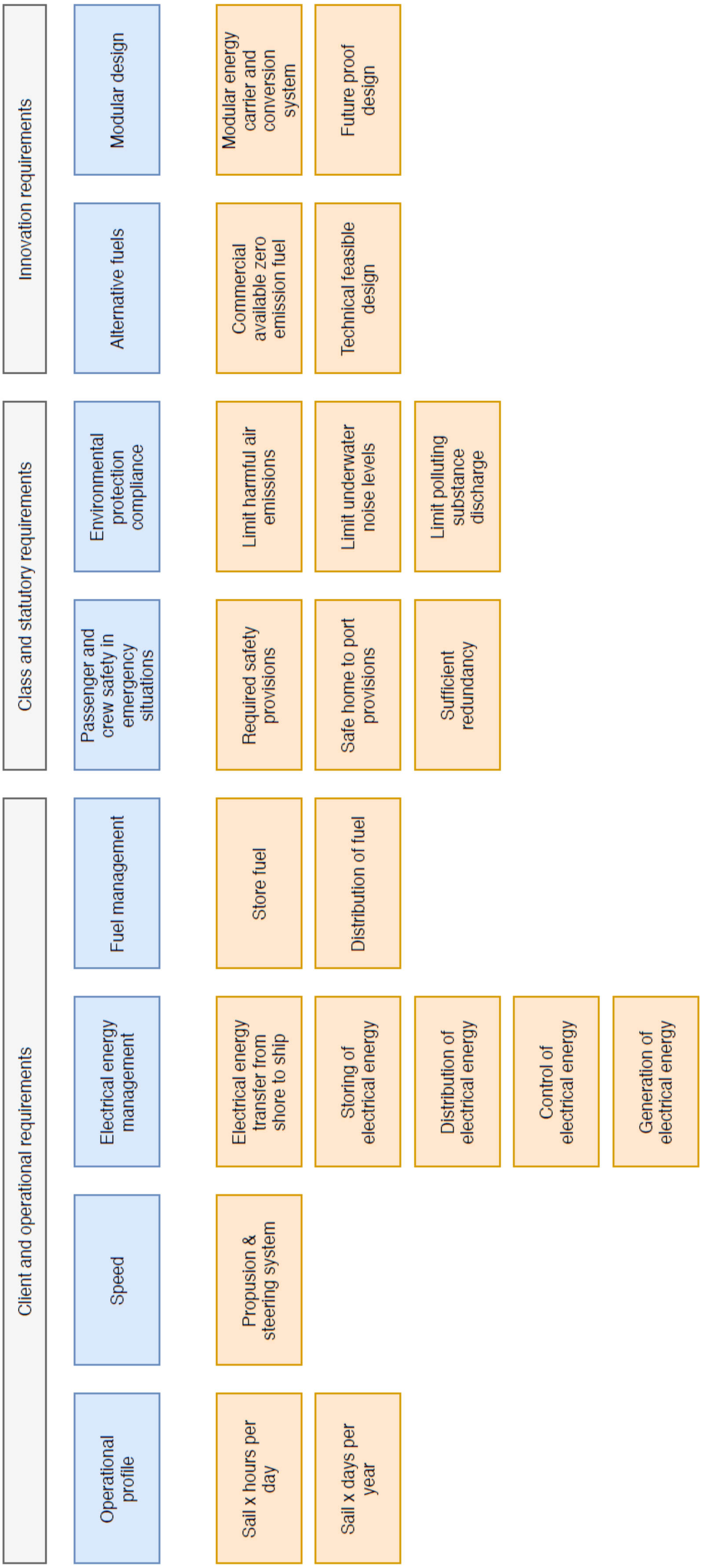


Figure 2.3: Main level requirements which apply to the energy storage and conversion system adapted from S. Brkic [77]

## 2.2. Vessel requirements

The operational requirements start with the requirements from the client. In this case there are requirements with regard to the amount of persons and cars that have to be transported and the time window in which this has to be done. The 9819 E3 ferry was first designed as a hybrid ferry and later changed to an all electric vessel. The vessel which is sold and is being build is a diesel electric configuration. The electric configuration in the normal sailing conditions and the diesel generator for the winter conditions. The decision for the vessel to have a diesel electric version of the vessel is based on the requirement for redundancy. Even though the vessel could be designed and delivered to be fully electric, the redundancy of systems was even more important. This means that the vessel in theory could be environmentally friendly, but based on client requirements still uses diesel generators as well.

The fixed requirements are based on the universal vessel type. However, for the required energy the all electric vessel type is used. Besides this, the vessel has two operational profiles. The first one is for the normal sailing and the second one is during the winter when there is an ice 1B situation. This means that the vessel is capable of navigating in moderate ice conditions, with the assistance of icebreakers when necessary[2]. As for the requirements all data is based on the specification document from Damen Shipyards[84] unless otherwise defined.

- During normal sailing condition the requirement is to do a crossing in 30 minutes including the loading, charging and mooring. Besides this, there is the operational profile for the ice 1B sailing condition. This profile limits the sailing speed to 5 knots instead of limiting the sailing time. The operational profile for both of these conditions is shown in Figure 2.4. The amount of cycles per year which are required are 12.600 in total of which 3.600 cycles are during ice conditions.

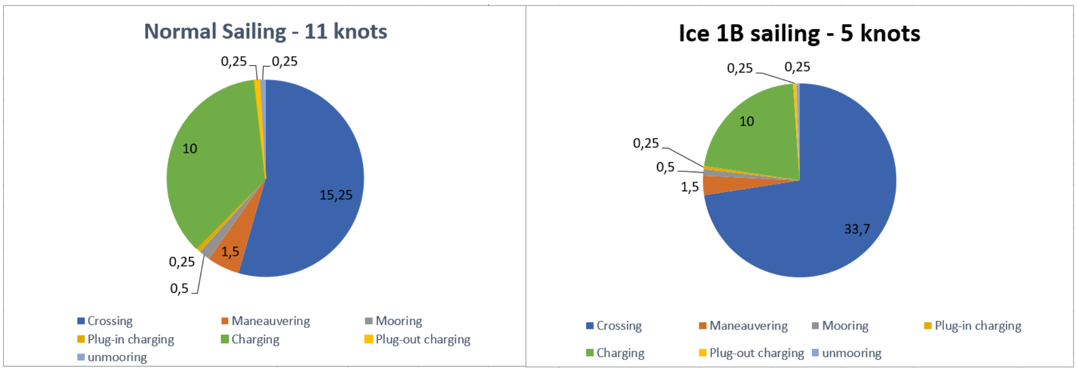


Figure 2.4: Operational profiles of the 9819 E3 ferry for normal and ice 1B sailing conditions in minutes

- The maximum number of people on board will be a 399 and the maximum amount of american cars will be approximately 83. This in combination with a lane meter of 2.8 meters width for a length of approximately 274 m and a lane meter of 3.4 meters width with a length of approximately 93 meters. This to ensure the required amount of cars and trucks. The translation of these requirements into vessel dimensions is shown in Table 2.2.

Table 2.2: Basic vessel details

| **Vessel dimensions:** | | |
|---|---|---|
| Length overall | 98 | m |
| Beam | 19.8 | m |
| Depth | 4.2 | m |
| Scantling Draugth | 2.7 | m |

- In addition to these requirements the specific power and energy requirements are calculated as well as the weight and volume for these systems. The results of these calculations is shown in Table 2.3.

## 2.3. Research Requirements

The desire of Damen and NAVAIS is to design a ferry with environmentally friendly or even zero emission energy carrier based on a modular design of the vessel. The requirements are the model requirements and include the commercial requirements and available technology. In the current situation the ferry is designed to be fully electric. Based on this configuration it is possible to add desired requirements for the vessel and its system. The energy carrier and conversion system should be:

- **Future proof** which means that the vessel will comply with the rules and requirements set by local government and IMO on fuel and emissions. This is a requirement from clients of Damen. The energy type that is used in the design is an environmental friendly or zero-emission energy type. Besides this, the energy type used requires a high TRL for the technology to be used in practice.
- **Modular** which means that the system is defined using modules which can be interchanged in the design with other modules. NAVAIS has as goal to design modules which can be pre-approved by classification society before implementing them in the vessel. This means that the total systems in the detailed design need less approval checks of classification society as the modules are already approved. These pre-approved modules can be fitted together in the total design to form a fully functional system.
- Able to **fulfil the energy and power requirements** of the ferry. These requirements, coming from the operational profile, have to be fulfilled based on the energy system itself or a combination of systems.
- Able to be **refitted or renewed** in the future with more optimized systems as an additional requirement for the future proof design using the same environment and most of the currently installed modules. This means that an improved energy system with regard to efficiency, design parameters or environmental optimization can be implemented in a modular way.
- **Technical feasible systems** used in the design which is a requirement of the used top-down method. The technical system in the fuel chain on board of a vessel associated with fuel which are the engines, storage tanks, pumps, pipes and exhaust funnel as well as the bunkering system and fuel storage terminal. All of these systems thus need to be technically feasible which comes back to the requirement of a high TRL.

## 2.4. Requirements overview

Table 2.3 shows the overview of the requirements for the vessel for the energy carrier and conversion system. The first part of the table shows the requirements where the value has to be equal or higher and the second part shows the maximal allowable values. The third part summarizes the model requirements based on the different stakeholders in this project.
The table shows the requirement for environmental friendly design as well as the requirement for redundancy. Where the need for zero-emission might be possible to reach, customer requirements have the largest influence. For this reason a focus in the research is into alternative environmentally friendly energy carriers. However, conventional energy carriers and conversion systems such as diesel and a diesel generator are also included. Next to this the development of the alternative fuels is ongoing which means changes are inevitable and sometimes not sufficient to fulfill the operational profile and requirements of the customer. This means that the conventional propulsion methods are expected to be relevant for the coming years which makes it also important not to leave outside the scope.

Besides this the values shown in Table 2.3 are specific requirements for the 9819 E3 Damen ferry and are not necessarily generally applicable for other vessels. Specifically it means that the overview of requirements is used as defined in Figure 2.3 for the start of a vessel design. In this research the step between the specified requirements and the calculated requirements is omitted. This extra step is to calculate and determine the resistance, sailing speed, propulsion power and energy consumption which was already provided by Damen Shipyards and is therefore not included. This is shown in Figure 2.5 where the extra step between the overview of requirements and the calculated specified requirements for the 9819 E3 ferry are shown.

The design and elaboration of this research will be based on these specified requirements and functionalities following the RFLP approach. Meaning that due to the systematic design approach and the basic functionalities and requirements which are common in other vessels it is possible for these requirements and approach to be used for other vessels.

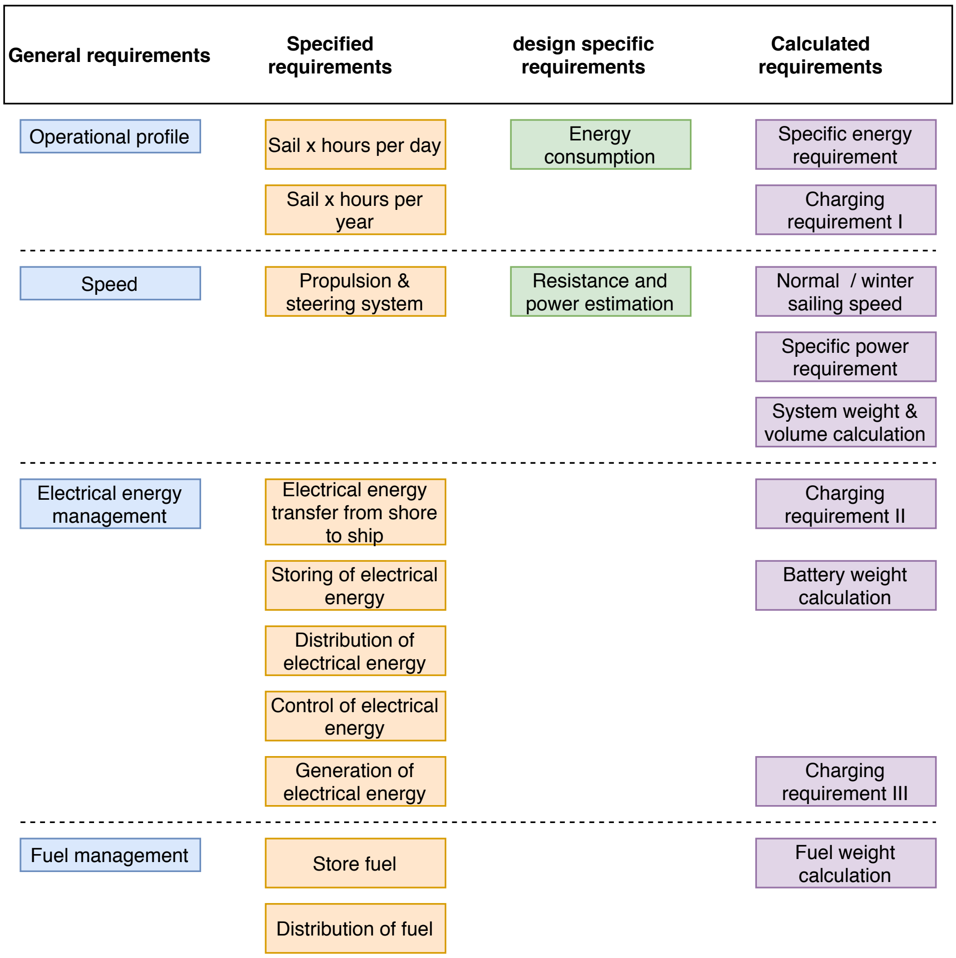


Figure 2.5: Different levels of requirements and specification

Table 2.3: Overview of requirements

| **Specific system requirements minimal values** | | |
|---|---|---|
| Normal sailing speed | 11 | knots |
| Winter sailing speed | 5 | knots |
| Energy requirement normal condition | 479 | kWh |
| Energy requirement winter condition | 1685 | kWh |
| Power requirement normal condition | 1613 | kW |
| Power requirement winter condition | 2393 | kW |
| Charging power output for batteries | 2875 | ekW |
| Minimal grid connection power | 575 | kW |
| Minimal system lifetime | 10 | years |
| Energy conversion system has redundancy | 2 | - |
| **Specific system requirements maximal values** | | |
| System weight for batteries and generators | 63 | tons |
| Fuel weight | 46 | tons |
| Total energy carrier and conversion system | 206 | tons |
| System volume | 928 | $m^3$ |
| **Research requirements** | | |
| An environmental friendly or zero emission fuel commercially available | | |
| Modular energy carrier and conversion system | | |
| Ability to fulfill operational profile | | |
| Ability for a refit using the same system environment | | |
| All systems are technically feasible | | |

# 3

# Feasible energy carrier and conversion possibilities

Marine fuel currently contributes to approximately 3% to global produced $CO_2$ emissions, 9% of all $SO_x$ and 18-30% of all $NO_x$[60][62]. Fuel alternatives have received a significant amount of attention in recent years where the focus was on the before mentioned emissions and other greenhouse gas emissions. Fuel alternatives have to fulfill environmental regulations and also the future course of these regulations as they become more strict[7]. As of the first of January there is a more stringent sulphur norm. Therefore many scrubber installations are installed. An alternative for this is Ultra Low Sulphur Heavy Fuel Oil, Liquid Natural Gas or blends of Heavy Fuel Oil and Marine Gas Oil. However, fossil fuels still contribute to greenhouse gasses such as $CO_2$ and alternative fuels can therefore significantly reduce the $CO_2$ emissions from Tank To Propeller (TTP) and also Well To Propeller (WTP)[100]. Therefore, the search for a new marine fuel is the topic in the energy transition. However, a clear answer still has to be found. Brynolf [7] stated that Hillman [49] discussed two major problems regarding using and interpreting the assessment of emerging technologies. Firstly, there is a risk that more advanced future technologies will be favoured more because they are likely to display better environmental performance. This viewpoint may result in a belief that there will always be more advanced future technologies worth waiting for. Secondly, it is impossible to include all relevant cause-effect chains thoroughly which may result in the inclusion of only the easily accountable effects. Within the short-sea shipping and passenger segments, fully electrical or hybrid vessels are emerging. Short-sea shipping is defined as vessels which are operating in limited geographical areas on relatively short routes with frequent port calls. They have relatively low energy demand and are therefore ideal candidates for testing new types of fuel which are marked by high energy or fuel storage costs[62]. In this Chapter first the energy conversion systems are elaborated after which currently available energy types are discussed.
The energy types are discussed based on the set requirements defined in Chapter 2.3. This means that the energy type requires a high TRL which means that it is now applicable and possible to be used. Besides that it has to be used on the vessel and thus has to fulfill the requirements.

## 3.1. Functionalities

Next to the requirements come the functionalities of the system. A function can be described as a specification of behaviour between in and outputs[45]. These functionalities are defined for the energy storage and conversion system. This means that the input of the energy carrier can be defined and also the required behaviour specifications of the energy conversion. The functional requirements are:

- To converge stored energy into electrical energy which can be used by the electric motor. Specifically a minimal power of 1612.7 kW in normal sailing conditions and 2392.9 kW in winter conditions has to be provided.
- To be able to be refueled in 10 minutes during the operational time or outside the operational time to supply the 479.1 kWh per cycle in normal sailing conditions and 1684.6 kWh per cycle in winter conditions.

- The ability to handle the power fluctuations based on the operational profile and sailing conditions.
- The emissions originating from the conversion system will be minimized.

## 3.2. Conversion technology

The approach in this research is based on the technical feasibility of systems and energy carriers. The possible conversion systems are shown in Figure 3.1. The steam turbine which is named in the figure is almost only used for nuclear powered vessels. Nuclear power is outside the scope of the vessel which means that steam turbines are also not taken into account. Gas turbines are used on Naval vessels or fast sailing vessels. As this is also out of the scope, the gas turbines are not taken into account.

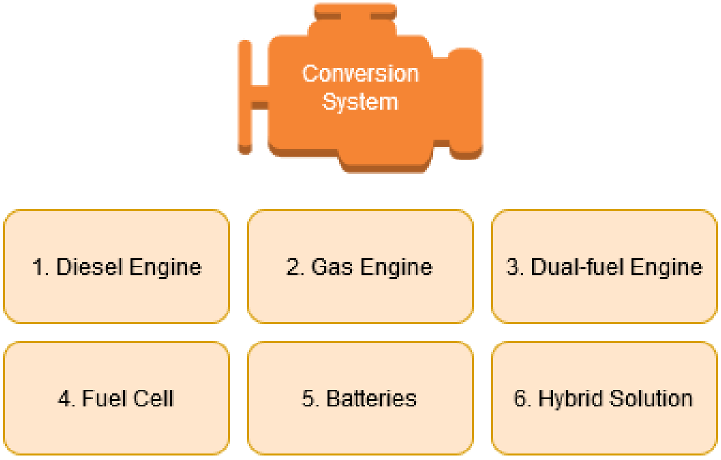


Figure 3.1: Commercially available conversion systems

### 3.2.1. Internal Combustion engine

The Internal Combustion Engine (ICE) covers the diesel, dual-fuel and Gas engine. The name ICE refers to the fact that there is combustion in the engine which means that there are emissions. However, based on the engine and the fuel type these emissions can be limited. These conversion systems have to comply with the requirements and the functional requirements of the vessel.

**Diesel engine**

The marine diesel engine is the main used energy conversion system in the maritime industry. Table 3.1 shows the functional requirements and the diesel engine specifications. The two-stroke diesels are used mainly on large cargo vessels which means that they are not relevant in this research due to their relative high power[1]. For the vessels built within Damen Shipyards two types of diesel engines are used which are the medium speed and high speed engines. The basic fuels that can be used in the diesel engine have the capability to fulfill the power requirements, emission requirements set by MARPOL and the power fluctuation requirement. With regard to the emission regulations these are defined by Tier levels within the marine industry. This limit is based on the $NO_x$ level based on rpm as shown in Figure 3.2. Besides this, propulsion systems have to comply with the $SO_x$ levels set by MARPOL. These levels are 0.5% of Sulfur limit in Fuel in % m/m and 0.1% in Emission Control Areas[27].

Table 3.1: Diesel engine functional requirements

| Functional requirement | Elaboration |
|---|---|
| Engine specification | Two stroke low-speed engine with a maximum efficiency of 50%<br>Four-stroke engine with a maximum efficiency of less than 50% with the configuration possibilities of having a gearbox or in a diesel-electric configuration[58] |
| Fuel types | Marine Gas Oil (MGO), Marine Diesel Oil (MDO or MDF) |
| Power | Starting with the high speed engine with a rpm between 1200 and 2400 up to the medium speed engines with a rpm between 600 and 1200 power ranges up to more than 11500 kW [91] |
| Emission minimalization | Engines comply with the Tier levels set by MARPOL |
| Power fluctuations | Diesel engines are able to handle the required power fluctuations |

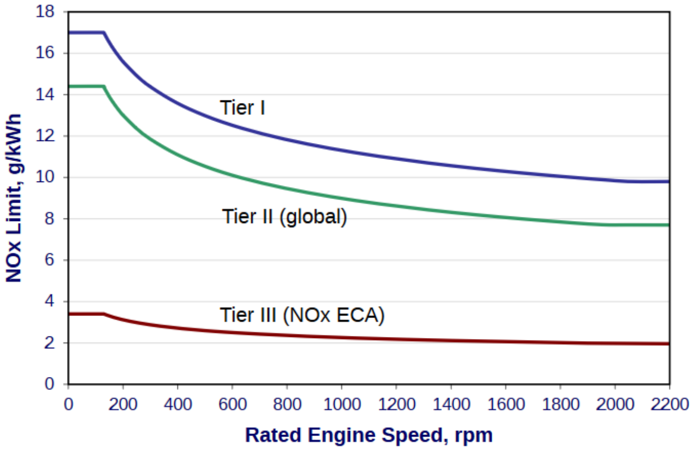


Figure 3.2: Maximum Tier emission levels based on rpm with regard to $NO_x$[27]

### Gas engine

There are many types of gas engines which can be distinguished based on gas insertion method, air excess ration, gas ignition method and combustion shape (heat release)[78]. The gas engine type can also be named spark ignited lean burn engine where there is a spark plug in the pre-chamber[72]. Gas engines have a small operating window in which the thermal efficiency is high and the emission of $NO_x$ is low. This operating window is shown in Figure 3.3.

The advantages of a gas engine are that the technology is relatively simple and reliable, the emissions are low with regard to normal diesel engines, there are no governing or low-load limitations and they are cost-effective. This means that the engine is well suited for maneuvering and part-load operation. However, the disadvantage is that emergency fuelling or propulsion is challenging. The power range of gas engines starts relatively high at about 4400 kW up to 8800 kW[21].

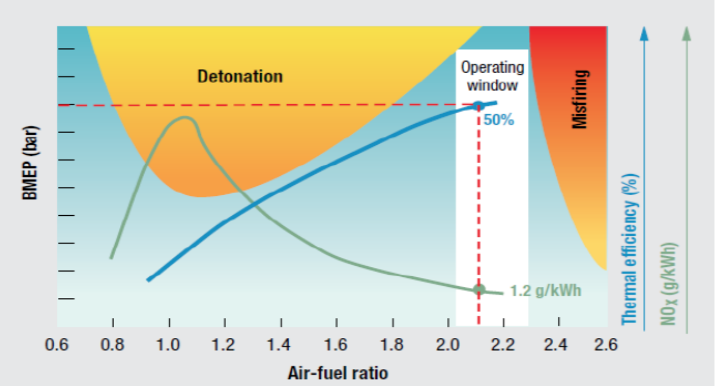


Figure 3.3: Operating window based on the pressure and air-fuel ratio of a gas engine

**Dual fuel engine**

A dual fuel (DF) engine is an engine which can run both on gaseous and liquid fuels. When running on gas, the engine works according to a low-pressure port injection which is the otto cycle. When running on a liquid fuel it works as a high-pressure direct injection engine which is a diesel cycle. These two fuel systems provide extra flexibility and single-engine installations are also allowed. However, the disadvantages are that the engines are more complex and expensive. Besides this there might be a difficult transient governing and variable speed operation. This type is best suited for multi-engine installations with an electric transmission. Key features of the DF engines are that the air-fuel ratio can be controlled and the fuel injection system which has double nozzle injectors and a common-rail pilot system. The engine can be operated on natural gas, light fuel oil or HFO. For the gas ignition using a low pressure cycle, a schematic figure is shown in Figure 3.4 that shows the cylinder. The power range of the engines lays between 1110 kW and 17100 kW using Wärtsilä[19].

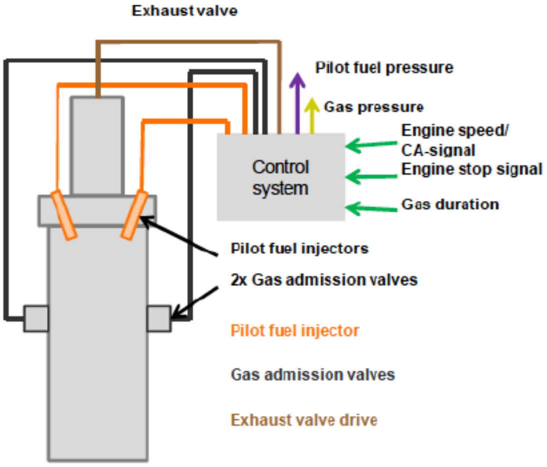


Figure 3.4: Schematic figure of a low pressure dual fuel engine cylinder[72]

With regard to the emissions there is a $CO_2$ and $SO_x$ emission reduction due to the fuel composition. Besides this, the $NO_x$ levels are reduced below the Tier III level

### 3.2.2. Fuel cell

It seems unlikely that fuel cells are fully going to replace combustion engines, but for a large number of Damen vessels it can be applicable. Due to sailing in urban and vulnerable nature areas with a high public opinion[5]. The main components of a fuel cell are the fuel cells themselves that convert chemical energy into electrical and thermal energy. This is a process based on electrochemical oxidation and can reach electrical efficiencies up to 60%, depending on the fuel and fuel cell type used. In the maritime industry there are currently only small fuel cell applications in operation up to a power output up to 100 kW. Similar to batteries, fuel cells are modular which means that the intrinsic performance of a single cell is not different from a big

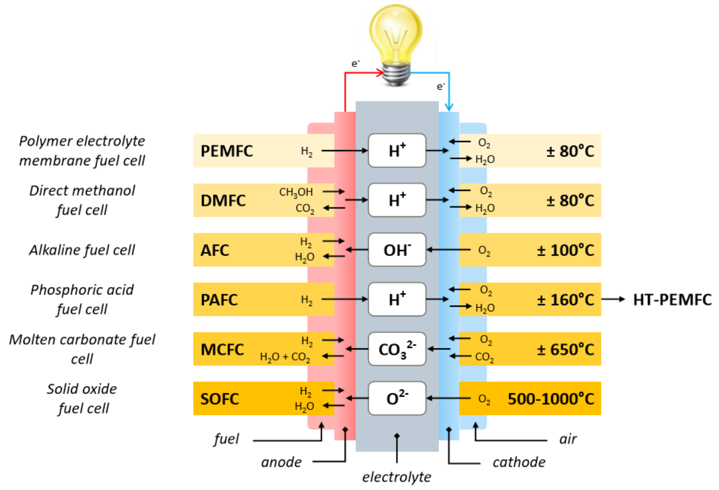


Figure 3.5: Fuel cell options and the electrical reaction[96]

stack. This leads to a high level of redundancy and also a high level of modularity. However, a fuel cell shows gradual performance degradation over its lifetime. The lifetime of a fuel cell is currently around 5 years which has a significant impact on the capital expense. However, this gives the opportunity for an improved fuel cell system with a decreased price. Besides this, there is an option to over capacitate the vessel to artificially increase the operational lifetime of the fuel cell[98]. The main sources used for the fuel cells are van Veldhuizen [98] and van Biert et al. [95]. The various types of fuel cells are shown in Figure 3.5

Not all fuel cells can handle power variations very well. Fuel cells combined with batteries for peak-shaving effects therefore are a promising option. Proton Exchange Membrane Fuel Cells (PEMFC) can be used thanks to the flexible material used with improved fuel cell lifetime. Currently, the installation costs of a fuel cell are between 2200 and 5600 USD per kW of electrical power. Developments aim to reduce these costs towards 1000 USD per kW. PEMFC are already significantly less expensive due to the investments in the automotive industry. The expected price for PEM fuel cells is expected to go to 280 USD per kW where the goal of Fuel Cell and Hydrogen Joint Undertaking aims to achieve a system cost of 100 USD per kW[62]. An overview of potential available fuel cells is given below:

#### LT-PEM fuel cell

The LT-PEM Fuel Cell stands for Low Temperature Proton Exchange Membrane fuel cell and has a TRL of 8 in general but a TRL of 6-7 for the maritime industry[96]. The limitation of the fuel cell is that the installation itself is not the problem, but it can only handle high quality $H_2$ as fuel. Besides this, replacement of the membranes is an issue and the effect off the marine environment is unknown. With regard to the application the LT-PEMFC is that it is used in the automotive and is scaled up to MW-scale in maritime demonstrator projects. It operates at temperatures from 65-85 degrees Celsius. For this system a complex water management system is necessary. The efficiency is about 50-60% and it has a DC-current output. It has a gravimetric power density between 125 and 750 W/kg and a volumetric power density between 50-400 W/l.
The Start-up time is less than 10 seconds and the load transients between 10 and 90% is possible within seconds. The price is multiple times higher than an IC and the price is 1900 euro/kW[98]. Including stack lifetime this becomes 3300 euro/kW at a lifetime of 50000 hours. However, van Biert [96] defines the system life time of more than 10 years when the stack is replaced. The stack lifetime is set there between 5.000 to 20.000 hours.

#### HT-PEMFC

HT-PEMFC is a newer technology than the LT-PEM which results in a lower TRL. The TRL for the maritime industry version is 5 to 6. The difference between the LT and the HT is that the operation temperature is between 100-200 degrees Celsius. Meaning that there is a higher impurity tolerance. Its efficiency is slightly lower than the LT-PEM. The gravimetric power density is between 25 and 150 W/kg and its volumetric power density between 15 and 120 W/l.
The start-up time is between 10 to 60 minutes where again the load transients between 10 and 90% and is possible within 5 minutes. The price is 2500 euro/kW and including the stack lifetime the price becomes

6100 euro/kW at a lifetime of 30000 hours. van Biert [96] defines the system life time of 10 years or more with stack replacement. Where the stack needs to be replaced between every 10.000 and 30.000 hours.

**SOFC**

The SOFC is the Solid Oxide Fuel Cell which has a TRL of 6. However, for the maritime industry the TRL is 4 or 5. The limitation of the fuel cell is that the dynamic performance is very low which means that it can only run at a steady load. Therefore the fuel cell must be applied in a hybrid solution with batteries for peak-shaving to be realistic in the maritime industry.

The high operation temperature results in fuel flexibility (natural gas, diesel distillates, methanol, etc.). It has a high efficiency of 60% or higher with a power range up to 500 kW and due to the high efficiency, it seems to be the future solution. The gravimetric power density is between 8 and 80 W/kg and its volumetric power density between 4 and 32 W/l.

The start-up time is more than 30 minutes where again the load transients between 10 and 90% which is possible within 15 minutes. Most options are in prototyping stage or first series resulting in very high pricing. The price therefore is 8000 euro/kW and 14000 euro/kW when including the stack lifetime of 40000 hours. van Biert [96] defines the system life again at 10 years or more with stack replacement every 20.000 to 90.000 hours.

**MCFC**

MCFC stands for Molten Carbonate Fuel Cell and has a relatively low TRL. The limitation is that MCFC requires an additional combustion chamber as not all fuel is converted and the temperature of the fuel cell needs to be maintained. It operates at a high temperature between 650-700 degrees Celsius and has an electric efficiency of 50%. With energy recovery systems it is possible to reach an efficiency of up to 85%. The price is 4000 euro/kW and including the stack lifetime of 30000 hours it becomes 9100 euro/kW.

### 3.2.3. Batteries

The technical readiness of batteries is 9 as it is commercially used for multiple vessels. The energy storage type is electrochemical which means that the battery is composed of one or more electrochemical cells. In these cells reactions take place that transfer electrons. The currently most used battery type is lithium-ion due to the relative low maintenance costs, low self-discharge rate, longer lifetime and a fast charging rate. The chemical composition of lithium-ion batteries can be different which affects the before mentioned properties. The battery has a high energy density relative to zero-emission energy storage.

Besides this, the efficiency of a battery is high and the technology is developed. However, the battery life is uncertain and dependent on the Depth of Discharge (DOD). Besides this, the capital costs are high, the energy density relative to fossil fuels is low and the recycling is relatively underdeveloped. Besides this, an important aspect of the battery is the (dis)charging rate. This rate is defined by a C-rate. With a C-rate of 1 it takes 1 hour to fully charge or discharge the battery and a C-rate of 2 means 0.5 hours to charge or discharge. This charging rate is of importance as the charging time is often limited as defined in the operational profile.

With regard to the environmental impact of batteries the local emission is zero. Also a battery system is made of modules where in a combination of modules also includes cooling and controlling systems. Currently Damen uses batteries of Corvus[29]. These batteries have a C-range between 0.5 and 6C where the 6C is for peak rates. The available pack size of a single pack for a C-rate between 0.5 and 1 is between 571-1142V with an energy capacity between 300 and 2400 kWh. For a C-rate between 3 and 6 the pack sizing becomes 130-1200V and 7.8-136 kWh. The standard pack weight of the Corvus battery developed for ferries has an energy capacity of 125 kWh using 1620 kg with dimensions or 2.24 m x 0.87 m x 0.74 m. This results in a specific energy of 0.078 kWh/kg and 0.087 kWh/l. When using the case study vessel the weight of the batteries is 47578 kg. Using a discharge rate of 3C this means that a single module provides a power of 375 kW. Also using the weight of the batteries for the ferry this means that the battery capacity is 3625 kWh. The power density for this energy capacity becomes 1612.7 kW / 47578 kg = 0.033896 kW/kg.

### 3.2.4. Hybrid solution

Hybrid solutions mean that a combination of systems is used. With regard to the energy conversion system two types can be used where often batteries are implemented. The combinations could be for instance to have a diesel generator and batteries. This setup ensures redundancy and can also be used for energy and system optimisation. Examples for this are shown below[16].

- A green mode with zero exhaust by for instance only using the batteries.
- A start and stop system where at low loads the power is supplied by the energy storage system alone and conversion systems start if the load increases.
- For instant load taking if power is instantly needed.
- Cold start-up for the system. By using only power from the energy storage, the ship can operate while the engines warm up.
- When the conversion system experiences load fluctuations these can be absorbed by the energy storage system. This allows a more stable machinery operation.
- A power boost can be generated in case this is required.
- There is also a level of redundancy that if there is a malfunction in one of the systems, the vessel still is able to sail.

### 3.2.5. Underdeveloped conversion systems

In this section are other conversion systems that exist, but are not developed enough to be seriously considered in the research. This is both the case for supercapacitors and flow batteries as elaborated below due to respectively the size and price for the supercapacitors and price and technical issues for the flow batteries.

**Supercapacitors[79]**

Supercapacitors, ultracapacitor or double layered capacitor is a device that can store energy by a static charge. There is no electrochemical reaction which means that there is significant less heat generation and degradation compared to batteries. Opposed to batteries supercapacitors make use of materials that are earth-abundant and non-toxic as they are mostly made from carbon-based starting materials. The devices thus are non-hazardous and can operate in a wide range of temperatures between -40 and 85 degrees Celsius. Besides this, is has at least 10 to 100 fold the power densities of any battery system.

Likewise batteries the supercapacitor contains a pair of electrodes containing active electrode materials. A porous membrane that separates both the electrodes physically and electrically preventing electrical shortening. The electrolytes containing the charged ions are generally soaked with the membrane separator and packing components in a single cell to avoid leakage. With regard to the application of supercapacitor, currently it is only used to provide an assisting buffer for the battery stacks in hybrid vessels. As the super capacitors works via electrostatic charge absorption it enables a faster charge or discharge than batteries and prevents safety hazards.

For the storage there is a trade-off between power and energy. The higher power densities leave them with low values of energy density. And as the supercapacitors are purely of electrostatic nature little can be done to achieve higher energy density without extensive material designing. When using the highest energy density supercapacitor it has an energy density of 0.3 Wh/kg. Compared to the Li-ion battery with the lowest energy density of 2 Wh/kg the difference is more than 6.5 times. Francis [42] even shows a specific energy 20 times lower for a supercapacitor and an energy density of 66.7 times as low as Li-ion batteries.

**Flow batteries[75][6]**

The flow battery is a redox flow battery. This is a modular system comprising of a cell stack which contains functional electrodes which are attached to current collectors. Besides that there are electrolyte storage tanks and delivery pumps and pipes. The system relies on the electrolyte circulation system to deliver electrochemically active species to the electrode surfaces. This way a charge transfer can be achieved which causes electrical current to flow.

The redox flow batteries belong to a class of secondary rechargeable batteries that operate on a redox reaction basis of electrochemical active species which are present in the electrolyte solution. The battery has a number of positive aspects with regard to scalability, modularity of the system components and a high degree of operational flexibility. However, the current operation and maintenance costs reduce the attractiveness for large-scale electrical energy storage. Also the operational efficiency, the relative short battery life cycle and the high potential for self-discharge are not solved yet.

The Zn/Br batteries have a specific energy of about 60-85 Wh/kg and have a theoretical maximal theoretic energy of 40 Wh/kg. Also the life cycle cost of a unit is about 1300 USD per kWh.

## 3.3. Energy types

Based on the elaborated conversion system a list of possible energy types can be elaborated. Figure 3.6 Shows the commercially available energy options with regard to the conversion systems elaborated in Chapter 3.2.

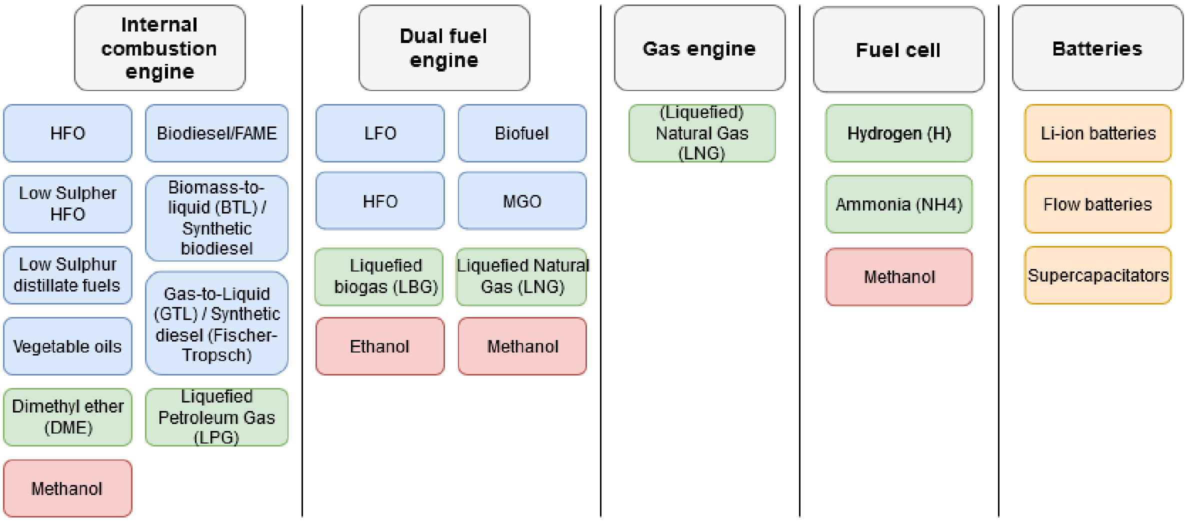


Figure 3.6: Potential energy types based on the established conversion systems[90][91][89][22][59]

Figure 3.7 shows the fuel types. However, not all energy types are discussed in this research. Ethanol and upgraded Pyrolysis Oil are not taken into account. Ethanol due to the price of the 2nd generation fuel and the 1st being not the best option because it competes with food. Pyrolysis Oil is not taken into account due to the low TRL level and it being more expensive than Hydro Vegetable Oil. Finally, OBATE-fuel is not taken into account. OBATE is On-Board-Alcohol-To-Ether which consists of a mixture of methanol, DME and water and is not yet developed enough[32][4]. Besides this, not all energy conversion systems are discussed as the steam turbine and gas turbine are not relevant for the case study vessel. Although Heavy Fuel Oil (HFO) might be used as reference for other fuels it is not considered as a viable solution.

The fuels which are available can be divided into three groups. These are the fuels of diesel quality, the gases and the alcohols which are shown in Figure 3.7. The first group of fuels of diesel quality can also be defined as drop-in fuels. These have a low auto-ignition temperature. The drop-in fuels for gas engines are generally fully compatible. The third group is the alcohols and ethers. These have a high auto-ignition temperature which make them suitable for spark-ignition engines. For methanol and ethanol there is already experience with dual fuel engines and the engine conversion for it is basically similar to LNG dual fuel engines. Another advantage is that engines can still run fully on diesel in the dual fuel option. Finally, adding an ignition improver to the alcohols results in the ability to burn them as diesel fuel type[100]. The data used for the energy types is based on multiple sources that all elaborate on the energy types. The sources are Kamaljit Moirangthem [52], Lloyd [62], Brynolf [7], Vogelsang [104], van Grootheest [97], Volger [105], Boonen [5], Verbeek et al. [100], van Veldhuizen [98] and Bosman [6].

**Methanol**

The technological readiness level of Methanol is 8. With regard to the fuel specification is methanol the simplest alcohol with the lowest carbon content of any liquid fuel. It is liquid at standard temperature and pressure which makes it less difficult to consume and distribute. The Lower Heating Value (LHV) is 19.5 MJ/kg and 15.46 kJ/m3. It has a boiling point of 338 Kelvin, flashpoint of 282 Kelvin and an auto ignition temperature of 713 Kelvin. The cetane number of 3 resulting in a non-reliable ignition in a diesel engine. The storage of methanol can be done in standard tanks with certain modifications to accommodate the low-flashpoint properties. The tanks require about 2.5 times more space due to the energy content with regard to HFO. However, as Methanol is liquid, the storage can be in regular tanks. The Effective volume of the tank is 95%. With regard to the conversion technology methanol can be used in a 2-stroke diesel-cycle as it is similar to LPG using an available 2-stroke engine is the MAN ME-LGI series or in a 4-stroke leanburn otto cycle engine using

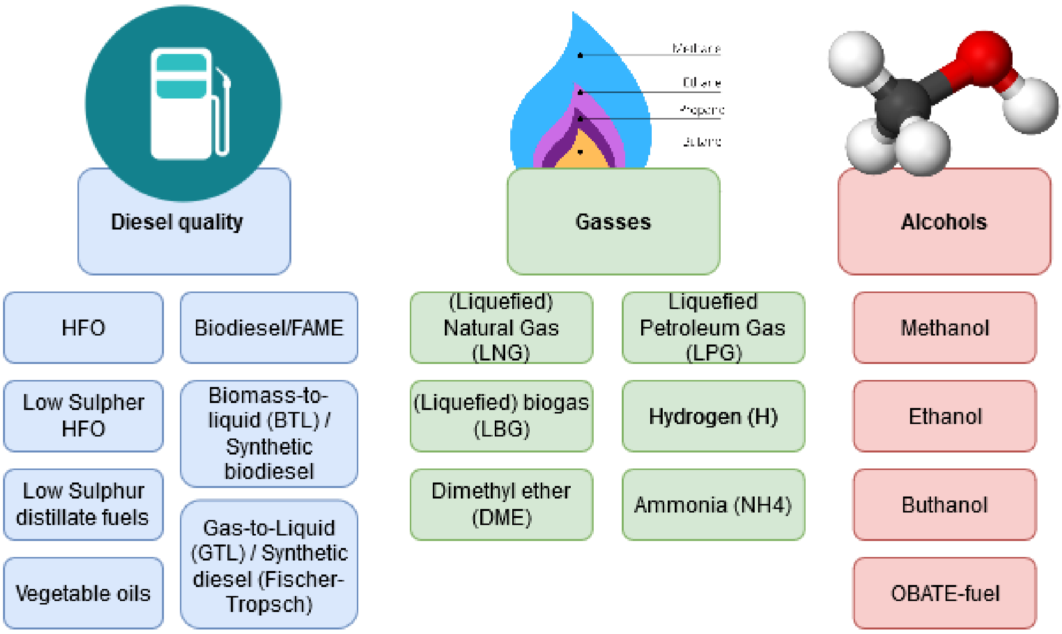


Figure 3.7: Fuel types divided in three categories according to Selma Brynolf[7]

a Wärtsilä 4-stroke engine which is in operation on passenger ferry Stena Germanica. Methanol requires a mix ignition improver up to 5% for it to be used in a diesel cycle. When blended with diesel fuel it can be used in a more or less standard diesel engine. Besides this, a duel-fuel engine in which diesel fuel is injected as an ignition source or it can be converted into dimethyl ether which means that it can be used as a fuel for diesel engines.

The second option is to use fuel cells as Methanol is tested in fuel cell application as part of MEETHANU project using a Wärtsilä WFC20 fuel cell onboard the Undine which is a car carrier. Based on production, implementation requirements and design impact of alternative fuels, methanol in a fuel cell shows the most feasible alternative carbon-neutral fuel. For the short term considering the TRL, methanol in a combustion engine has favourable characteristics causing it to be a feasible carbon-neutral fuel for the short term.

With regard to the environmental impact methanol is biodegradable and is therefore less environmentally harmful compared to conventional fuels in case of a spill. However, Methanol is highly toxic and can cause damage to the human body. It therefore has the labels GHS02 (flammable), GHS06 (toxic) and GHS08 (health hazard).

#### Dimethyl Ether

The technological readiness of DME is 5. With regard to the energy specification the behaviour it is similar to that of propane and has the same requirements for handling as LPG. It is also similar to methanol but completely different in engine application. It has a low auto-ignition temperature which makes it fit to diesel combustion. The injection however is different from a standard diesel engine. It has a LHV of 28.9 MJ/kg which is equal to 8.03 kWh/kg. DME can be stored non-carcinogenic and is liquid when stored at 5 bar. The storage is similar to that of LNG but does not need cooling.

With regard to the conversion possibilities it is possible to use a combustion engine of MAN which is the MAN Tier-III-compatible DME engine. More general, DME can be used in compression engines and along with spark ignition, diesel, turbine or fuel cell engines. This means that it can be a direct replacement for diesel fuel.

Finally, the environmental impact of DME is that it degrades rapidly in the atmosphere, but is not a global warming agent.

#### Biodiesel

The technological readiness level is 9. There is a significant amount of biodiesels of which Hydrotreated Vegetable Oil (HVO), Biomass-To-Liquids (BTL), Fatty Acid Methyl Ester (FAME) and Liquid Biogas (LBG) are most promising. Blends (up to 20%) have been reported as most promising bio-based alternative fuels (2012).

The actual GHG emissions from a biofuel will strongly depend on the production of the fuel. Therefore, the GHG emission reduction ranges from 19 to 88%. The $NO_x$ emissions from HVO are about 10% lower compared to diesel while FAME are considered to be higher than diesel. As biodiesel is a drop-in fuel, it can be directly used in existing installations without major technical modifications. However, FAME is not a drop-in fuel, but can be used in a blended fuel.

With regard to the storage, FAME has long-term storage issues and has to be monitored and tested if stored for more than 2 months. Besides this, it has degraded low-temperature flow properties and FAME material experiences decomposition on exposed surfaces.

With regard to the environmental impact, FAME has the tendency to oxidation and has affinity to water which also results in the risk of microbial growth.

### LPG

The technological readiness level of LPG is 6-8. With regard to the energy specification, LPG is a mixture of propane and butane in liquid form. It has a boiling point of -42 degrees Celsius and is liquid at 8.4 bar at 20 degrees Celsius. The LHV is 45.5 MJ/kg which means 12.64 kWh/kg[93]. LPG can be stored under pressure or refrigerated. But will not always be available in the temperature and pressure range a ship can handle. Therefore extra equipment is required for bunkering. A pressurized LPG fuel tank is preferred due to its simplicity and relatively easy bunkering using pressurized tanks or semi-refrigerated tanks without major modifications.

The conversion possibility is a combustion engine. More specifically, there is the possibility for a 2-stroke diesel cycle engine or a 4-stroke lean-burn otto-cycle engine or in gas turbine. However, currently only a single 2-stroke diesel engine is commercially available.

### LNG

The technological readiness level of LNG is 9. The specification of LNG is that it is a liquid gas which consists of 85 to 97% of methane. It has a LHV of 48.6 MJ/kg which is 13.50 kWh/kg at a temperature of -158 degrees Celsius[26][93]. The storage space for LNG is two times the amount of fossil fuel as the density is 2.4 times higher than CNG and 60% of diesel fuel. When using CNG, the required amount of space is 5 times the amount of fossil fuel. Besides these factors also additional insulation is required. When a comparison is made, the cargo capacity is reduced by 4% for LNG refit in the case of a feeder container vessel.

Technology required for using LNG a fuel is readily available. Piston engines and gas turbines, several LNG storage tank types as well as process equipment are also commercially available with an available power range from 5-50 MW. The fuel consumption will slightly increase from 0.057 for diesel fuels to 0.059 kWh/ton per km for LNG fuels. In the propulsion system, a 4 stroke medium speed otto cycle engine can be used that is ignited by pilot fuel or spark ignition. Regarding the availability there are mainly 2-stroke engines where LNG can be used as mono fuel with a lower efficiency than a diesel engine.

When LNG is mixed with inlet air in the diesel engine, which can be considered as a dual fuel process, high efficiency is maintained while a large part of the diesel consumption can be reduced. The use of LNG requires major modifications to a vessel engine in case of a refit such as valves, piston, fuel injector and the storage and fulling of the LNG. Therefore Retrofitting does not seem to be a viable option.

With regard to the environmental impact the LNG propulsion method experiences methane slip. The methane slip is said to practically eliminated in modern 2-stroke engines. However, the maximum 28-30% $CO_2$ reduction improvement cannot be achieved currently. Further reduction of methane slip is expected from a 4-stroke engine.

In the case of otto cycle engines, unburned methane can be reduced by using exhaust gas recirculation or by exhaust gas aftertreatment.

Also debunkering is necessary when a ship is anchored for a longer period in case of LNG as the gas would boil off resulting in huge methane losses.

Finally, bio methane or bio LNG is generally considered to be the most $CO_2$ friendly fuel of all and can be used as drop in fuel for an LNG engine.

### Hydrogen

The technological readiness of hydrogen is 7. There are rules for hydrogen in fuel cells which are under development. For now, hydrogen storage must follow the alternative design approach in accordance with SOLAS regulation II-1/55 in order to demonstrate a level of safety that is sufficient.

With regard to the specification, Hydrogen is the lightest of the gas molecules and thus offers the best energy-

to-weight storage ratio of all alternative fuels. The boiling point of hydrogen is at 20 Kelvin at 1 bar or at 33 kelvin at a critical pressure of 13 bar. It's LHV is 120 MJ/kg which is approximately 3 times the density of HFO. And the density is low which results in a density of 39 kg/m$^3$ when compressed at 298 Kelvin and 700 bar giving 4.72 MJ/L. The boil-off is unavoidable with liquid hydrogen and, depending on the surface area, can be 0.3 to 0.5% per day depending on the technology and conditions. The production of hydrogen is associated with a production efficiency of approximately 65% while additional losses of at least 30 – 35% should be expected from a well-performing fuel cell. Besides this, it is possible to process H2 into e-diesel, but this is energy wasting.
With regard to storage, compressed hydrogen requires 6 – 7 times more storage space than HFO where the tank size must be 10 – 15 times larger than that of HFO. Liquid hydrogen requires cryogenic storage at very low temperatures. This is associated with large energy losses and very well, non-pressurized, insulated fuel tanks. Another important aspect is that a liquid hydrogen tank can be filled up to approximately 94% of its volume. The effective tank volume is 51% due to the round tanks and very well insulated tanks. In current available technology there are tanks available for the storage of between 400 and 6700 kg of liquid hydrogen.
For conversion technologies, an internal combustion engine can be used using hydrogen. However, in 2016 no commercially available hydrogen fueled piston engines were available. Besides this, hydrogen-fueled internal combustion engines for marine applications are said to be less efficient than diesel engines. Therefore, fuel cells are considered to be the key technology for hydrogen. When a SOFC fuel cell is used in combination with batteries for peak-shaving effects, and in the future possibly super capacitators, the fuel cell is a promising option.
Finally, for the environmental impact when using Hydrogen the local emission of CO2 is zero. However, hydrogen has the labels GHS01 (Flammable) and GHS04 (compressed gas).

**Ammonia**

The technological readiness level of ammonia as a fuel is high. However, in the marine environment the TRL is at 6-8. With regard to the fuel specification ammonia has been tested successfully as fuel in multiple experiments in the last few years. Ammonia has a boiling temperature of 240 Kelvin which can be challenging when Ammonia is used in a combustion engine perspective. Besides this, the literature on ammonia as combustible fuel is limited and the feasibility therefore has to be proven.
The LHV is 18.6 MJ/kg and 13.3 kJ/m$^3$ and the density of liquid ammonia is 0.72 tonnes / m$^3$. The auto ignition temperature is at 903 Kelvin. And the storage of ammonia has an effective volume of 67% as round tanks are required.
Finally, with regard to the environmental impact, ammonia has the labels GHS05 (corrosive), GHS06 (toxic), GHS09 (environmental hazard). Besides this, in a combustion engine it is possible that NOx will be formed.

## 3.4. Future energy transition possibilities

At this moment LNG and Methanol do comply with the regulations and have advantageous costs compared to other alternative fuels. For emission abatement only bio-methanol has the potential to mitigate the climate change and is therefore the favourable fuel from sustainable point of fuel. As for now it is not competitive enough. It is noteworthy to state that the higher the enforcement of a regulation on emissions is, the less investments take place in methanol propulsion technology. Ship operators then are likely to make investments which are less radical.
Deployment of methanol as a total maritime fuel across Europe is not likely to emerge. However it might be possible to establish such a transition on a smaller geographical scale. It then only might be that the supply of methanol on a too small scale is not profitable[104].

For the maritime shipping industry biofuels seem to be an option. However, When looking into the permanency of biofuels it is poor for food crop made fuels and better for non-food cellulosic materials such as crop residues. However, in the European vision the energy supply from biofuels will be maximum 7% from (food)crops and maximal 1.7%from used cooking oil in 2030[100]. Therefore for the long term, synthetic fuels would be a good option as these can be based on wind and solar energy. The synthetic fuels include $H_2$, methanol, methane, ammonia and synthetic diesel. As for now methanol and ammonia are good options in the maritime industry due to the relatively economical producing possibility. However, cost projections are still higher than of current biofuels. The most likely situation is that biofuels will be the most important option for reducing GHG for the coming 10-20 years[100].

A prediction is to have a transition from biofuels to synthetic fuels where there are minimized investments in the powertrain of the vessel for the near future. Or a combination of drop in fuels and methanol would be possible. LNG is also regarded as an option to reduce GHG and its price is often lower than the price of HFO or MGO. Due to the lower carbon to hydrogen ratio its emission could potentially be up to 25% lower. Besides this, LNG might be the only solution which could make a business case without support from regulations or subsidies. However, methane slip is still a problem. Besides this, for the short term LNG seems a good solution, but as rules and regulations start requiring blending of LNG with Bio-LNG there will be great price uncertainties and connected risks. However, at lower blending ratio's up to 40% and a high utilisation rate of the engines (8000 hours per year) LNG or bio-LNG is the best option from the business case perspective as is shown in Figure 3.8. This high utilisation rate is the case for the 9819 E3 ferry.

| | | |
|---|---|---|
| Ship speed | 12 Knots | |
| Engine Power | 1,500 kW | |
| Consumption | 6.0 ton/day | 256 GJ/Day |
| Bunker Capacity | 350 ton | 15,000 GJ |

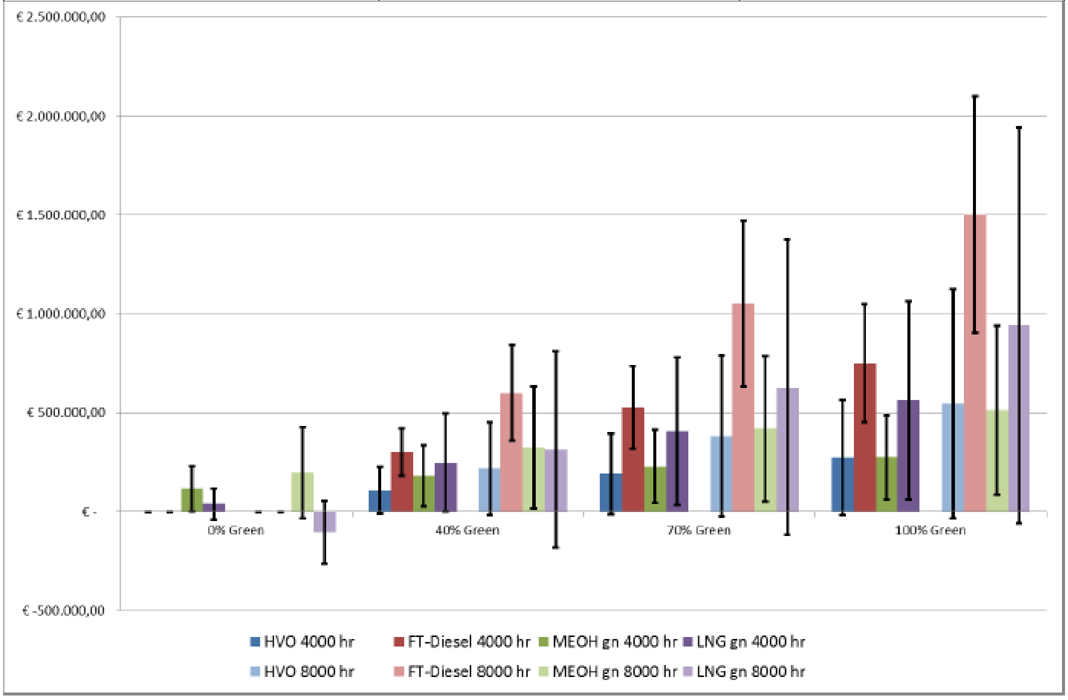


Figure 3.8: Comparison of system costs for HVO, FT-diesel, Methanol and LNG based on two operational profiles of medium and high utilisation rate of respectively 4000 and 8000 operational hours per year[100]

Blending HVO with rates from 70-100% offer good alternatives and is in cost perspective comparable to methanol / bio-methanol blends in the same range. The difference of high or low utilisation of engines hardly has impact on the price difference for MGO/HVO blends and methanol/bio-methanol. For low utilisation of engines, based on 4000 hours per year, and higher blends, 70-100%, bio-methanol offers a serious alternative for HVO.

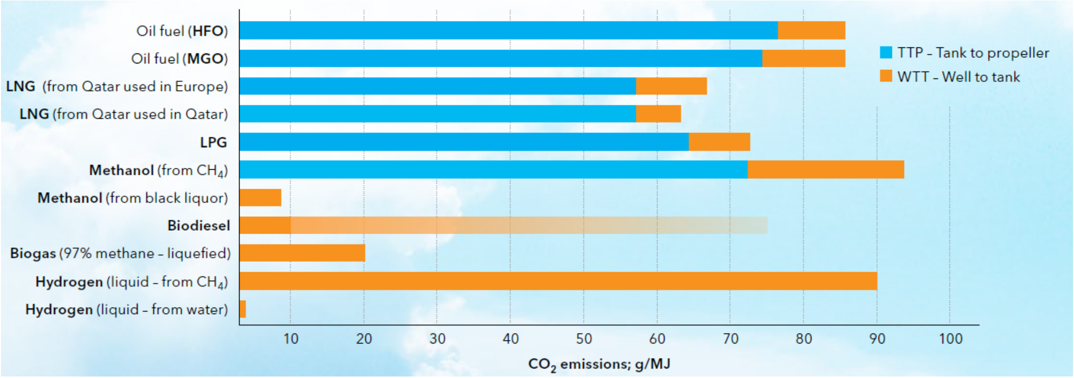


Figure 3.9: Different $CO_2$ emissions based on various sources including tank to propeller and well to tank emissions[62]

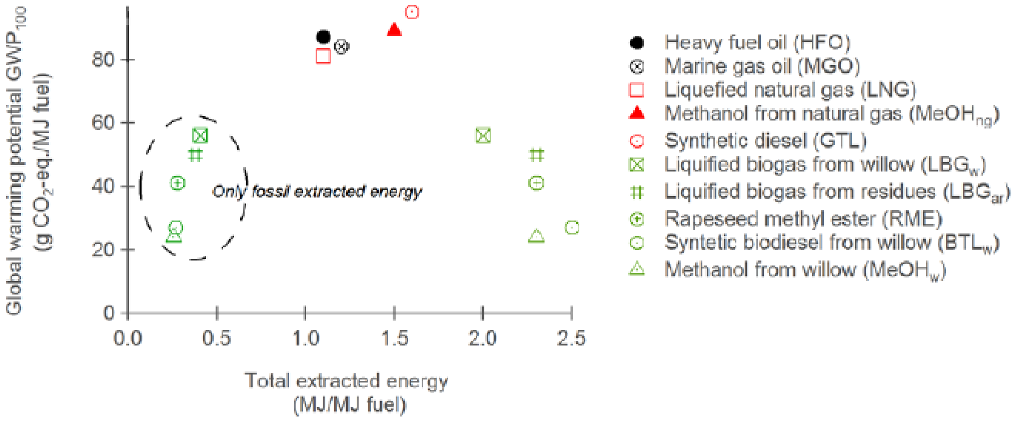


Figure 3.10: Global warming potential[7]

## 3.5. Energy carrier and conversion system overview

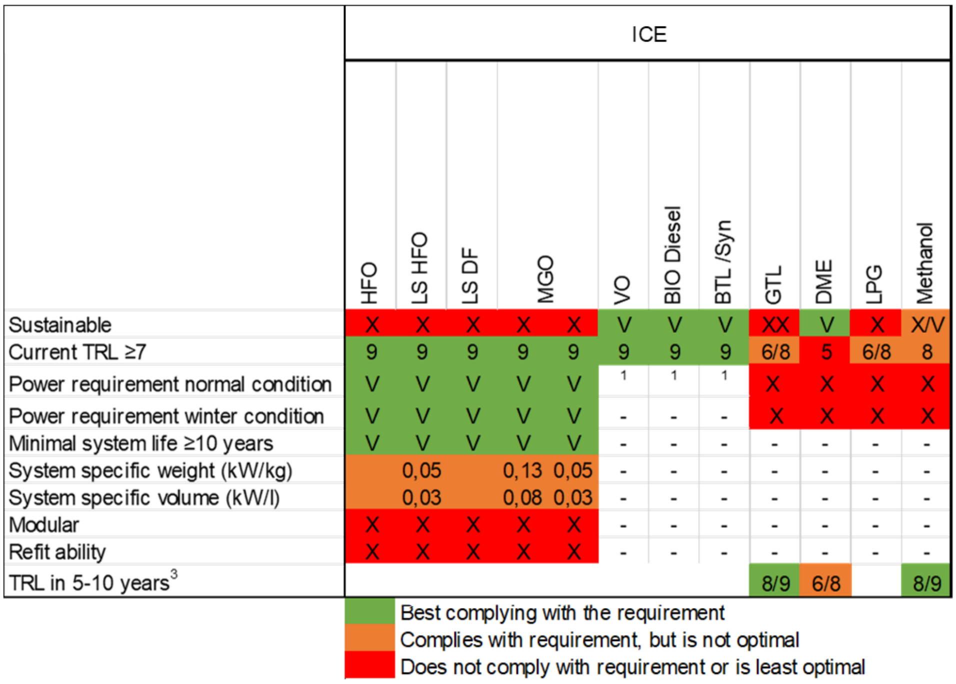
Figures 3.11 and 3.12 shows the table with the total overview of the possible conversion systems and energy carriers with regard to commercially available technology. The energy and conversion types are assessed using the requirements and functionalities and elaboration on the assessment is given below. The colors in the table help with to make the results more clear. The rating of the colors is done at a relative level. This means that green is the best option, orange is the medium option and red is the worst option. However, the colors do not necessarily quantify a system on feasibility.

- **Sustainability**
  The first requirement is sustainable where the 'X' stands for not fulfilled and the 'V' for fulfilled. The combination of 'V' and 'X' is used in the case that the requirement can be met by one way and not by another. For instance, methanol can be produced using natural gas or using renewable energy sources. This is also visualised in Figure 3.9. Sustainability becomes more and more important, but due to the commercially availability of conversion systems, it is not a decisive factor. GTL is a special case from this selection as Figure 3.10 shows that the global warming potential of GTL is even higher than HFO.

- **TRL** Current TRL has to be higher than 7 for the energy type or conversion system to be commercially available in a relative short term. GTL, DME and LPG are not used as potential energy sources due to their low TRL. However, LPG could have future potential according to DNV-GL[62]. The potential of fuel cells is high as this type of conversion system is seen as a future proof method. However, the TRL is still low which means that only the LT-PEM fuel cell fits in the requirement of the TRL.

- **Power requirement** The power requirement and functionality cannot be met by a gas engine as the commercially available gas engines are designed for higher power output[20]. Next to this, there are multiple energy types that are labeled as drop-in fuels[1]. This means that they can be used in a normal diesel engine or require only small modifications. Next to this the fuel cell and battery in single part are not able to deliver the required power, but this can be delivered in series.

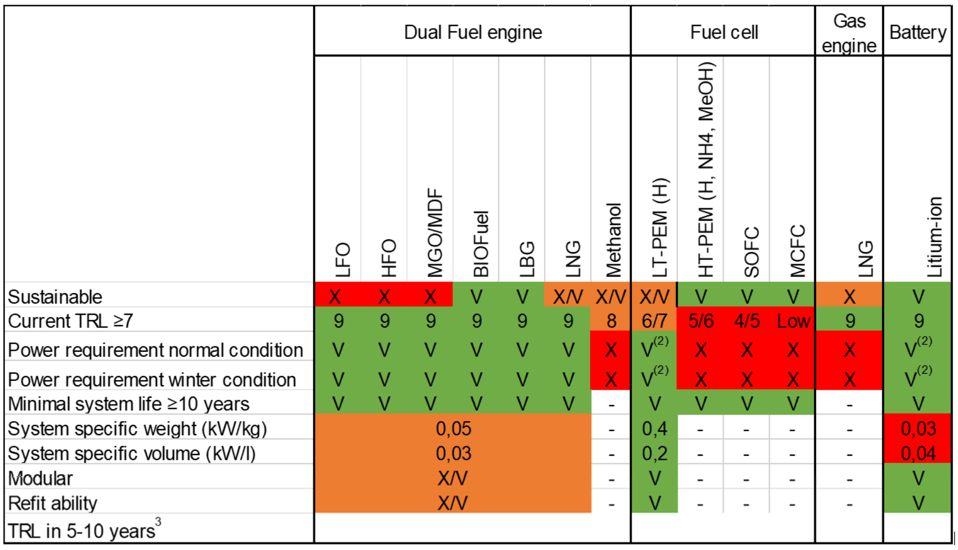
- **System life** The system life of every system is equal or larger than 10 years. However, for batteries this is the maximum given warranty and for fuel cells this means that the stacks in the fuel cell require replacement within the 10 years.
- **System weight and volume** For the system weight and volume the specific weight and volume is used. The data for these values is based on Wärtilä[17][18], MAN[91] and Caterpillar[13]. The difference in the MGO is that a high speed generator can be used with a relative high system specific weight and volume. However, this engine also has less fuel flexibility. Other ICE including the dual fuel engines are almost similar.
- **Modularity** With regard to the modularity of the conversion system the standard ICE is not modular as this conversion type is based on a single type of fuel. The dual fuel engine is already more modular as it is capable of handling more types of fuel without changes to the engine. This flexibility gives a level of modularity. The fuel cell and battery are modular as these systems consist of modules that can be exchanged or replaced.
- **Refit ability** The final requirement is the refit ability. This is similar to the modular requirement. In the case of an ICE the refit is costly due to a complete change of the engine. Using a dual fuel engine it might be possible to change a fuel type which means that the refit is less radical. However, changing the engine still is costly. The fuel cell and battery are module based which makes refit less extensive. The life time of the fuel cell and battery are such that a new system is required which increases the costs over the life time of the vessel.
- **Near future TRL** As an addition to the TRL for GTL, DME and methanol the fuel production TRL will be higher within 5-10 years[100]. This shows that DME has no commercially availability in the short term where as GTL and methanol are potential fuels.



| | ICE | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | HFO | LS HFO | LS DF | MGO | | VO | BIO Diesel | BTL /Syn | GTL | DME | LPG | Methanol |
| Sustainable | X | X | X | X | X | V | V | V | XX | V | X | X/V |
| Current TRL ≥7 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 6/8 | 5 | 6/8 | 8 |
| Power requirement normal condition | V | V | V | V | V | [1] | [1] | [1] | X | X | X | X |
| Power requirement winter condition | V | V | V | V | V | - | - | - | X | X | X | X |
| Minimal system life ≥10 years | V | V | V | V | V | - | - | - | - | - | - | - |
| System specific weight (kW/kg) | | 0,05 | | 0,13 | 0,05 | - | - | - | - | - | - | - |
| System specific volume (kW/l) | | 0,03 | | 0,08 | 0,03 | - | - | - | - | - | - | - |
| Modular | X | X | X | X | X | - | - | - | - | - | - | - |
| Refit ability | X | X | X | X | X | - | - | - | - | - | - | - |
| TRL in 5-10 years[3] | | | | | | | | | 8/9 | 6/8 | | 8/9 |

🟩 Best complying with the requirement
🟧 Complies with requirement, but is not optimal
🟥 Does not comply with requirement or is least optimal

Figure 3.11: Overview of possible conversion systems based on commercial availability and fuel availability part A
[1] *Can be used as drop-in fuel or in blends*



| | Dual Fuel engine | | | | | | | Fuel cell | | | | Gas engine | Battery |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | LFO | HFO | MGO/MDF | BIOFuel | LBG | LNG | Methanol | LT-PEM (H) | HT-PEM (H, NH4, MeOH) | SOFC | MCFC | LNG | Litium-ion |
| Sustainable | X | X | X | V | V | X/V | X/V | X/V | V | V | V | X | V |
| Current TRL ≥7 | 9 | 9 | 9 | 9 | 9 | 9 | 8 | 6/7 | 5/6 | 4/5 | Low | 9 | 9 |
| Power requirement normal condition | V | V | V | V | V | V | X | $V^{(2)}$ | X | X | X | X | $V^{(2)}$ |
| Power requirement winter condition | V | V | V | V | V | V | X | $V^{(2)}$ | X | X | X | X | $V^{(2)}$ |
| Minimal system life ≥10 years | V | V | V | V | V | V | - | V | V | V | V | - | V |
| System specific weight (kW/kg) | 0,05 | | | | | | - | 0,4 | - | - | - | - | 0,03 |
| System specific volume (kW/l) | 0,03 | | | | | | - | 0,2 | - | - | - | - | 0,04 |
| Modular | X/V | | | | | | - | V | - | - | - | - | V |
| Refit ability | X/V | | | | | | - | V | - | - | - | - | V |
| TRL in 5-10 years[3] | | | | | | | | | | | | | |

Figure 3.12: Overview of possible conversion systems based on commercial availability and fuel availability part B

[2] *Used in a series of fuel cell or battery modules*

[3] *TRL level based on fuel production[100]*

## 3.6. Energy carrier and conversion system conclusion

Literature shows that there is no clear single alternative as energy carrier. However, there are suggestions of potential types of which methanol, batteries and LNG are mentioned[52][7][62][100]. All of these energy types fulfill the defined system functionalities of the 9819 E3 ferry. However, there is not one perfect conversion method or optimal fuel. As elaborated above red is not bad by definition, but it shows that a conversion system performs worse with regard to the requirement or functionality. The result of the overview shows that batteries currently as the best solution based on the defined requirements. As for now a standard conversion system for the 9819E3 ferry is a diesel generator using MGO. However, a dual fuel engine which is capable of using energy carriers that have less green house gas emissions shows to be a better option. The LT-PEM fuel cell shows to be a good solution on all requirements with the remark that the hydrogen is produced in a sustainable way and the relative low TRL. The fuel cell is not yet a commercially available system, but is a feasible solution with regard to the other system requirements. Noteworthy is also methanol as this type of fuel currently can be used in a commercially available 2-stroke engine and will probably be available in 4-stroke engines as well. Next to this, methanol can be used in a fuel cell which would increase the sustainability even more. LNG as a fuel is also an option to be used in a dual fuel engine. However, there are multiple difficulties with LNG with regard to the storage which is costly and complex and the possible methane slip. CNG would be a better option with regard to these difficulties if available storage space is sufficient.

For the sub-question "What are feasible environmentally friendly energy carrier and conversion possibilities?" the energy and conversion types that are feasible and will be elaborated further are:

1. Battery system
2. Conventional diesel generator using MGO
3. Dual fuel engine with as possible fuels natural gas or biofuels
4. LT-PEM fuel cell using hydrogen

## 3.7. Discussion

The possible energy storage and conversion systems are based on the operational profile and ship type. This means that the overview made is specific for this ship type. For this reason a methanol and LNG engine cannot be used as the vessel functionalities are not met. A 2-stroke engine is available for the use of methanol but is only used in larger vessels with a higher power requirement.

When looking into the high TRL there is also a note to make. Although there are multiple options for future possible energy type and conversion system, these systems may take multiple years for them to be commercially available. This means that there is an uncertainty with what is optimal to use. A part of the modular approach is to look into multi-applicable systems. A multi-applicable system can be explained by the the example of methanol. If a 4-stroke methanol ICE would be commercially available, it can be implemented in a vessel. However, the fuel cell has a higher efficiency than an ICE and could replace the ICE when it becomes commercially available. A modular refit could then be possible if the system is multi-applicable which means that the energy storage and transport only needs little adaption and in basic is fit for both conversion methods. It is possible to implement future system compatibility to the system, but this might come at a significant cost. The additional potential options added to the energy carrier and conversion system bring uncertainty and possible redundancy. Therefore in the approach to multi-applicable systems a thoughtful approach is required with costs taken into account.

The result of the research is in line with what is currently is seen in the market. For the ferry industry the full electric or hybrid system is a good solution and is also asked for by clients from Damen. A combination of systems or hybrid system seem the way to go. This is also based on the requirement for redundancy. This requirement is not elaborated in the overview as this is mainly based on a combination of systems. Next to redundancy a hybrid system is necessary in the case of a fuel cell for peak shaving for instance.

Even though the table shows that the more conventional fuels do not fulfill the requirement for sustainability still the conventional diesel generator is used. Next to the requirement for an environmentally friendly energy carrier and conversion system the same argument is used as elaborated in Chapter 2.4. As the requirement for redundancy or for a fully known system of the customer is important, the current diesel fuels are also taken into account. This also falls within the goal for a future proof vessel where a combination of systems can be used which fall within the emission requirements.

# 4

# Module definition of the energy storage and conversion system

The focus of this project is to make the energy storage and conversion system modular and besides this to implement alternative fuels. This means that different design methods are required which can fulfill the focus of the project next to the current approach of Damen. The question regarding this chapter is "How can the energy storage and conversion system be defined using modules?". Again the reason to use modularity is as a next step into standardization which allows for variations and is the foundation for reduced project lead-times and costs. Standard vessels are a good method to optimize the design, however, if a customer requires for instance a larger version of the ferry, a higher sailing speed or a different energy carrier changes are required that, possibly, fall outside the standard design. This means that the advantage of standardization is lost. Next to this, Modern vessels become increasingly complex and instead of having a single system, new vessels have combinations of systems which are also integrated with each other.This means that safety of the system becomes an even more important and complex design aspect which has to be considered at a system level to mitigate the risks [56]. In the current working approach using standardization in the design these standards are also limited to design guides and personal knowledge which are again depending on supplier information. Where optimized modularisation provides the ability for tailoring to user requirements by using standardized modules with options and variants. The modular approach also allows for early verification and validation and performance analysis which reduces project risks and costs.[56].

However, in order to start using modularity a clear approach for modularity is necessary as a requirement management data structure is necessary to define a module [56]. This management structure defines the link between the requirements and functions which are used in the RFLP approach and also important the decomposition level can be determined. Starting with the description of the vessel system there is a system hierarchy which can be defined for it. This starts with the system itself. The system performs a significant, useful service and could be part of a super system. A sub-system operates a subset of the overall system functions. Dependently on the modular definition a sub-system might be able to operate independently. The next level is a component which performs a primary function. It is often defined as a physical and often common building block. It represents a building block and not a process. Finally there is a sub-component which performs elementary functions and is composed of parts where a part represents an element which does not perform a significant function.

For a clear overview on the approach and the relation of the different literature Figure 4.1 visualizes the theory approach and course in this chapter.

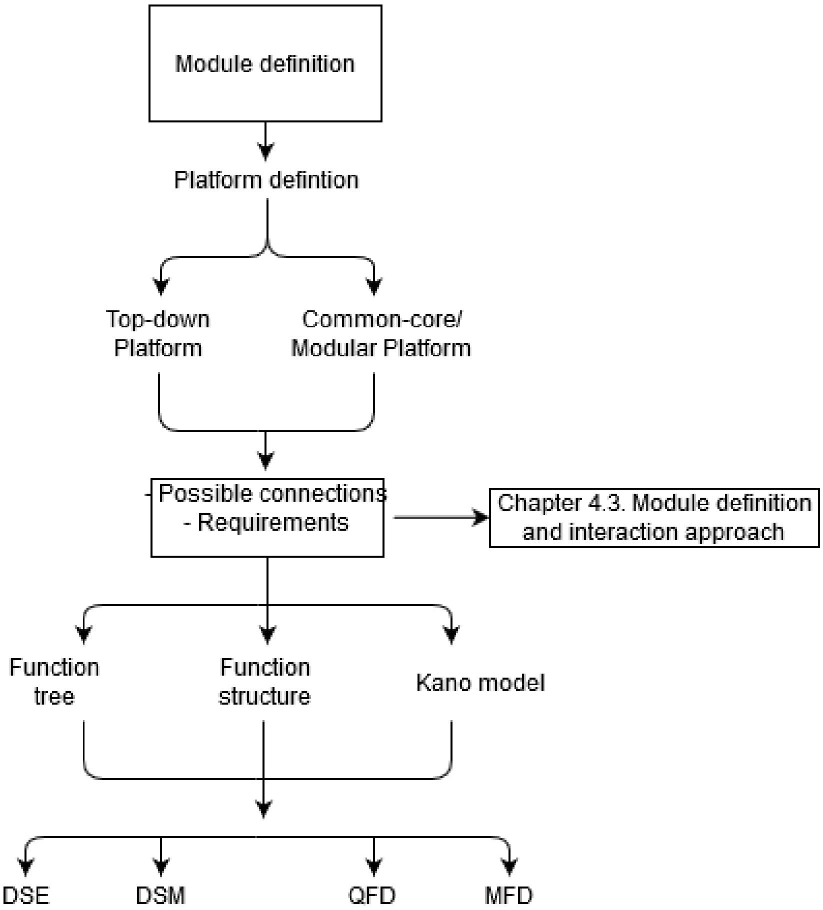


Figure 4.1: Modularity theory approach including various modular design possibilities

## 4.1. Modularity definition

The first focus within modularity is on the methodology and is a prerequisite for successfully designing modules. According to Largaider [57], modularization is a form of standardization where standardization is described as a methodology by which the number of unique guidelines, drawings, procedures, processes, documentation and parts and components to design and manufacture the ship are minimized. The benefits of standardization with regard to the design and engineering are[57]:

- A reduction in design time for the components and parts
- An improvement of reliability or pre-designed parts or components and a reduction in technical errors
- A more optimal design process due to standard approaches
- A reduction of redesign and an improvement of the interchangeability of parts
- A reduction in price due to larger purchase orders for components

However, purely standardized products often fail the requirements and needs of the customer of fail to meet the targeted market segments. As vessels are designed for different operational areas which come with different requirements as well as possible changes ranging from vessel speed to the personalising preferences of the client and the requirements by local authorities. Therefore modular design becomes a solution where standardized modules assembled into a final product can meet the requirements of the customer. This is made possible due to the design of modules which have adjustable features. The concept of adjustable features for the modules is used to build products and is called mass customization [57].

Modularity can be defined as "A general systems concept: it is a continuum describing the degree to which a system's components can be separated and recombined"[80]. Based on this definition which is also used by Erikstad [33] modularization both involves decomposition and encapsulation. Decomposition usually follows hierarchical structures of the system with for instance functional breakdown structures or assembly or part structures. This is used to define and understand the system in a systematic way to be able to define modules within the system. Encapsulation involves an effort to hide the complexity of the part or module using well-defined interfaces which control the complex interactions. According to Erikstad [33] this means that the definition of modularity does imply that simply splitting up a product and assembling it back together falls outside modularity. Therefore there needs to be a certain flexibility level in the interconnections of the parts or modules. In the case that there would not be complexity in the modules, the definition and usages of them would only cause extra work instead of reducing the overall complexity of the system which is a goal of modularity. Specifically it means that the design and engineering is done once for the module after which the modules can relatively easy be combined in a working system for multiple vessels. The interfaces then have a certain level of flexibility for the modules to be used and connected to other modules. As modules encapsulate complexity, they enable more efficient processes within the platforms and configuration-based design and besides this, they enable a wider search for new and innovative solutions within the defined design space [33].

This definition used for the modularity relates to axiomatic design where an independent axiom states the preference of one-to-one mappings between the functional requirements and the design parameters. More of the theory within system engineering and the different theory regarding modularity approach is based on the axiomatic design principle. Therefore this principle is later elaborated to better understand the approach used in system engineering and modularity. The axiomatic design principle is based on a framework to design objects and a set of axioms to evaluate the relation between functions and the means by which they are achieved [102]. When modules are combined with templates they will support a swift and partly even automated design solution. Where again the key point is the decoupling between the modules and the arrangement assembling or interconnection.

**Modular design stage options**

Within modularity there are three options [33][57]. The first one is the modular design in the ship production phase where the strategy can support distributed production with suppliers by enabling a high degree of preoutfitting. The second option is in the operation phase where modularity supports flexibility in the missions, markets and regulatory changes. The third option is the one which is relevant for this research is the design stage. In this stage, modularity can support three aspects [33][44]:

1. Modularity can support standardization and diversification concurrently using a product platform strategy. This means that standard modules can be developed which can be used to design a variety of product designs based on the same modules.

2. It lays the foundation for a configuration-based design resulting in a more efficient design. This means that modularity enables the reuse of earlier designs by making structural complexity manageable with a simplified representation which is possible due to hidden interactions within the modules. Where a configuration can be described as a specified class of routine design in which major modules or design elements are known. These modules can then be combined into a solution that meets the requirements of the customer without developing new solution modules or elements.

3. Modularity may support an effective configuration process which can be used for the customer needs and requirements based on a product platform. This means that modules can relatively easy be combined into an optimal system or even total vessel.

Coming back to the configuration system there are three main aspects it will comprise of. Firstly, it is a collection of configuration entities which are a collection of modules. Secondly, it is a configuration process representation which means that the process implementation is done based on a workflow management system. This enables a type of 'plug-in' of external applications and a process logic definition. And Thirdly, it has a configuration knowledge representation which means that it includes rules and constraints.

There are significant variations in the usage of modular design. However, according to Erikstad [33] there are basic characteristics:

1. Modularity is about the division of a larger system into smaller components or parts

2. The principle of modularity is focused on the (relative) self-sufficiency of the individual parts

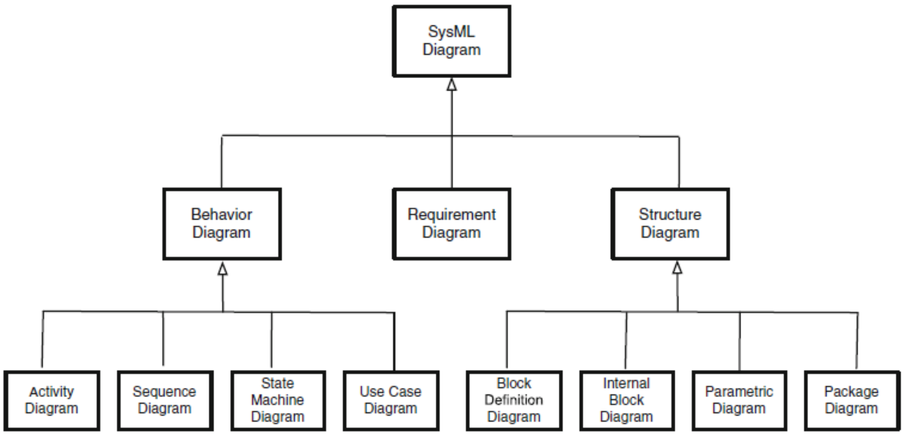


**Fig. 1.3** Taxonomy of SysML diagrams (adapted from [17, 18])

Figure 4.2: Taxonomy of diagrams for functions, requirements and structure towards a SysML diagram

3. When using modularity, the recombination of the parts into one or more end products is done according to a defined set of rules within the total system architecture

### 4.1.1. Axiomatic design approach

To better understand the approach for modularity, also the axiomatic design is shortly elaborated as terminology used in axiomatic design is also found in Model Based System Engineering (MBSE) and SysML. Model based Engineering is an approach to engineering that uses models as an integral part of the technical baseline. Likewise to the SE approach, MBSE includes requirements, analysis, design, implementation and verification of a capability, system and/or product throughout the life cycle[14]. This approach has data-centric specifications to enable automation and optimisation using computer modelling[48]. SysML is the modelling language for the system engineering and supports the MBSE. MBSE and SysML are not specifically part of the scope of this research. However, the research in this thesis leads up to the use of both of these methods which makes it relevant to know the overall goal. Classification and characterization of systems is a challenge for which consistent methodological foundations are required within the engineering. As well as the defined RFLP approach, Axiomatic design has four domains which are the stakeholder requirement domain, the functional architecture domain, the physical architecture domain and the process architecture domain. However, the difference with the RFLP approach is that axiomatic design uses five functions in the classification which are: transform, transport, store, exchange and control. And for the description of the relation or interaction between the function and part, five operands are used which are: living organisms, matter, energy or information and money. Specifically, each function is defined as a measurable verb and is followed by its associated object. It must be defined in a solution-neutral way to assure that there is no bias towards a certain technology within the physical architecture [39]. In this approach the definition a functional requirement and a function are interchangeable.

Within the axiomatic design it is also possible to apply 'reverse engineering' to generate the functional architecture. This can be done if the system is already developed and built and the functional architecture is required to optimize the system. This can be seen as the bottom up approach where the system elements are already known and are optimized. However, as discussed before, this approach is not used in this thesis.

An overview of the taxonomy or classification of diagrams used in axiomatic design and SysML is shown in Figure 4.2. In this figure the schematic approach is shown with the diagram requirements towards a connection between functions, requirements and the structure. This approach helps to clarify the combination and requirements for a function and structure combination.

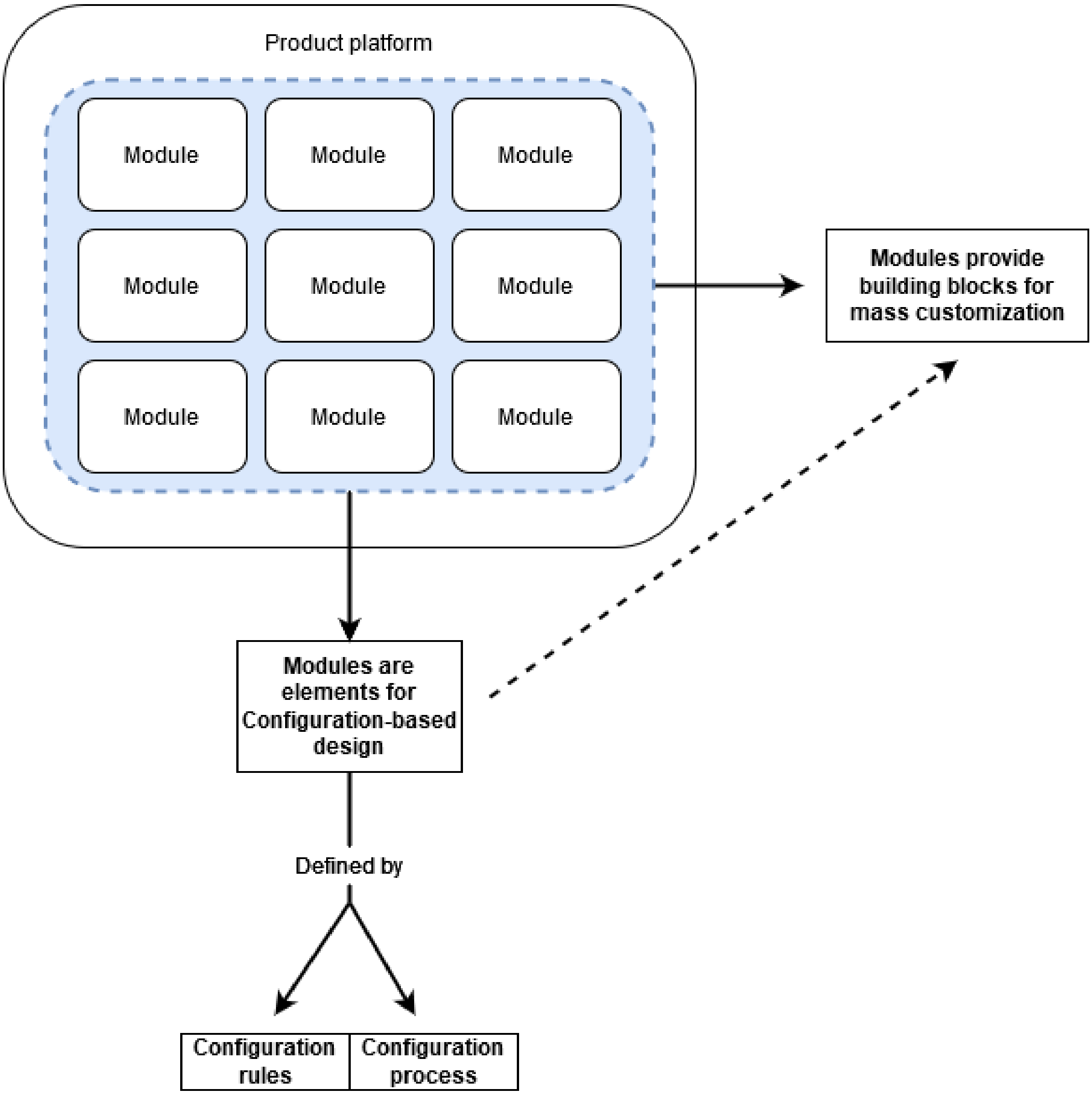


Figure 4.3: Core concepts of the interconnection between modules, architecture and possibilities adapted from Erikstad [33]

## 4.2. Modular platform based approach

Continuing with the system engineering and axiomatic design approach the basis of the approach is now set on the requirements and functionalities. The next important aspect in the research is the ability to design a vessel in a modular way. Therefore a combination with another design method is required which is based on the product platform approach defined in Chapter 1.2. A product platform can be defined as a structured coherent collection of resources which includes systems and template hierarchies or taxonomies, textual components, variation possibilities, rules and interface definitions. And from which a range of customized product definitions can be designed and derived [33]. Erikstad [33] also has a visual overview with the connection between the modules, platform architecture, mass customization and the configuration-based design. A platform as in the main body module of a modular design has the ability for other modules to be optionally be attached[56]. An adapted version of this overview is shown in Figure 4.3 which helps to understand the possibilities of using modules and a modular platform. The platform defines a way for the modules to be connected and to be used and includes all modules. This means that using these modules multiple variations of the designed product can be made using the product platform definition.

### 4.2.1. Top-down or Bottom-up approach

For platform based approaches there is the possibility for a top-down or bottom up approach[44] [87]. The bottom-up approach starts with specifying the requirements and capabilities of the individual components. This means that the system requirements are already available and these are the basis of the project. The top-down approach starts with the global system state and global knowledge of the system [23]. This means that the start consists of the requirements of the system. This approach is not constrained by current work practice and is heavily driven by domain knowledge which means that the result can be different or even futuristic [76]. The top-down approach gives more weight and importance towards modularisation. The overall function is described first in this approach and remains constant after which the components and technologies can be changed to fulfill the requirements and functionalities[87]. Modularity itself is also linked to the similarity between the architectures of the physical and functional part where there is a one-to-one relationship in the design between the functional and physical part [57]. The top-down approach also avoids many of the problems encountered with the bottom-up models. However, as the data collection is based on technology and institutions existing at the time, rapid expansion of new technologies may cause difficulties[7]. This top-down approach is also recommended by literature according to Fixson [40]. The result of the top-down approach is:

- The possibility to research and implement alternative energy carriers based on the requirements and functionalities.
- The possibility to implement modularity within the system.

### 4.2.2. Modular / common-core platform or an integral / inclusive platform

The second platform idea for the modular approach is also elaborated the thesis of Ruben Smit[87] which was executed for Damen Shipyards Group as well. The research and the goal of the thesis were different than in this research. However, as the platforms are general ideas it is possible to use the literature and to evaluate the possible applicability for this research. Smit [87] states that for a successful platform development instead of an integral product architecture, the focus should be on a common core platform concept based on Fuchs and Golenhofen [44]. Using an integral product platform is commonly referred to as an architecture where there are multiple product functions which can be accomplished by one physical element. It there shows a one-to-one relationship between each of the functions and each of the total physical components or defined modules. The overall product can generally be optimized in a better way compared to a modular-core approach due to elimination of interfaces [57]. This integral platform thus means that a single part is used which has limited applications and because of this, the part cannot be replaced by a different component or module. The integral product platform thus leaves significantly less room for interchangeability which is key in this research.

However, when using the common-core platform this also automatically means that if more market segments are addressed, the common core will be smaller due to the high degree of variety. Modular approach is defined as the prominent platforming approach by et al. [37]. With this approach family members are derived by substituting and/or removing modules, possibly complemented with individually designed product portions.

Modular architecture typically compromises on performance due to the over-design. In this approach, each physical element implements one or a few functional elements in the module. Interfaces between the elements are not coupled but require a clear definition of the interfaces. A change in the functionality has only impact on the element that carries the function. With regard to the definition of a module based on NAVAIS this means that the element is interchangeable with a module. This method is effective for product families and not for singular products where independent development is possible. Specific to this project this means that different types of energy storage and conversion systems can be developed in parallel.
Within the platform development the fundamental idea is to design a modular core platform rather than an inclusive platform, visualized in figure 4.4[44]. Where an inclusive platform targets all market segments or all possibilities at once, the modular core platforms refers to the elements that all products have in common. This approach excludes the differentiating elements and standardizes through the commonalities. This means that a total system actually can exist is based on more than one platform type. The reason for the modular platform instead of the inclusive platform is based on the following three problems according to Fuchs and Golenhofen [44]:

- The problems with using an inclusive platform is that the platform is viewed as a Swiss army-knife. It can fulfill many different functions and it can fulfill these functions at once. However, such a platform is too expensive and complex as multiple functions are not used for a regular customer. The manufacturing of this metaphoric Swiss army-knife is modular but the end product is not for the customer while a large toolbox is carried. Specifically it means that for instance when batteries, an ICE running on LNG, diesel and a bio-fuel could be used, all of these connections and system structure for the ability to implement these different types would be included in the design. This would then make the system expensive, heavy and also overdimensioned for most or all of the configurations.

- The next problem is that a platform fulfills all the desired functions and requirements at once. This means that there are limits within the platform and what is realistic. Practically this means that unrealistic high functionalities all are included in the platform that is too complex to be build. This could be for instance the implementation of the conversion system including waste heat recovery which can be used for other applications. To implement this at once would be highly complex and difficult to implement at once.

- Thirdly the inclusive platform is based on uncertainty. With regard to this research topic, the uncertainty of the technological future with regard to energy carrier and conversion systems. Therefore all possibilities are included in the platform making it too complex and costly. This is somewhat similar to the first problem. Specifically it would mean that already the connections and system structure is implemented in the design for the case that methanol can be used even though the development is still ongoing and designs might change.

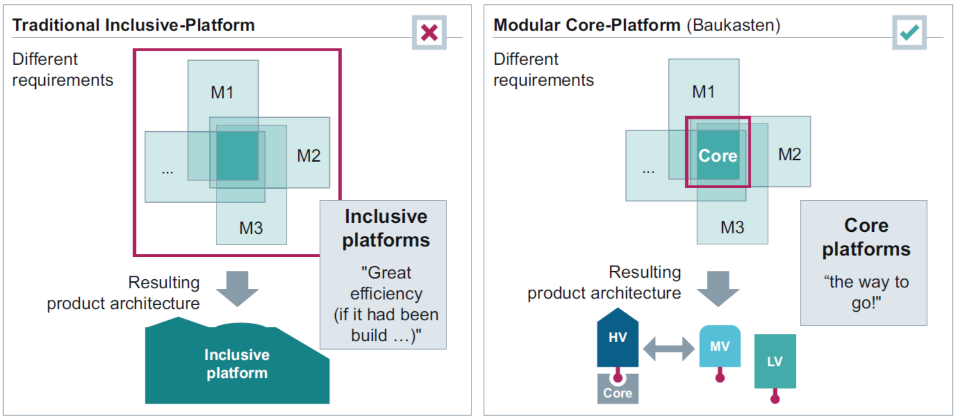


Figure 4.4: Visualized difference between traditional inclusive-platform and modular core-platform[44]

A larger number of platforms will solve the problem of over-design to a degree. However, the integration benefits decrease as well. The over-design has a significant effect on the performance of the platform and also the cost of the platform. Therefore a cost-benefit could be made to assess the level of use of the modular core-platform. An example of the different use of the modular core-platform is shown in Figure 4.5. For this situation the BB1 platform is the core platform and is common for all products. BB2 has two different variants and BB3 has three variants. The setup has a core platform and platforms/modules that fit on this platform. Thus BB2 and BB3 are predefined solutions which can be varied or interchanged. These are named baukasten which translates to something similar as modular platforms. Within the specification of the type of platform there are multiple options which will be elaborated later in the report.

### 4.2.3. Sub-conclusion platform approach

Product platform is a structured coherent collection of resources that include systems and template hierarchies. From this platform, customized products can be designed. The first basis in the platform approach is the decision to use a top-down approach which allows for the implementation of alternative energy carriers and designs based on requirements and functionalities. This approach also allows for the implementation of modularity in the system design and uses the already chosen RFLP approach. The second basis platform is the decision to use the modular platform or also named common-core platform. This approach means that

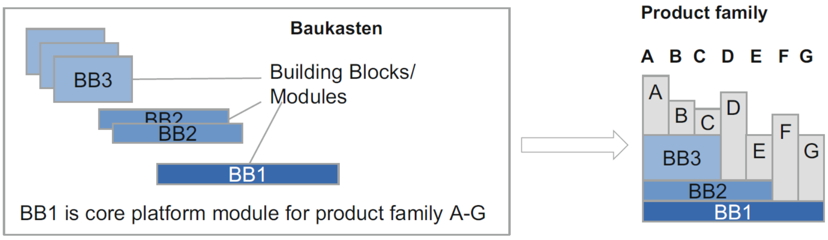


Figure 4.5: Example of the use of the modular core-platform[44]

there is a single common core to the platform and multiple modules can be attached to this core. This is instead of including all the systems into a single module. This platform reduces the over-design and interfaces are not coupled but require a clear definition. Next to this, different system configurations can be developed parallel to be able to innovate the energy carrier and conversion system. Specifically this allows for the two goals of a modular design and alternative fuels to be implemented in the design.

## 4.3. Module definition and interaction approach

The next step is to define the module and the interaction between modules. This is based on the specific approach of the design or system architecture. System architecture is based on how the functionalities of a product are mapped to physical parts. Specifically this means how functional requirements and descriptions for a system can be solved or translated into a actual system which fulfills the functionalities. A system architecture model emphasizes how modules fit together into a consistent whole. It is repository-based to support the capture of inter-relationships meaning the interactions between modules or elements. This model is then used to capture data to be used to define modules which is shown in Table 4.1.

Table 4.1: System architecture model input data[48]

| **System architecture model includes:** | **meaning:** |
|---|---|
| Functions or behavior | Requirements for the system to be fulfilled<br>*e.g. provision of a power, storage of a medium, transport of a medium* |
| Structure or objects | Definition of the structure requirements which fulfill the functional requirements<br>*e.g. the material used, the strength required, the components or sub-systems it includes* |
| Information flow or interfaces | The definition of the interaction between the element or module<br>*e.g. the definition of the amount of fluid transported, power transport or the connection type between sub-systems* |

In the system architecture model the overall functions of the product then are organised into physical parts where the parts carry out assigned sub-functions[56]. These steps are to happen in the order of the RFLP or V-cycle approach to achieve the overall functions. According to Fixson [40] current developments of processes in the industry point towards an increase of complexity. This is due to the increase of interconnections and customization which means that the interconnectedness of the processes or systems have to be studied. The understanding of the system then can be used in the modular design which is the basis of the NAVAIS project including all relevant aspects for the design approach and goal. The system architecture model is therefore used in this thesis towards a modular design. More specifically, within modular architecture a module has to fulfill a function where the function is defined with a verb such as move, store, etc. Also as used in the axiomatic design approach in Chapter 4.1.1. Here, modular architecture is used for highly standardized operability and standard connections for sub-systems where interaction between modules is small or even non-existent.

When defining the modules there are four important aspects according to Fuchs and Golenhofen [44]:

1. The modular architecture usually compromises on performance due to over-sizing the design of the system. *This is due to the ability to use the modules for multiple systems resulting in a range of applicable*

*design specifications instead of a single design specification of for instance the flow through the exhaust system.*

2. Each of the physical elements or parts implements one or more functional elements in their entirety. Largaider [57] even goes to the definition that a completely modular design implies a one-to-one relationship between each functionality and the physical component. For this definition, the interaction is critical to the function of the system. This is agreed on by Erikstad [33] but to the extent which is possible. *Meaning that e.g. the functional requirement of storing fuel oil is fulfilled by the physical solution of a tank and not by a day tank, overflow tank and bunker tank.*

   The modular design of interfaces means that the interfaces are not coupled, but do require a clear definition of the interaction. This also has the goal to minimize interaction between modules or components [57]. The Schematic idea of the module interaction definition is shown in Figure 4.6. However, even though the system is divided physically into components that are based on functionalities there might still be incidental interactions. These interactions can be between the components which are not accounted for in the function structure. For instance the heat which is produced in an engine due to the combustion process and is defined in the functional description as energy flow from the ICE to the cooling system to the environment. However, the flow also has losses in the system which means that there are other interactions between the components that are not desired or defined. This can be the effect of heat to the seals, joints and piping.

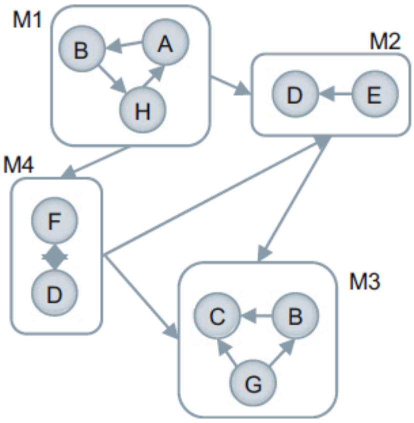


Figure 4.6: Module interaction schematically made visual[44]

3. Any changes made in functionality of a module will only impact the module itself that carries the function and no other modules.

4. Organization teams are decoupled to ensure that modules can be developed in parallel and independently. *Which means for instance that the method of defining modules is not connected to the actual module definition and usage environment.*

The degree to which the functional description is mirrored by the physical part or architecture contributes to the design modularity. For example, if the engine and transmission of the power system would be implemented as the same physical component, the design then would be less modular in comparison to the separable implementation of the components. This means that a characteristic of the level of modularity is the degree to which interactions between components are confined to the function of the product [57].

Next to the advantages of modularity and the implementation of it there are also potential costs associated with according to Largaider [57]. These are:

- A *static product architecture* as the design is based on a chosen functional and physical architecture. Therefore it might be difficult to change for a future product innovation.

- *Performance optimization* as the performance of a product usually can be improved by reducing its modularity. A highly modular product generally is of larger dimensions which also means a larger mass.

- *Reverse engineering* by competitors due to the clearly defined functions and flows. As these functions and components are obvious and the interconnections and interactions are well defined it is possible to copy the product for competitors.

- An *increase of unit costs* as several end products may have excess capabilities due to the most stringent demands within the application to meet the requirements of the design.

**Modular interaction definition for functionalities**

The module interaction possibilities are dependent on the modeling type. As elaborated in the module definition this starts with the functional modeling. This means that a functional description links the functional elements by determined flows. A functional description is a description starting with the main function of the system and based on the functions decomposing it into sub-functions to where a function represents an elementary task. When this point is reached, the lowest level of functions are then the functional elements. The relation between a sub-function and the function above is often determined by a constraint or relations between the in- and output. The functional decomposition is done to understand the complexity of the task which the product performs. In this approach there are levels of complexity where each function can be assigned to. A functional breakdown however is limited to the specific functions. This means that some aspects cannot be included which are relevant in the design. These aspects are for instance regarding the weight, costs and the reliability[44]. However, these constraints can be added to the modules that are used. The steps taken in the modular interaction definition are also shown in Table 4.2.

Table 4.2: Functional modelling towards sub-systems

| Functional Modelling: | Description: | Connection: |
|---|---|---|
| Functional description | Based on 'flows' | |
| Main function | General task | Determined by a constraint or relation between in-/output |
| Functions | More specific tasks | |
| Sub-functions | Elementary task | |

**Modular interaction definition for modules**

With regard to the different modularity types there are 7 options[87] [57]. These are based on the physical interactions between the modules. This means that the interaction or interconnection between modules is defined as well as how the modules are connected to the common platform. The different types of modularity can also be derived based on the manufacturability of the components. The possible modularity types are shown in Figure 4.7. The interaction between modules has to be described as elaborated in Chapter 4.3. By defining the modularity type it is possible to better group functions or elements into modules and to limit the interaction between modules. The connection possibilities are:

- *Combinatorial modularity* which is operationally effective if the product variety demand is high [40]

- *Component swapping modularity* which is a sub-type of slot modularity in which the interfaces are specific to the module type. This means that a type of module has a defined interface. Specifically it means that two or more components can be used in the same basic end product as variants where the variants belong to the same product family.

- *Sectional modularity* where there is no platform module. However, modules have one or more common interfaces that allow for a larger variety in the physical design or layout of the product. On a ship level this is also used on the SIGMA modular ship where there are standardized hull sections based on specific needs and mission requirements. SIGMA is an abbreviation for Ship Integrated Geometrical Modularity Approach. The configuration based on a number of components can be connected in arbitrary ways through standard interfaces with an idea of Lego toy building.

- *Bus modularity* where the interface is standardized for several module types and there is a common core architecture. The common core or standard interface allow for a quick assembly and connection between the modules.

- *Component-sharing modularity* where components or modules can be shared by more core architectures or across multiple products to provide economies of scale.

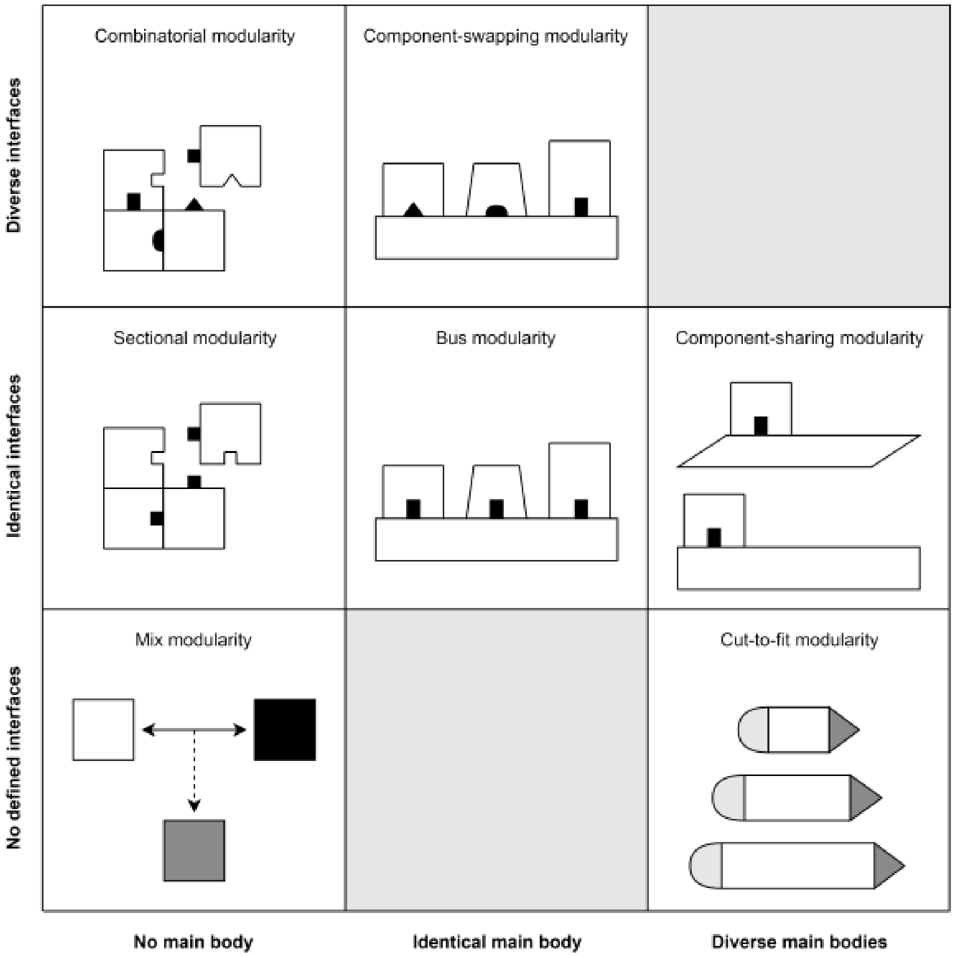


Figure 4.7: Interfaces or interaction definition between modules[87]

- *Mix modularity* with the example of a paint being mixed. In this concept there are no main body and also no defined interface which also means that this type is not used in the system design as the module has to fulfill a function which is not the case for this type of modularity.
- *Cut-to-fit modularity* which is based on the SIGMA concept and mainly based on an adaptable size. This is somewhat similar to fabricate to fit modularity where the standard components in the product are designed to be variable within pre-defined limits based on dimensions and configurations.

### 4.3.1. Sub-conclusion module interfaces

As elaborated in Chapter 4.2 for this research a platform architecture will be used which means a combination of methods and approaches is used. This means that for the functionality decomposition functional modelling is used where the main function is decomposed to sub-functions where the connection between functions is determined by a constraint or relation between in-/output. For the technical or logical solution of the modules there are a number of modularity types. When looking to the the bottom row and the fist column of the modularity types they are not used for the basic approach due to the lack of a common-core platform. These modularity types are more similar to an inclusive-Platform which is not used in this research as elaborated in Chapter 4.2 as well. Combinatorial and sectional modularity might be used, but at a lower system level which in this case means more towards the basic functions towards the elementary task elements. The reason for this is that at a more basic function level, the interconnections of components may have more similarities with these modularity types.

## 4.4. Method and tools for module definition

For methods and tools for module definition and system breakdown there are multiple possibilities. Three main methodologies are powerful for the connection definition according to Fuchs and Golenhofen [44] and another methodology is added according to Smit [87]. These are:

- *Quality Function Deployment (QFD)* which is a predecessor of the concept of Form Follows Function, Design to Value and Modularization and Agile. Where due to the focus on cross-functional collaboration the market and technical aspects are taken into account.
- *Design Space Exploration (DSE)* which diverges the solution space for concept generation, problem solving or specific solution-finding.
- *Design Structure Matrix (DSM)* that visualizes and optimized dependencies between the components of a complex system.
- *Modular Function Deployment (MFD)* that supports a method discussion of module candidates within a modular platform based on modularity drivers.

However, before starting with the tools to define the system interaction, a function definition or decomposition is required as based on the chosen approach. For this there is the possibility to use a function tree, a function structure and a system architecture assessment using the Kano model.

### 4.4.1. Function tree

The function tree approach of functional product description is to decompose the product function hierarchically into relevant sub-functions. Each sub-function or group of sub-functions represents a physical component of the system or product. This process can be repeated until functions become elementary functions which means at the lowest complexity and being unable to be further decomposed. This is also according to the approach elaborated in Chapter 4.3 regarding the module definition approach. Function trees are fast and simple, but the ease is gained in the cost of understanding the interactions or flows between the expanded / defined sub-functions. The interconnections among sub-functions are not considered which means that the approach is not as effective in helping to establish specifications and structuring the development process. For the interconnections another approach is needed.

### 4.4.2. Function structure

For this next approach the first option is the function structure [57]. This results in a technical understanding of a product based on its inputs and outputs which are the elements defined in Chapter 4.1.1. Starting from the overall product function, the functionality is decomposed at a specified level of detail. The start of this approach is the function tree after which the level of functions to be used are defined for the function structure. the approach itself is based on tracing respective flows through the product or system. A note for the decomposition is that some of the modules may vary in size and also have distinct boundary conditions. This makes it difficult to establish modules in a single platform which adds to the decision to use a common-core platform. Next to this, a modularity matrix can be used as a tool to establish and identify modules across a family of products. Where a modularity matrix lists possible functions from a function structure of a family as rows in a matrix and lists possible products from the family in the columns. Each element in the matrix then contains a value that represents the required specific level of the function. The values then represent targets for functions of each product for commonalities to be found and modules to be based on these commonalities [57].

For this approach there are multiple identification possibilities for a single product.

- By following the *dominant flow* where the flow can be followed until it exits the system or is transformed into another flow. The sub-functions through which a flow can be traced, define a module. More specifically it means that sub-functions through which a flow passes from entry or formation of flow to exit or conversion of the flow define a module.
- By *Branching flows* where the flow that branches or converges from parallel function chains is examined. In this case each branch of a flow can become a module and each of these modules interfaces within the product are through the branching or conversion point.

- By *Conversion-transmission* where it examines the flows that are converted from one type to another type of flow. A conversion-transmission module thus converts a type of energy or material into another form. An example for this is the ICE.
- By *Shared function and by unique function* which means that these functions define a portfolio module. These are functional groups which share similar flows and exist multiple times within a portfolio and as a result can be grouped into a single module.

### 4.4.3. System architecture assessment using the Kano model

The Kano model can be used to define important activities and outputs of a system. This model starts with the definition of an important base (or core), performance and the excitement requirements. The goal of the model is to classify the requirements of the customer and the approach thus focuses on defining the basic requirements, the differentiation requirements and minimal thresholds. Next to this potential disruptive innovations and priorities can be assessed.

A functional analysis can be done after a market segmentation which has the focus on architecture requirements and maps the requirements with their functions. Based on this analysis the functions can be mapped to be coupled to a physical decomposition. This step is again based on the RFLP approach but in this case it is also possible to check the functional decomposition using a bottom-up approach. This is possible as some of the configurations are already designed and built. The main advantage to this is that the functional decomposition can be checked using this method. After the visualization and decomposition of the system DSE can be used to extend the solution space and to iterate the concepts towards an optimal design architecture or into combinations of architectures / configurations. At this point a modular or integral architecture can be decided and used [44]. For this project the modular architecture is used and the module framework can be applied to the decomposition. The approach is visualized in Figure 4.8.

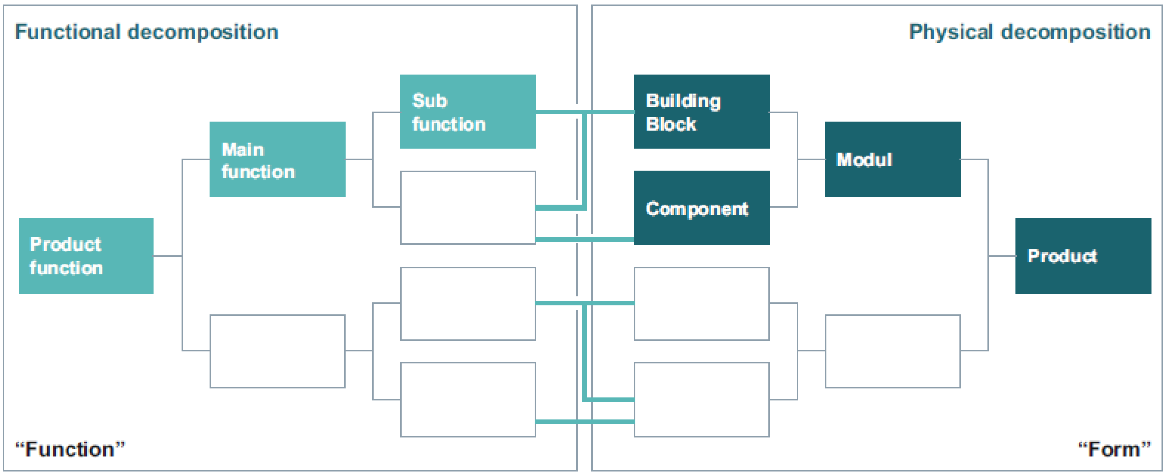


Figure 4.8: Visualization of the overview for a connection between the functional and physical decomposition[44]

### 4.4.4. Design Space Exploration

Design Space Exploration which is also named set-based design and is a structured method to explore many design alternatives. This method is a kind of decision tree-style where many design alternatives are explored in advance of the trade-offs. These trade-offs are important for integrating systems where there are competing requirements. The "set" in set-based refers to the product design proposal family. A key aspect of this method is to delay design decisions to later in the process to achieve the ability for an optimum trade-off. The basic idea for this method is visualized in Figure 4.9. This method is less focused on the definition of modules with regard to the specific possibilities. However, when designing alternative designs, these can be compared based on the same goal where modules can be found based on the commonalities in the different concept designs. This means that commonalities can be found between different product configurations such as a conventional diesel engine and a hybrid solution for instance.

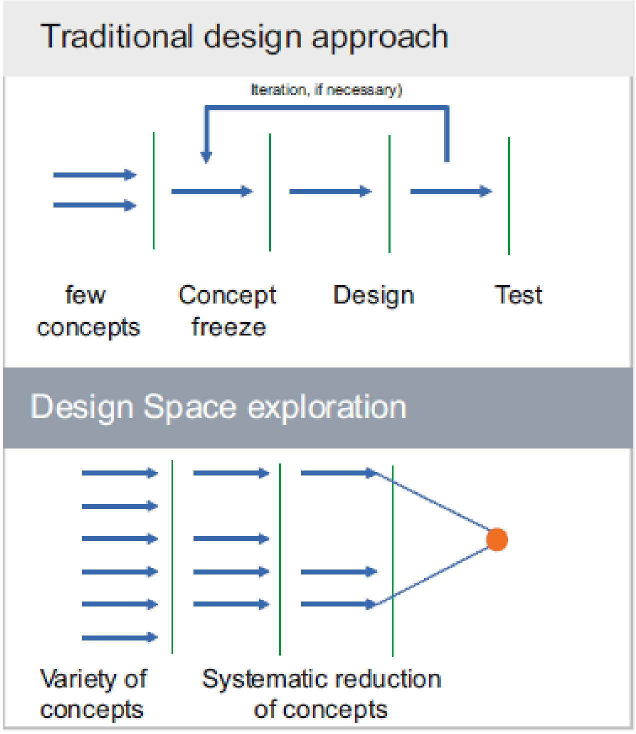
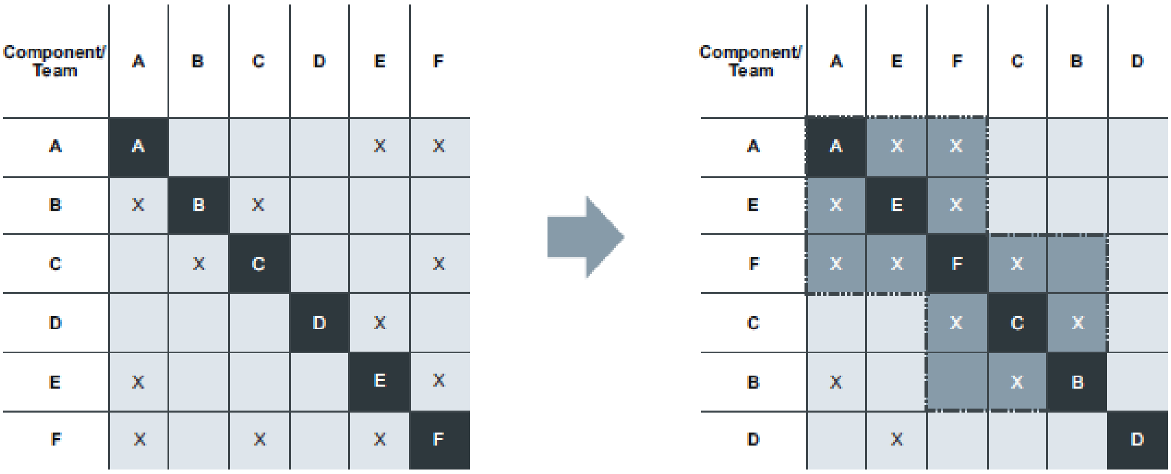


Figure 4.9: Idea visualisation of Design Space Exploration compared to the traditional design approach[44]

### 4.4.5. Design Structure Matrix

Design Structure Matrix is used to define modules within a single product's architecture based on a technical oriented approach. It visualizes and optimizes dependencies between components within a complex system[44]. There is the decision to base the DSM on components or functions where these are placed on the row and column headers in the matrix. Components or functions are mapped to each other and based on this the interactions are marked. After this, a clustering algorithm can be used to group functions or components that maximise interactions within the groups and minimizes the interaction between groups. These groups or clusters are then possible candidates for modules or a common platform [87][44]. The approach for finding dependencies and grouping them is shown in Figure 4.10.



| Component/ Team | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| A | A | | | | X | X |
| B | X | B | X | | | |
| C | | X | C | | | X |
| D | | | | D | X | |
| E | X | | | | E | X |
| F | X | | X | | X | F |

| Component/ Team | A | E | F | C | B | D |
|---|---|---|---|---|---|---|
| A | A | X | X | | | |
| E | X | E | X | | | |
| F | X | X | F | X | | |
| C | | | X | C | X | |
| B | X | | | X | B | |
| D | | X | | | | D |

Figure 4.10: Visualization of the Design Structure Matrix where dependencies between functions or components shown by a 'x' which can be grouped to define possible modules[44]

Advantages of DSM for system architecture modeling are:

- DSM is concise as structured arrangement of elements and interactions provide a compact representation format. The combination of the representation of the data is most powerful.
- The visualization is clear as relationship patterns to the interest of the system designer are highlighted.
- After properly displayed there is intuitive understanding of the basic structure of systems.
- The matrix setup allows for the application of powerful analysis in graph theory and matrix mathematics. Where also direct links can be illuminated, propagation can be changed, there can be process iteration, convergence, modularity and other important patterns.
- DSM is also highly flexible as the basic DSM can be improved or extended as additional colors or data can be added.

The steps taken in this approach are:

1. *Decompose* the system into elements up to a predefined level
2. *Identify* the relationships between the elements are defined
3. *Analyze* the element and relationships are rearranged to understand the structural patterns and their implication on the systems behavior
4. *Display* a representation of the DSM model is created which highlights features of particular importance
5. *Improve* the results of the DSM can be used to improve the system using the DSM analysis and interpretation

### 4.4.6. Quality Function Deployment

QFD is a method used in the early product development phase and has three important aspects which are:

- Features, qualities, characteristics
- Function, mechanizing
- Development, chart, distribution, deployment

The core of QFD is a correlation matrix which shows what is required by the customer and how a product is realized in the end to meet the demands. In this approach the influencing factors are systematically prioritized, quantified and displayed in an iterative approach. Thus the relationship between technical characteristics and requirements are quantified and documented [44]. QFD puts the voice-of-customer first which drives the design process [53]. To elaborate the setup and usage of this method, Figure 4.11 visualizes the different aspects of the approach.

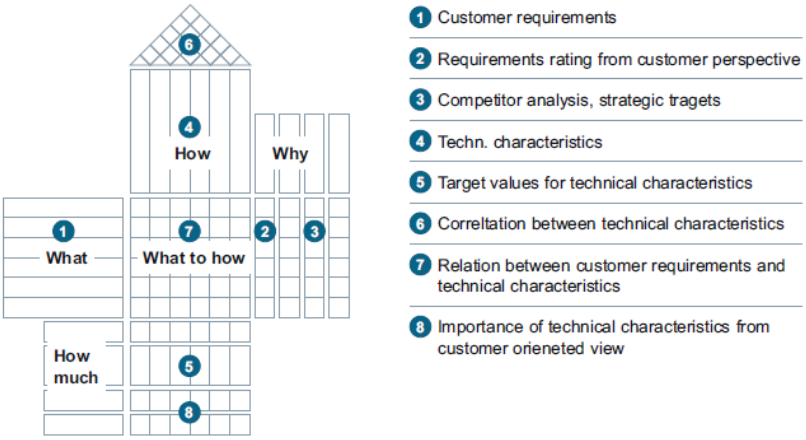


Figure 4.11: House of Quality that combines the what and how in design as part of the Quality Function Deployment[44]

### 4.4.7. Modular Function Deployment

Modular Function Deployment (MFD) is similar to QFD which is used traditional [87]. MFD helps to identify the modules based on the modularity drivers which help with an elaboration to cut the system or product into modules. The difference between the two tools is that in MFD the modularity drivers are mapped against the functions in contrary with QFD where the requirements are mapped against the functions. For this approach the first step is also to start with a functional decomposition to define the different (main) functions of the system. The modularity drivers are [55]:

1. *Carry over* which means that a part of a product can be reused from another design
2. *Technology push* where a sub-system or a part of a sub-system is likely to change technical dramatically due to customer demands
3. *Product planning* which is based on the road-map of a product with possible changes at certain times
4. *Different specifications* based on product variations that are assigned to one or few parts in the product / system to ensure that variations are not spread through the whole product / system
5. *Styling* where there is the possibility for a change of style in the product without disrupting the total product
6. *Common units* which is for parts that typically contain basic functions which can be translated into a common core
7. *Process & organisation* which focuses on similar types of operations which can be grouped in a team working area
8. *Separate testing* the possibilities for a module to be tested separately before being installed or supplied in the total system with the ability to receive instant feedback on the quality
9. *Black box engineering* for the possibility of purchasing completely standardized modules instead of individual parts that have to be combined later
10. *Service & maintenance* for the possibility to quickly replace a damaged module by another one which leads to a fast service and maintenance
11. *Upgrade* which is based on the possibility for enhancing / innovating the product or to rebuild the product for a refit to be used for other purposes
12. *Recycling* for the ability to limit the amount of different material types and also to group materials environmentally in the same module

## 4.5. Discussion and sub-conclusion methods and tools

When looking into methods to define modules and their interactions it is clear that there are some methods specifically designed for this. However, other methods can be used even though they are not designed or developed for this application.
Starting with the function tree and the function decomposition this really follows the RFLP approach including with the top-down approach. With regard to the specific decomposition and interpretation of the functions the function structure approach can be used in Chapter 4.4.2 or the system architecture assessment using the Kano model in Chapter 4.4.3. The Kano model focuses more on optimizing one product where the function structure is more system based. Therefore the Function structure approach will be used where as the combination or interaction between the functional and physical decomposition shown in Figure 4.4.3 is implemented in the function structure approach. This way it is possible to connect the functional and logical decomposition according to the RFLP approach. This decision also means that DSE is not used also as this method is more focused on finding an optimal single design which is not the goal at this point.

With regard to the other methods for module definition the best options are the Design Structure Matrix and the Modular Function Deployment. Quality Function Deployment has a focus towards an optimal design which can be used for module definition. However, results and evaluation of these values is highly based on the input information which can be subjective. Therefore this option is not used for this thesis. MFD is similar to QFD but has already defined modularity drivers which make this method less sensitive for the input information and subjectivity. DSM has the focus to define modules but within one product's architecture. This means that additional work is required to fit the different configurations in the overview. This is possible by developing the functional decomposition such that different configurations are implemented in a hybrid method. The most complex aspect within modularity is the definition and the interaction between modules. When looking into the usability of the defined theories or methods Table 4.3 shows a selection of usage of the different methods. Where the first three connection types are used in navy applications. With regard to the platform strategy it is used for several years in the automotive industry and as well some years ago by Ulstein to optimize their design process. Finally the decision to use DSM is supported by the design approach of Ford, AgustaWestland and Kodak. Here the focus is on defining modules and minimizing interactions between modules to minimize the influence of a design change. The focus of DSM is on the components and their interactions and the focus shown in the table is common to the focus of this thesis and therefore is the best approach for this problem.

To summarize the modularity approach:

1. First a function decomposition is made into a function tree
2. The function tree is connected to the logical design components
3. DSM is used to group function into possible modules and to define the interfaces / interconnections

Table 4.3: Modular design strategies used by various companies

| **What** | **Company** | **Elaboration** | **Source** |
|---|---|---|---|
| Component Swapping modularity | US Navy | Uses predefined locations for each equipment type | [33] |
| Bus modularity | US Navy littoral combat ship | Uses a standard interface which specifically means containerized modules which can be added/removed<br>It uses a base model seaframe and therefore has the possibility to plug in different modules | [33] |
| Sectional modularity | SIGMA Dutch navy | Standardized hull sections and space allocation. Piping systems can also be defined using sectional modularity | [33] |
| Platform strategy | Volkswagen | A common core platform | [33]<br>[86] |
| Platform strategy | Ulstein | Focused on building blocks for mission modularity | [33] |
| DSM | Ford | To better understand network of component interactions. Where interaction interest is based on physical elements and not modularity.<br>Tended to have more interfaces among components of different sub-systems and relatively few interfaces within each subsystem. And has a large focus on interactions inside a modular sub-system. | [31] |
| DSM | AgustaWestland | Helicopter change propagation<br>How change in one part will result in changes of other parts. For which both a product architecture DSM and change propagation DSM (product risk) are done. | [31] |
| DSM (3D) | Kodak | Managing variety within the product family | [31] |
| Common modules | US navy | Common modules focused on structural pieces | [34] |

## 4.6. Advantage of modular design by using the RFLP approach in combination with the Design Structure Matrix

With regard to the advantages of modular design there is the advantage of the usage of the RFLP approach combined with the design structure matrix and the general advantage of modular design also when using the aforementioned methods.

#### The advantage of the RFLP approach in combination with the Design Structure Matrix

An important aspect in this process is to understand what the advantage is of using this approach and method in the design of a vessel. Meaning what the advantage is for the designer or engineer when designing a new or redesigning a vessel. The start of every design is by defining requirements which the vessel has to fulfill based on the requirements of for instance the client. It is often not possible to immediately translate the requirements into a logical design. There are multiple possibilities starting from the requirements. Requirements which are defined in Figure 2.3 which for instance shows the requirement for fuel storage and distribution of fuel or the propulsion and storing system. To translate such a requirement into a logical design with the possibility for design freedom and multiple design solutions requires an extra step. Translating the requirements into functionalities enables an overview of the different design possibilities.

When only wanting to translate the requirements into one design it might be possible to skip the functionalities especially when it is similar to previous designs. At this stage the design can be based on this previous design where all the logical parts can be used as example. However, when using a standard functionality approach it gives the opportunity to systematically improve system design. When designing a single vessel this might not be the optimal solution. However, when designing multiple vessels a change in a requirement for a similar vessel can be followed to a functional description which can be followed to the logical design. It then is significantly faster and more efficient to change this part instead of having to find the effect of a requirement change. Also when using the DSM method it means that the interactions between elements are defined. This means that next to finding the specific part which needs to be changed in order to fulfill the requirement set by for instance a client also the influence on other parts is instantly known. As the DSM shows the interactions between other sub-systems in this case a change in requirements can be followed to the change in functionality and logical design including the potential influence on other sub-systems based on the interactions. The visualization of the advantage of the usage is shown in Figure 4.12 where it shows that a change in requirements can directly be traced to the functionalities to the logical design where a change in the module can be made. Also changing the logical design of a module then only has influence on that part. Including the DSM means that the interaction between the modules is also known and thus the effect of a change is even more detailed and known.

#### The advantage of modular design

The advantages of modular design require elaboration in addition to the use of the RFLP approach and the usage of DSM. In case of a one-off design all the systems are designed from a similar vessel or from the basic design rules. When using the RFLP approach it means that for each of the systems all of the functions are defined as well as all of the system requirements up to the level of component. As defined, the maximum level of decomposition will be the sub-system design. When using defined sub-systems it means that for each subsystem which is combined, the design specifications have to be determined. A list of potential specifications is shown in Table 4.4 where documenting the data is required in all cases to be able to manage the design.

However, a module consists of a combination of sub-systems when using a modular design. This means that for instance 5 sub-systems are designed into a single module and the requirements are defined for the combined modules instead of the separate sub-systems. Resulting in combining now only the requirements of the modules that have to be combined instead of the requirements of all the different sub-systems. Combining this with the module elaboration in Figure 4.12 a system solution is comprised of 3 modules with 5 sub-systems which means that instead of matching 15 lists of requirements only 3 lists of requirements are to be matched to form a feasible system. Additionally, it is possible to have the modules checked by class which means that extra checking of that module is not required anymore and more time and costs can be saved.

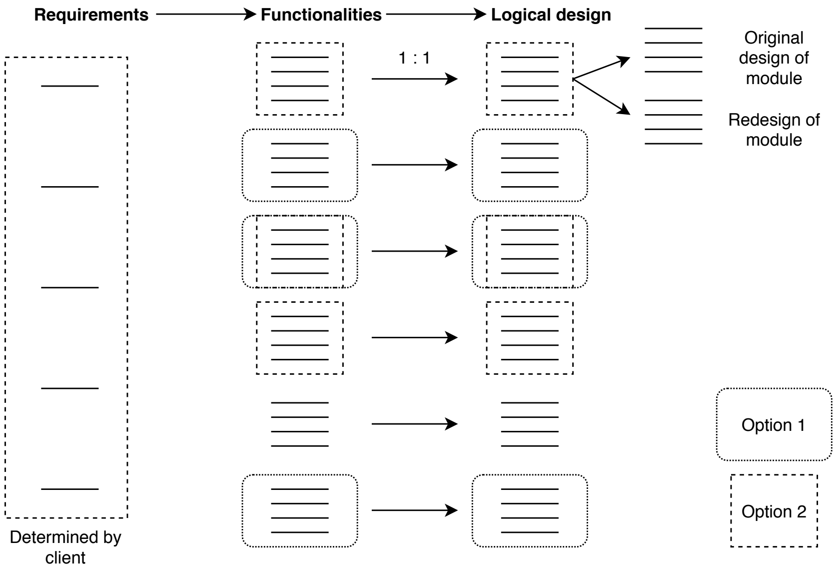


Figure 4.12: Flowchart of the Requirements, functionalities, logical design as part of the RFLP approach

Table 4.4: Functional and sub-system requirements example

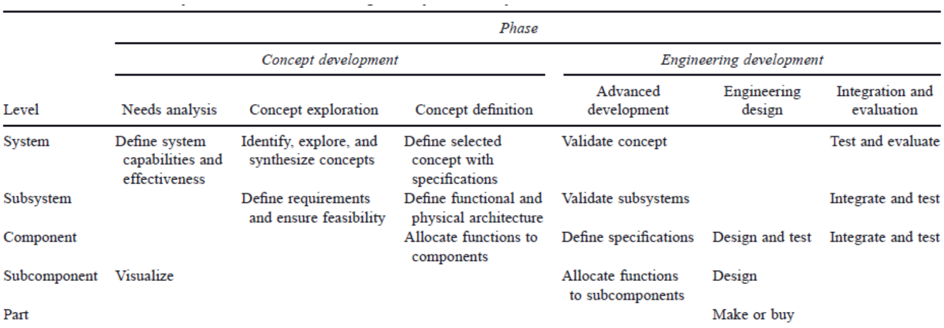
| **Functional requirements** | **Sub-system requirements** |
|---|---|
| General requirements | Specific requirements |
| - kW/kg | - in-/output value range |
| - kW/m3 | - Connection specification |
| Sub-functional requirements | - Material specification |
| System limitations | - Power / strength / etc. |
| - min and max | |
| - (storage, power, etc) | |

# 5

# General interface definition approach

The first step in the approach towards a general interface definition is the start of the DSM method. As elaborated in Chapter 4.5 the DSM is based on the function tree and the logical design. Figure 5.1 shows the concept development phase including the different levels of decomposition which will be used in the method. The needs in the figure are energy carrier and conversion system requirements in this report and are defined and shown in Figure 2.3. However, before exploring concepts the needs are also translated into functional requirements[54]. The visualization of the steps in the application of the platform approach and the Design Structure Matrix are shown in Figure 5.2.

The level for the functional and logical decomposition is done to the level of sub-function and sub-system as a further level becomes complex with regard to managing of the data as elaborated in Chapter 1.3.4. In the definition of the different functions and the physical design there are multiple levels of design as also can be seen in Figure 5.1. Where the top-level is the system which consists of subsystems. The sub-systems then consist of components, sub-components and parts. However, based on the position of design these levels could be different for the user with regard to the specific design. Where the main system of an engine builder is the engine itself thus it is one of the systems in the ship design. Therefore, the decomposition of the functional and logical decomposition is done to a sub-system level based on the position of the ship builder.



| | *Phase* | | | | | |
|---|---|---|---|---|---|---|
| | *Concept development* | | | *Engineering development* | | |
| Level | Needs analysis | Concept exploration | Concept definition | Advanced development | Engineering design | Integration and evaluation |
| System | Define system capabilities and effectiveness | Identify, explore, and synthesize concepts | Define selected concept with specifications | Validate concept | | Test and evaluate |
| Subsystem | | Define requirements and ensure feasibility | Define functional and physical architecture | Validate subsystems | | Integrate and test |
| Component | | | Allocate functions to components | Define specifications | Design and test | Integrate and test |
| Subcomponent | Visualize | | | Allocate functions to subcomponents | Design | |
| Part | | | | | Make or buy | |

Figure 5.1: Specific approach during the concept and engineering development[54]

The algorithm used for the DSM method in this chapter is based on the research of Thebeau [92] and describes a single system for the determination of potential module solutions. This means that the optimal or a feasible solution is defined for modules for one system. However, for this thesis the method is extended for the implementation of more than one energy storage and conversion system. Specifically, it means the inclusion of the system configurations for the energy storage and conversion system as elaborated in Chapter 3.6:

1. Battery system
2. Diesel generator using MGO
3. Dual fuel engine using LNG and MGO
4. LT-PEM fuel cell using hydrogen

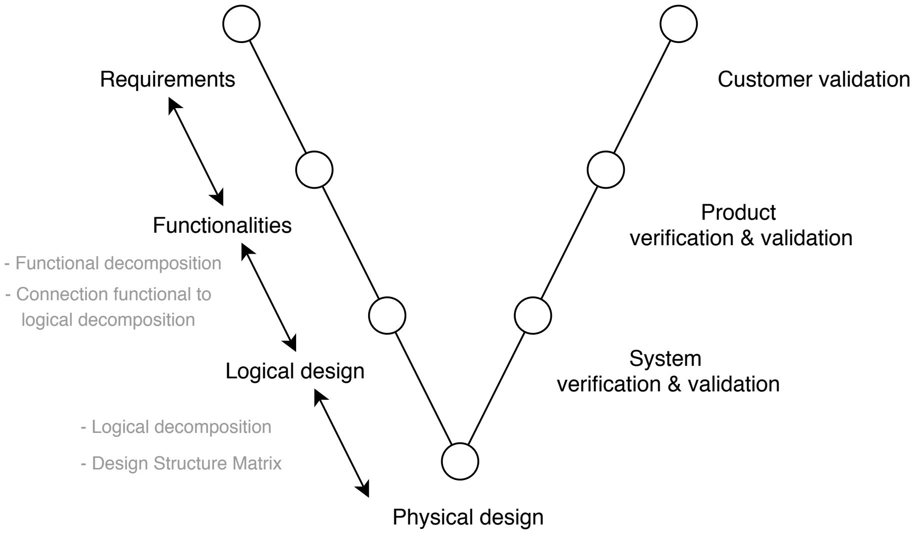


Figure 5.2: RFLP or V-cycle approach visualizing the DSM approach adapted from Figure 1.7[85]

When using the RFLP approach and previously defined methods it specifically means that the systems above are defined in parallel in one decomposition. Where the decomposition is translated to one Design Structure Matrix. The final Design Structure Matrix then includes the four system configurations in one matrix. The goal of the research is to define a modular based energy storage and conversion system but also to design future proof. This means that the modules have to be able to be connected in parallel or series or in another configuration. To ensure that the module based system will work without the modules having negative effect being combined in a total system. The goal therefore becomes to find modules that will match not only for one configuration but also for all the configurations which are possible to combine. Meaning that the modules which are used will never conflict when combined together and are therefore highly modular and also have a higher level of interchangeability.

## 5.1. Functional decomposition

The first step from system requirements to functional requirements is the system functionality decomposition. Starting with the functional decomposition it is important to elaborate on the setup of the decomposition. The functional decomposition is based on functional descriptions made for the Damen ferry as well as S. Brkic [77] and Ghiran [46]. As this is a first attempt of making a functional decomposition it might not yet be perfect as a decomposition requires iterative design revisions.

### Description approach of the decomposition

The functional decomposition and definition of the functionalities is done to be able to specify the limitations of the system and to specify the connections between functions. The specification of functionalities is a systematic approach of describing the abilities and also allowing for improvement of the system.
For the specification of the connections between the functionalities only the interaction is defined. A next step in the functional decomposition can be to specify the interaction with regards to the type of interaction. Examples for this are a physical connection, a medium connection such as fluid transfer or an electrical or data connection. However, this thesis only defines the interaction itself as the goal of the research is to apply the RFLP approach in combination with the DSM method for different energy storage and conversion configurations. After proving the usability of the method it is possible to extend the detail of functionalities or to specify the functional limitations and capabilities in a modelling tool.

There are multiple possibilities for the description of functions. The first possibilities are based on the functional descriptions defined by Axiomatic design which are: Transform, transport, store, exchange and control. Next to these descriptions two more are used. The firsts one is to 'provide' which is a general function description after which this function can be decomposed in more specific functions. The description of 'provide' is also further visualized in Figure 5.4 where it shows the relevant descriptions for the DSM where the provide function is used to describe and connect top-level systems. However, the description 'provide' is not used in the relevant sub-function/sub-system level for the DSM as the description of provide only connects systems and does not describe a function itself.

The second one is to 'convert' which is similar to transform but makes a difference as the transform function description implies a change in form and not a change of form. Meaning that the form remains the same which means for example when using an electrical transformer which is a device that trades voltage for current in a circuit. However, this change will not affect the total electrical power[63] which is the medium in this example. To 'convert' means a change of form or function which means one type of energy into another. For example hydrogen and oxygen into water in a fuel cell. The overview of main functions used in the decomposition is shown in Table 5.1.

Table 5.1: Main function definition elaboration

| **Function** | **Specification** |
|---|---|
| Transform | Change IN form of a medium where the medium remains the same |
| Transport | Move a fluid or gas from one place to another |
| Store | Storage of a gas or fluid |
| Exchange | Interaction between fluids or gasses with the result of exchanging energy |
| Control | To manage or control processes, levels or quality |
| Convert | Change OF form of a medium where one medium type is converted in another |
| Provide | General function description of top-level system descriptions or non-functional description connections |

**Elaboration of the functional decomposition**

The functional decomposition is done for the energy storage and conversion system implying that not the total vessel with all its systems is taken into account. The total overview of the functional decomposition is shown in Appendix A. For the specific function decomposition the division is shown simplified in Figure 5.3. As the focus of this research is the energy storage and conversion system the main function requirement is to provide electric power where the consequent function to convert energy to electric power. Starting from this point it is possible to use the three groups for the three different energy conversion possibilities. The groups represent a setup with a battery system, a conventional diesel generator running on MGO which has an extra 'branch' for a dual fuel possibility and a LT-PEM fuel cell option. The reason for this setup is to be future proof which specifically means that in the case that another energy source or conversion possibility should be implemented this is possible in a parallel way. By adding another branch the function decomposition remains the same for the most part and changes can be made without changing the rest of the setup. This also means that the first setup of the functional decomposition already has a modular focus where changes in one part will not influence another part. This way it is possible to develop separate solutions in a separate way.

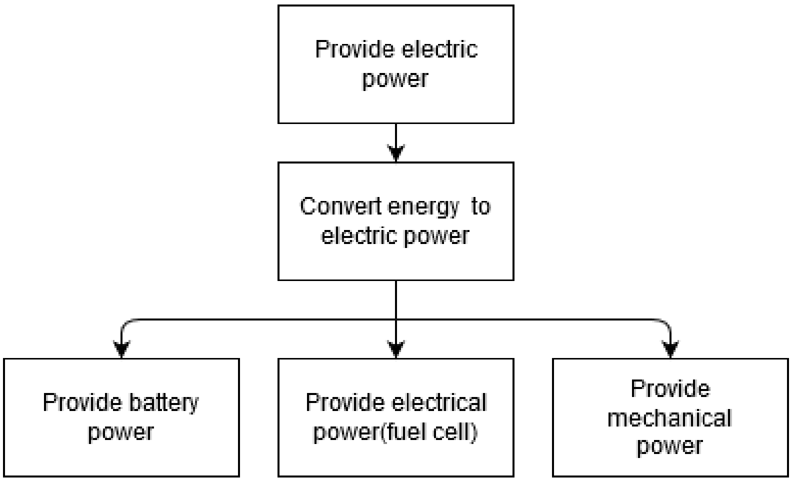


Figure 5.3: Top level function decomposition

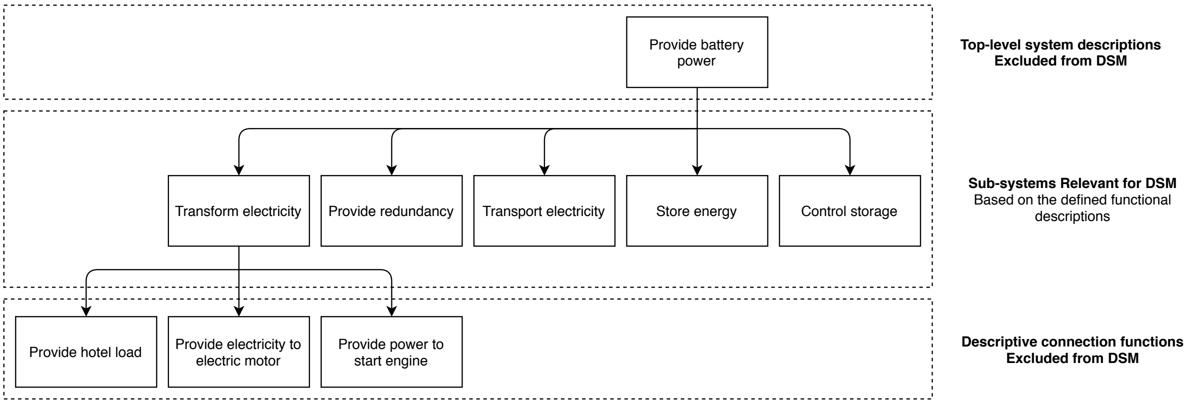


Figure 5.4: Functional decomposition of batteries with the elaboration of the functional descriptions

Next to the top level of function description a more detailed decomposition of batteries is shown in Figure 5.4. In this functional decomposition the functions are relatively simple defined but include a number of design design decisions:

*Redundancy functional requirement*
One of the functional requirements is to provide redundancy for the system which is not a complex functional requirement, but is difficult to connect to a logical design decomposition. For a more complete overview and approach it is included in the decomposition but has no specific functionality.

*Specification of storage control*
The decision is made for this research not to specify the control of the storage further than is shown in in the decomposition. What can be included in the control functional requirement for instance in controlling the storage is the electrical control as well as cooling of the systems.

*Decomposition levels and specification*
After transforming electricity there is a specification on the different potentials for hotel load, electricity for the electric motor and as well for the starting of the engine. These are not specifically required in the functional decomposition but are included to decrease the level of abstractness. The functional descriptions using 'provide' also indicate the low level of functional description. The visualization of this is shown in Figure 5.4.

Finally a part of the conversion system is elaborated further on in Figure 5.5. for the provision of energy carrier there are two options where there is one for MGO and another for LNG. However, this figure only shows the MGO part. Where the function starts generally the next level is more specifically dividing the MGO provision into storage, transport and control of the energy carrier. Furthermore, the storage requires a better specification as redundancy is required, as well as managing of the storage, filling of the storage and internal transport. In this figure it might show that there are 4 levels of specification. However, even though there is another level below the storage of the energy carrier the goal of the figure is to show that more specification is required to define the storage. The third and fourth level therefore are at the same level of specification.

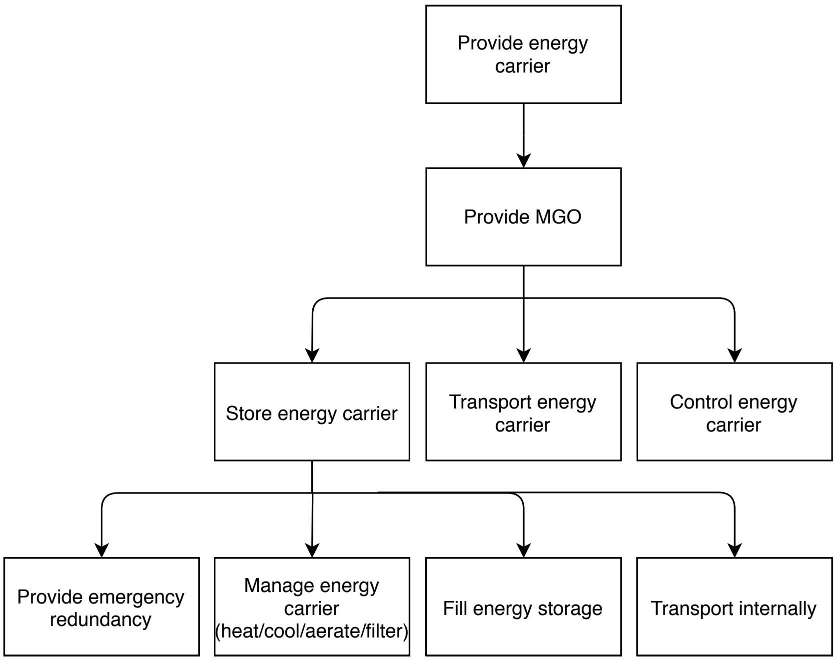


Figure 5.5: Functional decomposition of a part of the energy provision for the combustion engine

## 5.2. Logical decomposition

The next step in the approach is the logical decomposition of the system. In this decomposition for every functional requirement defined in the functional decomposition a physical implementation is required in the logical decomposition. Meaning that for each function or sub-function there is a physical element[92] to the level which is possible[33].

### Description approach of the decomposition

The decomposition of the logical design is the translation of the functional requirements into technical solutions. This means that for each of the functional requirements a logical solution is required. For the decomposition the decision is made to define all elements of the logical solution only once in the decomposition. Meaning that for instance redundant designed systems are defined once. Thus for a redundant system it can be defined as two similar modules or sub-systems but is only defined once in the decomposition.
Furthermore, the RFLP approach is used in combination with the top-down approach. Resulting in the definition of the logical solution is based on the functionalities. However, for this step the combination is made to use the top-down and bottom-up approach. As there are examples for the logical design of the battery and diesel generator systems the 'proven' systems can be defined using both the top-down and bottom-up approach. Where the alternative fuel systems or 'future' systems are not yet designed which means that the top-down approach is the only possible approach for the decomposition. For the first part of the decomposition the functional decomposition is used as a guideline and basis. Next to this the Piping and Instrumentation Diagrams (P&ID) are used which were designed for the Damen ferry. These drawings do show the logical design for all the different systems on board. Beside, Caterpillar [12], Wartsila Marine Solutions [88], Wartsila Corporation [15] and MAN Diesel & Turbo [94] are used for the logical decomposition.

### Elaboration of the logical decomposition

After evaluating the decomposition of both the functional and logical decomposition it is possible that there is a difference between the logical elements and functions. Thebeau [92] elaborates the difference between the decomposition diagrams and that it might appear that there can be several physical elements to implement one functional requirement. However, in his case, the functional requirement then existed of more than one functional requirement. This functional and logical decomposition connection therefore is an excellent method to evaluate both the decompositions for correctness with regard to omitted elements and unclear definitions.

In the start of the logical decomposition there are five branches instead of the three defined in the functional decomposition. The reason for this is that in this decomposition there are two extra 'branches' for the cooling water system. This system is not completely in the scope of the energy storage and conversion system, but it cannot be defined without the cooling. Therefore the cooling is a separate branch but is included in the logical decomposition. For this reason there are five groups which are the battery power, cooling water system generators, cooling water system auxiliary system, generator system and hydrogen system. In the later use of the DSM these two branches for the water cooler are left out to simplify the DSM. Furthermore in the generator system there is an extra branch for the supply of LNG instead of only diesel fuel. This is done to define all elements only once in the decomposition which is required for the use of the algorithm. When both the branches of LNG and MGO are used the system configuration is a dual fuel configuration. When only the MGO branch is used, the configuration is a normal diesel configuration.

The total overview of the logical decomposition is shown in Appendix B. The top level of this logical decomposition is shown in Figure 5.6. A more detailed decomposition part is shown in Figure 5.7. As can be seen in the functional decomposition of the MGO provision, the functional requirement elements are recognisable in the technical solution. Where there is the storage of the fuel, the transport is translated to fuel oil supply and fuel oil transfer to better determine the incoming flow and the user flow. The control of the system is included in the transfer system. When looking at the logical decomposition there are multiple tanks in this part in the decomposition which fulfills the redundancy functional requirement. However, in most cases the redundancy is difficult to define in the logical decomposition. In addition to clarify some sub-systems the decomposition is done to a lower level than the sub-system level. For instance the valves and filters which are part of the piping system are shown in the logical decomposition. However, these are pars or assemblies which is at a lower level than the defined sub-system level. The only purpose of this extra elaboration is to give an idea of what is included in these sub-systems.

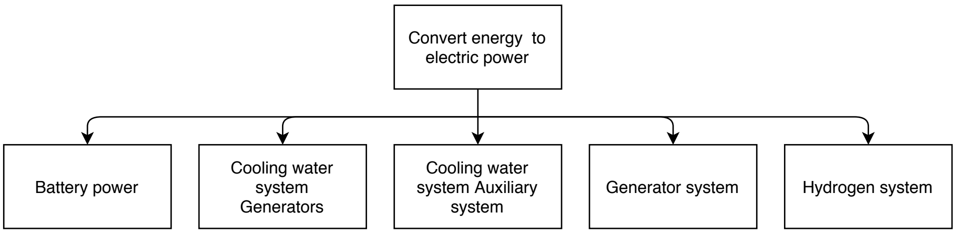


Figure 5.6: Top level of the logical design decomposition

*Defined design approaches by Damen*
For the logical design there are already some ideas defined regarding for instance the distribution of systems[77].

- With regard to the electrical distribution system the preference is to have a decentralized distribution system. For the modular design this means that there will be a number of separate modules and no effort should be made to group the modules together. Specifically the different modules could consist of the generators, batteries and thrusters which can be coupled to the electrical system. Then changes can be made for instance to the generators without changing the functionality of the system.
- Another defined design idea is regarding the fuel oil system. For this system it is important to group the systems at the centre of the ship for stability and to have the shortest possible pipelines. As there is fuel transfer between tanks, grouping is required to meet the design aspect of minimizing pipe length.
- The third group for which design ideas are defined is the cooling water system. The fresh water cooling should be a centralized system and should be able to store heat to balance heat recovery optimization. This applies specifically for electric ships as the systems on board generate far less heat than a conventional internal combustion engine. Where the heat of the combustion can be used for the HVAC system this is not possible in the case of an all electric ship. The heat generated during the charging then should be stored to be used for for instance the HVAC system.

The list of all the decomposition elements is shown in Appendix C decomposition version 2. The appendix also shows the development of the logical decomposition and the adaptions. These changes are firstly based on optimizing and more standardizing the decomposition. Whereas version 3 without the water cooling sys-

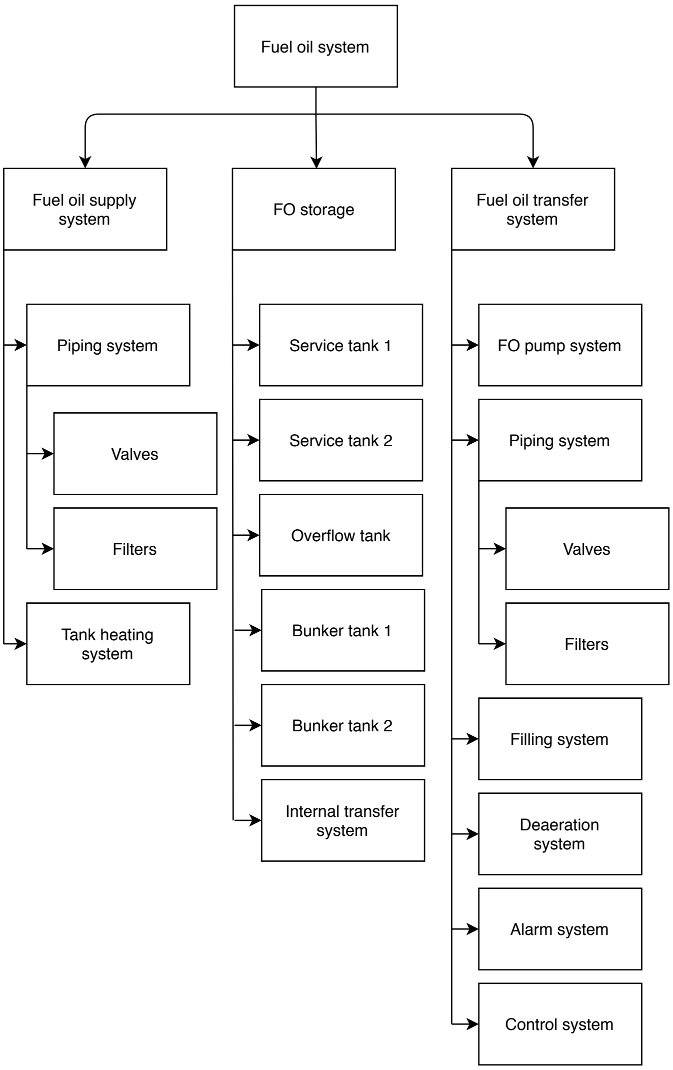


Figure 5.7: Logical decomposition of the MGO fuel system

tem is used in the DSM to start with a smaller DSM in order to reduce the complexity.

**Visualization of the sub-system determination based on P&ID drawings**
To visualize what the sub-systems are in the logical decomposition Figure 5.8 is included. The figure shows system parts which can be grouped due to their specific function. The approach of coupling a function and defining a logical physical solution is applied for all the different sub-systems and functions of the 9819 E3 ferry. The connections between the different sub-systems are highlighted in the figure as these are important in the design of modules. 10 sub-systems are defined which fulfill different functions and are specified in Table 5.2:

Table 5.2: Sub-system definition based on Figure 5.8

| Sub-system specification | | | |
|---|---|---|---|
| 1. | Lubrication oil filling system | 6. | Lubrication oil pumping system |
| 2. | Oil exhaust system | 7. | Lubrication de-aeration system |
| 3. | Diesel generator | 8. | Lubrication oil storage system |
| 4. | Lubrication oil piping system | 9. | Sludge system |
| 5. | Dirty oil system | 10. | Lubrication oil drum filling system |

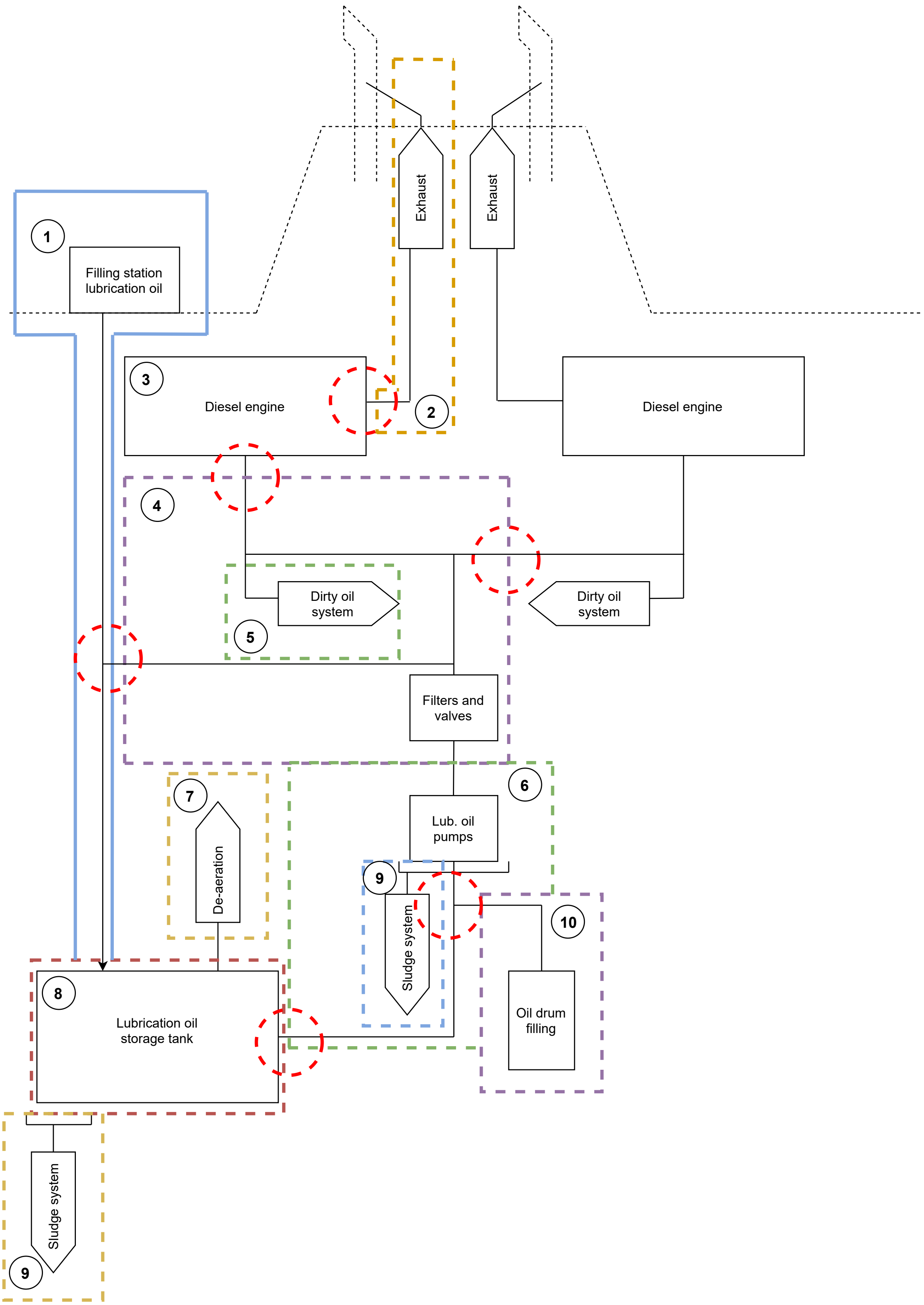


Figure 5.8: Visualization of the determination of sub-systems adapted from the P&ID drawings for the Damen 9819 E3 ferry

## 5.3. Decomposition evaluation

When making the function and logical decomposition the first idea was to make it complete in order to map and understand the system completely. This means that the functional and logical decomposition was elaborated to a lower level than sub-function and sub-system. This way it is possible to understand the system fully as all functions and components can be connected to fully understand the system and to be able to down-scale the decomposition back to the sub-system level. However, this resulted in a problem with regard to time and complexity as the total decomposition up to the component level is too extensive. Based on this approach a number of design decisions are made with regard to the decomposition:
Firstly, the full decomposition for functional requirements resulted in double technical solutions due to the interconnections of the technical solutions. An example is that extra energy from the generator could be stored in batteries and thus a storage function was added to the generator as well as in the battery part where these are the same thing. Therefore the storage was deleted from the generator to avoid double entries and the link will be provided in the DSM matrix that there is a connection.

Secondly, at this stage the electrical connections are not taken into account due to the lower level of specification. Where for instance the piping system of a diesel generator is important to plan due to the difficult integration of the piping for cooling, exhaust, lubrication and fuel supply it is more easy to implement the electrical cables. Therefore at this point the electrical connection system is not defined in the functional and logical decomposition.

Thirdly, an aspect is that the requirement definition also states a requirement for redundancy which is also translated into the functional requirements. However, when plotting the functional requirements to the logical design, this requirement is hard to connect as the main idea is to connect one function to one sub-system. This means that when redundancy is required, another subsystem is required or a connection between systems has to be defined. This means that redundancy is a difficult requirement to implement in a DSM where it is possible to take it into account during the design of modules.

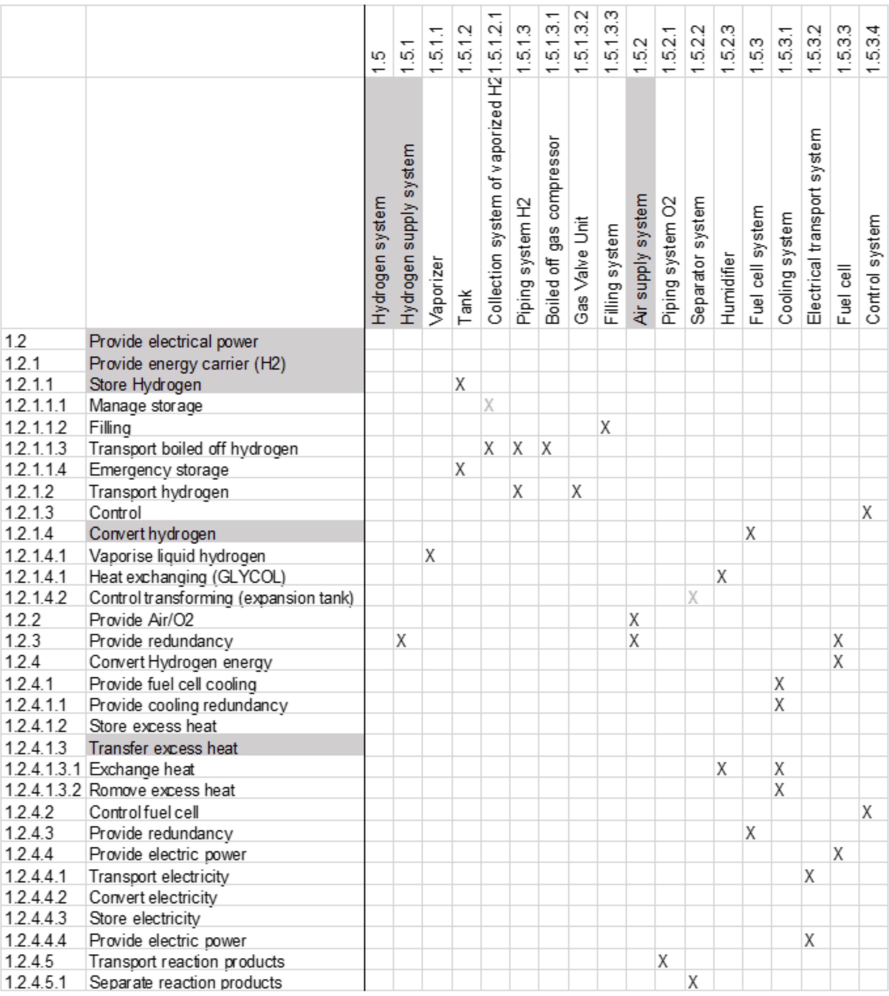
Finally an important aspect in the approach and setup of the usage of the Design Structure Matrix is that the setup and the usage of this method is iterative. This means that an initial definition can be made after which the method can be applied and tools can be used to determine clusters which are possible modules. After analyzing the results it may become clear that results do not satisfy certain requirements or functionalities and therefore the input should be changed. This adaption is part of the overall process and for that reason the connections and decisions on the approach are elaborated on to be able to improve the setup.

## 5.4. Connection between functional and logical design

Appendix C shows the connection between the functional and logical decomposition. In this figure colors are used for extra information on the connection. The purple color is used for the redundancy functional requirement which is a difficult requirement to connect to a logical part and therefore connections can lack as elaborated before. The yellow color is used for interactions which might not perfectly connect between the function and logical design but are accepted. And finally the orange is used in the case that there are more than one connections for a single function. In this case it is possible to further decompose the functional design. However, as the DSM is done for the logical design, the decision is made not to extend the function decomposition. As elaborated on in Chapter 4.3 the goal is to match one functional requirement to a logical sub-system entry to the extend which is possible. However, in practice this is more complicated than the ideal theory. Where a functional requirement may seem sufficiently specified, the system can consist of multiple sub-systems.

For example in the mapping of the functional to logical decomposition is the functional requirement “Transport boiled off hydrogen” which is shown in Figure 5.9. It fits to the tank with its collection system for vaporized hydrogen as well as the piping system which is defined as a sub-system in this research as well. In order to resolve this problem it is possible to go back to the functional requirements and add a specification with “collecting vaporized hydrogen” and the actual “transport of the vaporized hydrogen”. However, as the collection system is already built in the tank it means that the addition of function requirements have no impact on possible modular designs. The tank and collection system is a sub-system which is bought of a supplier and a change in it is therefore not possible. For this reason a double connection between the hydrogen collection system and piping system is allowed and is carefully watched in the DSM to ensure that the module possibilities comply with the sub-systems which are bought “off shelf”.

When taking a more detailed look at the selection shown in Figure 5.9 the grey fill color is used for the main-functions which are not required to have a connection. This means that a grey fill color cell is a sub-system or sub-function itself it can be included in the DSM where a more general system or function is not elaborated to the level of sub-system or sub-function. When looking at the function decomposition the transfer of the excess heat is also coupled to the cooling system at this stage. As previously explained, the water cooling system is excluded at this point which means that the cooling is more general and not connected to the cooling system. Also when looking at the fuel cell there are connections to converting hydrogen and providing electric power. This is accepted as these processes take place at the same system being the fuel cell.



| | | 1.5 | 1.5.1 | 1.5.1.1 | 1.5.1.2 | 1.5.1.2.1 | 1.5.1.3 | 1.5.1.3.1 | 1.5.1.3.2 | 1.5.1.3.3 | 1.5.2 | 1.5.2.1 | 1.5.2.2 | 1.5.2.3 | 1.5.3 | 1.5.3.1 | 1.5.3.2 | 1.5.3.3 | 1.5.3.4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Hydrogen system | Hydrogen supply system | Vaporizer | Tank | Collection system of vaporized H2 | Piping system H2 | Boiled off gas compressor | Gas Valve Unit | Filling system | Air supply system | Piping system O2 | Separator system | Humidifier | Fuel cell system | Cooling system | Electrical transport system | Fuel cell | Control system |
| 1.2 | Provide electrical power | | | | | | | | | | | | | | | | | | |
| 1.2.1 | Provide energy carrier (H2) | | | | | | | | | | | | | | | | | | |
| 1.2.1.1 | Store Hydrogen | | | | X | | | | | | | | | | | | | | |
| 1.2.1.1.1 | Manage storage | | | | | X | | | | | | | | | | | | | |
| 1.2.1.1.2 | Filling | | | | | | | | | X | | | | | | | | | |
| 1.2.1.1.3 | Transport boiled off hydrogen | | | | | X | X | X | | | | | | | | | | | |
| 1.2.1.1.4 | Emergency storage | | | | X | | | | | | | | | | | | | | |
| 1.2.1.2 | Transport hydrogen | | | | | | X | | X | | | | | | | | | | |
| 1.2.1.3 | Control | | | | | | | | | | | | | | | | | | X |
| 1.2.1.4 | Convert hydrogen | | | | | | | | | | | | | | X | | | | |
| 1.2.1.4.1 | Vaporise liquid hydrogen | | | X | | | | | | | | | | | | | | | |
| 1.2.1.4.1 | Heat exchanging (GLYCOL) | | | | | | | | | | | | | X | | | | | |
| 1.2.1.4.2 | Control transforming (expansion tank) | | | | | | | | | | | | X | | | | | | |
| 1.2.2 | Provide Air/O2 | | | | | | | | | | X | | | | | | | | |
| 1.2.3 | Provide redundancy | | X | | | | | | | | X | | | | | | | X | |
| 1.2.4 | Convert Hydrogen energy | | | | | | | | | | | | | | | | | X | |
| 1.2.4.1 | Provide fuel cell cooling | | | | | | | | | | | | | | | X | | | |
| 1.2.4.1.1 | Provide cooling redundancy | | | | | | | | | | | | | | | X | | | |
| 1.2.4.1.2 | Store excess heat | | | | | | | | | | | | | | | | | | |
| 1.2.4.1.3 | Transfer excess heat | | | | | | | | | | | | | | | | | | |
| 1.2.4.1.3.1 | Exchange heat | | | | | | | | | | | | | X | | X | | | |
| 1.2.4.1.3.2 | Romove excess heat | | | | | | | | | | | | | | | X | | | |
| 1.2.4.2 | Control fuel cell | | | | | | | | | | | | | | | | | | X |
| 1.2.4.3 | Provide redundancy | | | | | | | | | | | | | | X | | | | |
| 1.2.4.4 | Provide electric power | | | | | | | | | | | | | | | | | X | |
| 1.2.4.4.1 | Transport electricity | | | | | | | | | | | | | | | | X | | |
| 1.2.4.4.2 | Convert electricity | | | | | | | | | | | | | | | | | | |
| 1.2.4.4.3 | Store electricity | | | | | | | | | | | | | | | | | | |
| 1.2.4.4.4 | Provide electric power | | | | | | | | | | | | | | | | X | | |
| 1.2.4.5 | Transport reaction products | | | | | | | | | | | X | | | | | | | |
| 1.2.4.5.1 | Separate reaction products | | | | | | | | | | | | X | | | | | | |

Figure 5.9: Selected section of the function to logical decomposition mapping as part of Appendix C

In addition to this a better specification in the logical decomposition can be defined than in the functional decomposition. The example for this is the usage of tanks for the storage of MGO. In the “fuel oil storage system” is the service tank 1 and 2, the overflow tank and the bunker tank 1 and 2. In the functional decomposition these tanks are grouped into the storage of the energy carrier as they can be seen as the sub-system of storing the fuel where the assemblies are the different tanks. However, as the tanks can be separated in location and specific usage the logical design further decomposes the storage system into the different tanks. For this case it is possible to extend the functional decomposition into more entries. However, due to the current size of the decomposition the decision is made for now to keep this decomposition and to allow for the function to have more logical sub-systems.

The final input which is discussed is the managing of the fluids. The term “Managing” is somewhat vague and includes multiple managing sub-systems. These include de-aeration, alarm system, control system and sounding system. However, as these systems are relatively simple, the decision is made to group them in the functional decomposition and only to show the specification in the logical decomposition. Even more important is that these sub-systems cannot be grouped together with the other entries as the only connection of these systems is with the tank from the perspective of the energy carrier and conversion system.

## 5.5. Design Structure Matrix setup and clustering analysis

The Design Structure Matrix itself is only the matrix in which the elements are plotted against each other on both the axis. In this matrix the interactions between elements are defined where in this thesis the elements are the sub-systems of the energy storage and conversion system. The next part of the DSM method is the usage of the clustering algorithm and the analysis of the results from the clustering. However, before starting with the elaboration on the working principle and the usage first the goal and important aspects of the analysis are elaborated.

### 5.5.1. Goal and starting aspects of the DSM analysis

The goal of the DSM method starts with the two goals of the research which are the design for a future proof vessel and the modular design. When combining these two goals DSM provides a combining solution where in the matrix all the sub-systems are defined which are relevant for the energy storage and conversion system. This includes the different systems defined in Chapter 3.6 in one matrix with the interactions between the sub-system. As elaborated in Chapter 4.1 the principle of modularity is based on the focus of the (relative) self-sufficiency of individual parts. Where in this case the parts are the sub-systems. The clustering in a DSM finds the clusters or groups of sub-systems in which between the interaction is minimized. This means that between the clusters there is minimal interaction which is one of the three defined basic characteristics. Specifically for this research the goal of the DSM is to find clusters for possible modules that remain constant in system configurations. This is done by searching for the minimum interaction between clusters and by defining the interactions between and outside clusters to be able to standardize those interactions.

Before defining the DSM matrix there are 6 important aspects[31]:

1. The *boundaries* or limits of the designated system might not be understood well. Therefore the boundaries of the DSM should be chosen such that all the relevant components and interactions of the scope are included in the matrix. Later revisions can be used to change boundaries to include or exclude components or interactions. The boundaries for this research are with regard to the energy storage and conversion system and excluding the systems outside of this.

2. There are different types of interfaces, relationships and interactions also named *interaction types* among the components. Where some interactions can be defined specifically for instance physical adjacency of components or flow between sub-systems with fuel oil. However, other might be less apparent or might be hidden but still can have influence and should be described and taken into account.

3. Most interactions in the DSM are *symmetric* which means that component A interacts with component B and vice versa. However, asymmetric interactions can be present as well.

4. With regard to *granularity* or level of specification there is a trade-off between simplicity of the model and decomposing the system more detailed. However, the level of detail has influence on the interpretation of the results where it is more difficult for a larger decomposition. Therefore, the results may show more practical solutions for a larger decomposition. The recommendation to start a DSM is to start with 20 to 50 components where components can be added if additional specification is required or can be removed for parts which require less detail without much loss of information or insight.

5. The *identification of interactions* might come from product documentation or interface specification. However, for most models discussion is required with the system design experts as there can be interactions which are tacit which means that they are understood among the system designers but are not stated.

6. *Interaction strengths* are also a possibility to define interactions between components. In this situation there are different levels of strength or a degree of interactions between components that are defined in the DSM. The result is that there is a different importance between the interactions which has influence on the potential clusters.

In addition to this, the design structure matrix itself does not consist of all the input components of the functional or logical decomposition. As the decomposition has various levels of complexity, the top level is the overall system which consist of multiple systems which again consist of sub-systems. As elaborated before the DSM will be executed at the level of sub-system. This means that the entries of a higher level than sub-level are removed in the matrix to have all the same level sub-systems which can be grouped to be able to find possible modules.

### 5.5.2. Matrix setup based on the logical to logical interaction definition

The final DSM which is used in the Matlab algorithm is shown in Appendix D. First the usage of the DSM matrix and the definition of the interactions is elaborated before getting to the results. The Matlab code which is used for analysing the results is based on the work of Thebeau [92] and also elaborated online[70]. A roped elevator system is used as example in this algorithm code. The system itself which is used in that thesis is not totally correct or complete as some entries are high-level system requirements and others more detailed. However, it elaborates the theory behind the usage of a Design Structure Matrix and the clustering.

#### Interaction definition

For the input of the DSM the layout is such defined that the first column and the first row represent different element descriptions which are all in the same order for the column as for the row. This means that the diagonal of the matrix has no interpretation as this is the interaction with itself for the element. The elements in this research are the sub-systems of the energy storage and conversion system. When using the binary matrix it useful to show the presence or absence of a relationship between pairs of elements in the system. The major advantage of this setup is the compactness and the ability to systematically map interactions to be used in an analysis of the overall system. However, the compactness and abstractness of the matrix also bring the risk of including errors in the matrix without seeing it until the analysis of the results. This means extra care has to be taken when implementing data in the DSM. The interactions work as follows when the idea is that the system is a representation of a project in which elements are tasks that need to be performed. Specifying this to the usage of a system there are sub-systems where there are in- and outputs which connect the sub-systems.

- Off-diagonal marks or interactions in a single column of the matrix represent all the tasks of which the output is required to perform the task which corresponds to that column.
- Off-diagonal marks or interactions in a single row show the information or input which is required or received which corresponds to that row.

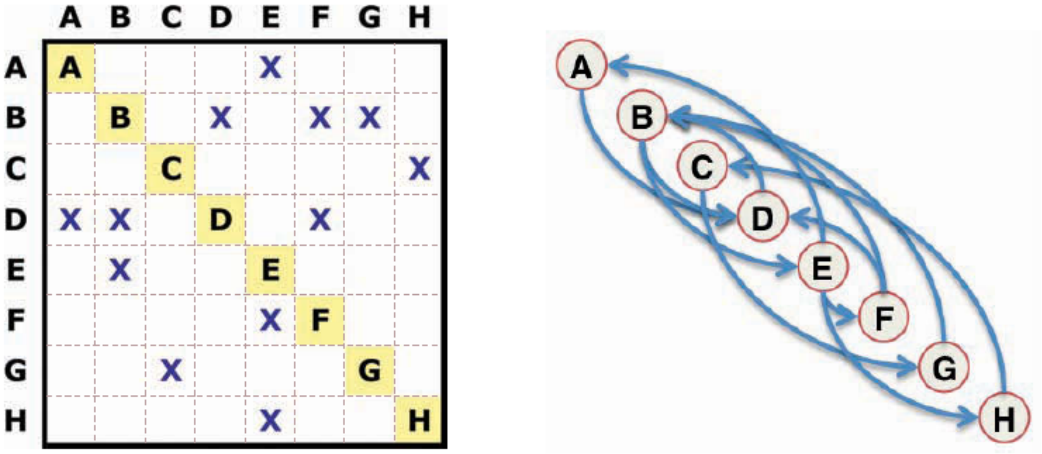
To be more specific, Figure 5.10 shows a simple DSM without further meaning. In this figure there are the elements A to H which are the same for the rows and columns. When reading the DSM for row D it shows that element D has input from the elements A, B and F which is represented by the “X”. When looking down column F it shows that element F has outputs going to elements B and D. In this example the diagonal is shown with the element letter as an element cannot interact with itself.

#### Interaction specification

When using the interactions there are three possibilities for connections which are the parallel, sequential and coupled interaction. A visualization of these three interaction possibilities and their implication to the DSM interactions is shown in Figure 5.11.

In the *parallel configuration* the elements do not have interaction with each other but exist simultaneously. For example it would show the existence of the fuel supply for the diesel generator and the air supply for the diesel generator. Both supply something for the generator but don’t have interaction with each other. This also means that at this point the first is independent from the second and no information or other exchange is required between the two.

In the *sequential configuration* one element influences the second sequentially. This means that there is interaction between the two elements. The example for this can be a tank for MGO and the piping system which connects the tank to the generator. The tank is the first element and the piping the second where fuel can be transported from the tank through the pipes. In this element there is a connection and interaction from the tank to the piping but not in reverse as the flow of the process goes one way.



| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| A | A | | | | X | | | |
| B | | B | | X | | X | X | |
| C | | | C | | | | | X |
| D | X | X | | D | | X | | |
| E | | X | | | E | | | |
| F | | | | | X | F | | |
| G | | | X | | | | G | |
| H | | | | | X | | | H |

Figure 5.10: Elaboration of interaction explanation for a DSM

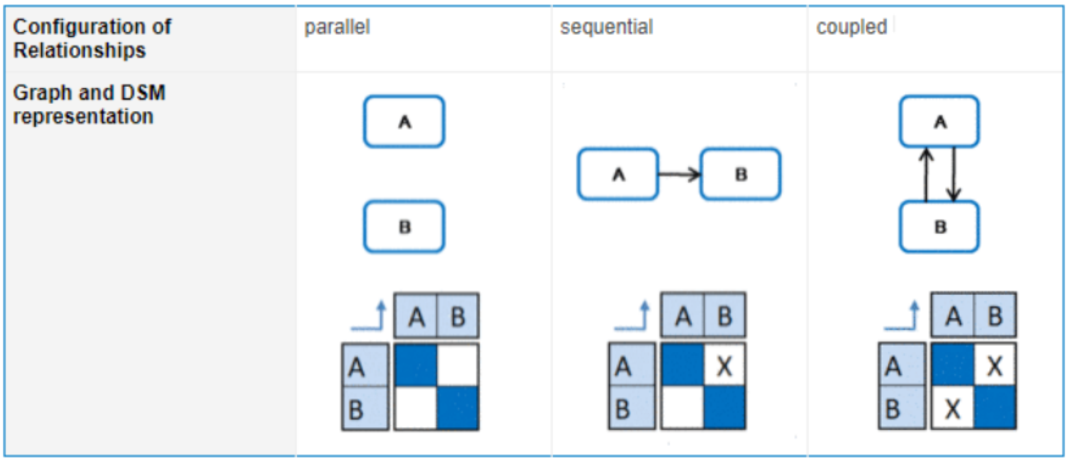


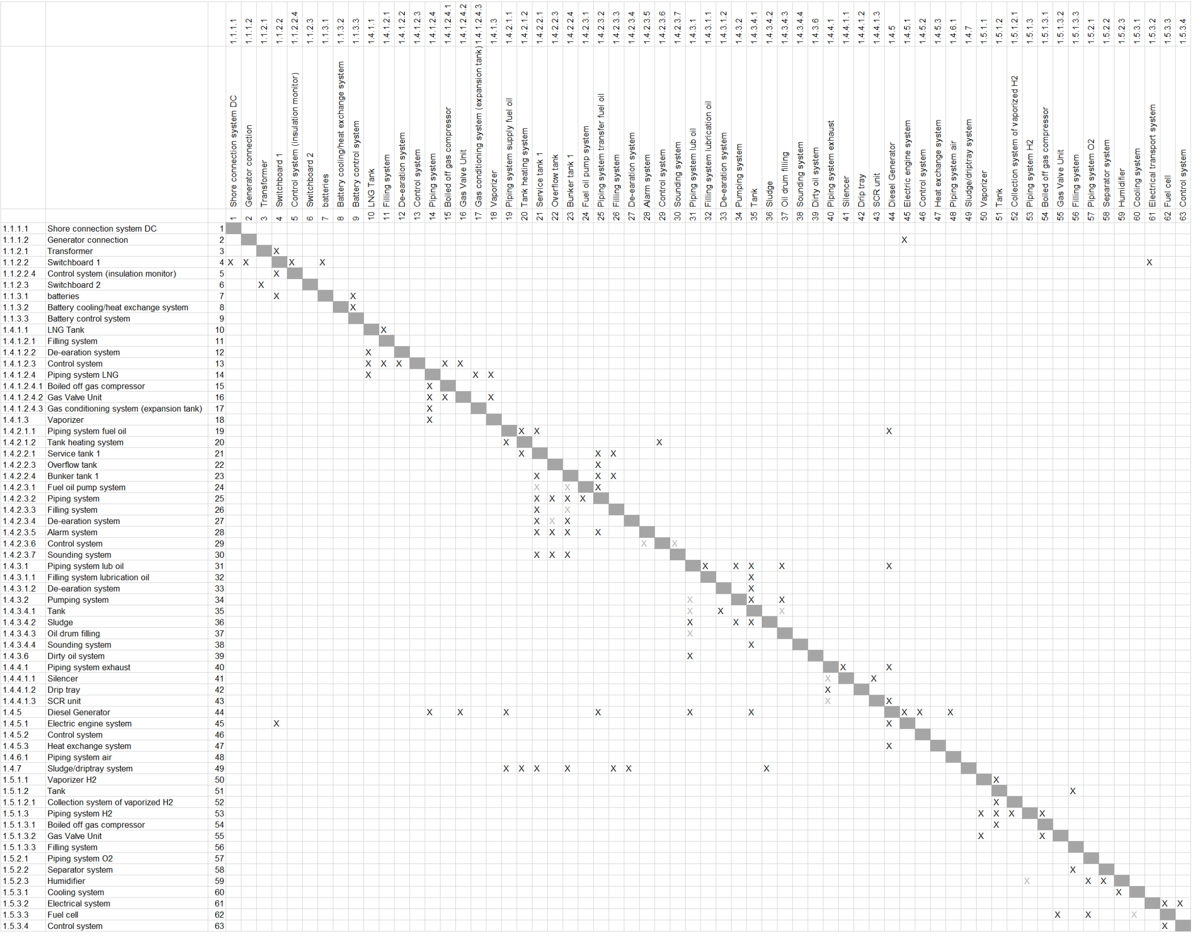
Figure 5.11: Visualization of the interaction specification in the DSM

The third possibility is the *coupled interaction*. In this case the interaction is intertwined which means that both elements influence each other. This can occur in the case that the parameters of the first element cannot be determined without first knowing the second parameter and the other way around. An example for this situation is a cooling system which is based on the working of the generator. Meaning that the two systems are coupled to ensure that the cooling is based on the working of the generator.

The connections made between sub-systems can have three possibilities as elaborated above. For the most part these connections are based on the P&ID drawings which are made for the Damen ferry. In the input the sequential input is mainly used based on the P&ID drawings. In these drawings the lines can be followed for fuel oil: from for the tank - to the piping system - to the pump - to the engine - to the piping system - to the tank again. In this situation only the following connection is shown in the matrix and the connection after is not even though there is a cycle which groups the sub-systems into a system. This means that the setup of systems is not specifically taken into account and there are no separate fuel oil transfer system, cooling water system, gen-set system, etc. as elaborated in the P&ID drawings. The DSM therefore reviews the total connection between sub-systems and therefore separating system thinking into total 'system thinking' in order to possibly find better combinations or modules. Specifically it means that for a diesel generator it is possible that part of the cooling system, air supply and fuel supply might be combined into one module even though it consists of multiple systems.

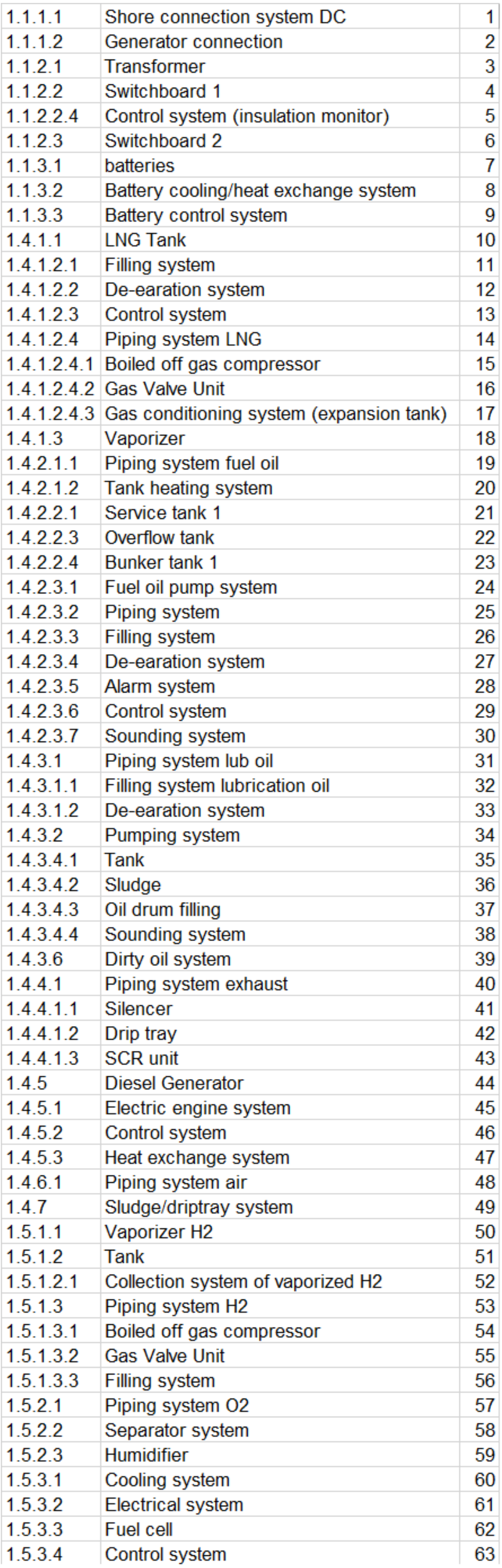
### 5.5.3. Final Design Structure Matrix

The final DSM including corresponding numbers is shown in Figure 5.12 and in a larger scale in Appendix D. This matrix includes only the sub-systems and the interactions between sub-systems. The translation of this matrix into workable data for the clustering algorithm is based on this and is shown in Appendix E. In the actual data all the lines are below each other. However, to show the results more compact they are shown in multiple columns. In this appendix the crosses in the table are shown as ones for existing connections. The rest of the matrix is filled in with zero's.



| | | | 1.1.1.1 | 1.1.1.2 | 1.1.2.1 | 1.1.2.2 | 1.1.2.2.4 | 1.1.2.3 | 1.1.3.1 | 1.1.3.2 | 1.1.3.3 | 1.4.1.1 | 1.4.1.2.1 | 1.4.1.2.2 | 1.4.1.2.3 | 1.4.1.2.4 | 1.4.1.2.4.1 | 1.4.1.2.4.2 | 1.4.1.2.4.3 | 1.4.1.3 | 1.4.2.1.1 | 1.4.2.1.2 | 1.4.2.2.1 | 1.4.2.2.3 | 1.4.2.2.4 | 1.4.2.3.1 | 1.4.2.3.2 | 1.4.2.3.3 | 1.4.2.3.4 | 1.4.2.3.5 | 1.4.2.3.6 | 1.4.2.3.7 | 1.4.3.1 | 1.4.3.1.1 | 1.4.3.1.2 | 1.4.3.2 | 1.4.3.4.1 | 1.4.3.4.2 | 1.4.3.4.3 | 1.4.3.4.4 | 1.4.3.6 | 1.4.4.1 | 1.4.4.1.1 | 1.4.4.1.2 | 1.4.4.1.3 | 1.4.5 | 1.4.5.1 | 1.4.5.2 | 1.4.5.3 | 1.4.6.1 | 1.4.7 | 1.5.1.1 | 1.5.1.2 | 1.5.1.2.1 | 1.5.1.3 | 1.5.1.3.1 | 1.5.1.3.2 | 1.5.1.3.3 | 1.5.2.1 | 1.5.2.2 | 1.5.2.3 | 1.5.3.1 | 1.5.3.2 | 1.5.3.3 | 1.5.3.4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 Shore connection system DC | 2 Generator connection | 3 Transformer | 4 Switchboard 1 | 5 Control system (insulation monitor) | 6 Switchboard 2 | 7 batteries | 8 Battery cooling/heat exchange system | 9 Battery control system | 10 LNG Tank | 11 Filling system | 12 De-earation system | 13 Control system | 14 Piping system | 15 Boiled off gas compressor | 16 Gas Valve Unit | 17 Gas conditioning system (expansion tank) | 18 Vaporizer | 19 Piping system supply fuel oil | 20 Tank heating system | 21 Service tank 1 | 22 Overflow tank | 23 Bunker tank 1 | 24 Fuel oil pump system | 25 Piping system transfer fuel oil | 26 Filling system | 27 De-earation system | 28 Alarm system | 29 Control system | 30 Sounding system | 31 Piping system lub oil | 32 Filling system lubrication oil | 33 De-earation system | 34 Pumping system | 35 Tank | 36 Sludge | 37 Oil drum filling | 38 Sounding system | 39 Dirty oil system | 40 Piping system exhaust | 41 Silencer | 42 Drip tray | 43 SCR unit | 44 Diesel Generator | 45 Electric engine system | 46 Control system | 47 Heat exchange system | 48 Piping system air | 49 Sludge/driptray system | 50 Vaporizer | 51 Tank | 52 Collection system of vaporized H2 | 53 Piping system H2 | 54 Boiled off gas compressor | 55 Gas Valve Unit | 56 Filling system | 57 Piping system O2 | 58 Separator system | 59 Humidifier | 60 Cooling system | 61 Electrical transport system | 62 Fuel cell | 63 Control system |
| 1.1.1.1 | Shore connection system DC | 1 |■|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.1.1.2 | Generator connection | 2 ||■|||||||||||||||||||||||||||||||||||||||||||X||||||||||||||||||||
| 1.1.2.1 | Transformer | 3 |||■|X|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.1.2.2 | Switchboard 1 | 4 |X|X||■|X||X||||||||||||||||||||||||||||||||||||||||||||||||||||||||X|||
| 1.1.2.2.4 | Control system (insulation monitor) | 5 ||||X|■|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.1.2.3 | Switchboard 2 | 6 |||X|||■|||||||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.1.3.1 | batteries | 7 ||||X|||■||X|||||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.1.3.2 | Battery cooling/heat exchange system | 8 ||||||||■|X|||||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.1.3.3 | Battery control system | 9 |||||||||■|||||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.1.1 | LNG Tank | 10 ||||||||||■|X||||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.1.2.1 | Filling system | 11 |||||||||||■||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.1.2.2 | De-earation system | 12 ||||||||||X||■||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.1.2.3 | Control system | 13 ||||||||||X|X|X|■||X|X||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.1.2.4 | Piping system LNG | 14 ||||||||||X||||■|||X|X|||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.1.2.4.1 | Boiled off gas compressor | 15 ||||||||||||||X|■|||||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.1.2.4.2 | Gas Valve Unit | 16 ||||||||||||||X|X|■||X|||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.1.2.4.3 | Gas conditioning system (expansion tank) | 17 ||||||||||||||X|||■|||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.1.3 | Vaporizer | 18 ||||||||||||||X||||■||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.2.1.1 | Piping system fuel oil | 19 |||||||||||||||||||■|X|X||||||||||||||||||||||||X|||||||||||||||||||||
| 1.4.2.1.2 | Tank heating system | 20 ||||||||||||||||||X|■|||||||||X||||||||||||||||||||||||||||||||||||
| 1.4.2.2.1 | Service tank 1 | 21 |||||||||||||||||||X|■||||X|X|||||||||||||||||||||||||||||||||||||||
| 1.4.2.2.3 | Overflow tank | 22 |||||||||||||||||||||■|||X|||||||||||||||||||||||||||||||||||||||
| 1.4.2.2.4 | Bunker tank 1 | 23 ||||||||||||||||||||X||■||X|X|||||||||||||||||||||||||||||||||||||||
| 1.4.2.3.1 | Fuel oil pump system | 24 ||||||||||||||||||||X||X|■|X||||||||||||||||||||||||||||||||||||||
| 1.4.2.3.2 | Piping system | 25 ||||||||||||||||||||X|X|X|X|■||||||||||||||||||||||||||||||||||||||
| 1.4.2.3.3 | Filling system | 26 ||||||||||||||||||||X||X|||■|||||||||||||||||||||||||||||||||||||
| 1.4.2.3.4 | De-earation system | 27 ||||||||||||||||||||X|X|X||||■||||||||||||||||||||||||||||||||||||
| 1.4.2.3.5 | Alarm system | 28 ||||||||||||||||||||X|X|X||X||■|||||||||||||||||||||||||||||||||||
| 1.4.2.3.6 | Control system | 29 |||||||||||||||||||||||||||X|■|X|||||||||||||||||||||||||||||||||
| 1.4.2.3.7 | Sounding system | 30 ||||||||||||||||||||X|X|X|||||||■|||||||||||||||||||||||||||||||||
| 1.4.3.1 | Piping system lub oil | 31 ||||||||||||||||||||||||||||||■|X||X|X||X|||||||X||||||||||||||||||||
| 1.4.3.1.1 | Filling system lubrication oil | 32 |||||||||||||||||||||||||||||||■|||X|||||||||||||||||||||||||||||
| 1.4.3.1.2 | De-earation system | 33 ||||||||||||||||||||||||||||||||■||X||||||||||||||||||||||||||||||
| 1.4.3.2 | Pumping system | 34 ||||||||||||||||||||||||||||||X|||■|X||X||||||||||||||||||||||||||||||
| 1.4.3.4.1 | Tank | 35 ||||||||||||||||||||||||||||||X||X||■||X||||||||||||||||||||||||||||||
| 1.4.3.4.2 | Sludge | 36 ||||||||||||||||||||||||||||||X|||X|X|■||||||||||||||||||||||||||||||
| 1.4.3.4.3 | Oil drum filling | 37 ||||||||||||||||||||||||||||||X||||||■||||||||||||||||||||||||||||
| 1.4.3.4.4 | Sounding system | 38 ||||||||||||||||||||||||||||||||||X|||■|||||||||||||||||||||||||
| 1.4.3.6 | Dirty oil system | 39 ||||||||||||||||||||||||||||||X|||||||■||||||||||||||||||||||||
| 1.4.4.1 | Piping system exhaust | 40 |||||||||||||||||||||||||||||||||||||||■|X|||X|||||||||||||||||||||
| 1.4.4.1.1 | Silencer | 41 |||||||||||||||||||||||||||||||||||||||X|■||X||||||||||||||||||||||
| 1.4.4.1.2 | Drip tray | 42 |||||||||||||||||||||||||||||||||||||||X||■|||||||||||||||||||||
| 1.4.4.1.3 | SCR unit | 43 |||||||||||||||||||||||||||||||||||||||X|||■|X|||||||||||||||||||||
| 1.4.5 | Diesel Generator | 44 |||||||||||||X||X|||X||||||X||||||X|||X||||||||||■|X|X||X|||||||||||||||||
| 1.4.5.1 | Electric engine system | 45 ||||X||||||||||||||||||||||||||||||||||||||||X|■||||||||||||||||||
| 1.4.5.2 | Control system | 46 |||||||||||||||||||||||||||||||||||||||||||||■|||||||||||||||||
| 1.4.5.3 | Heat exchange system | 47 |||||||||||||||||||||||||||||||||||||||||||X|||■||||||||||||||||
| 1.4.6.1 | Piping system air | 48 |||||||||||||||||||||||||||||||||||||||||||||||■|||||||||||||||
| 1.4.7 | Sludge/driptray system | 49 ||||||||||||||||||X|X|X||X|||X|X||||||||||X||||||||||||||■|||||||||||||||
| 1.5.1.1 | Vaporizer H2 | 50 |||||||||||||||||||||||||||||||||||||||||||||||||■|X|||||||||||||
| 1.5.1.2 | Tank | 51 ||||||||||||||||||||||||||||||||||||||||||||||||||■||||||X|||||||||
| 1.5.1.2.1 | Collection system of vaporized H2 | 52 ||||||||||||||||||||||||||||||||||||||||||||||||||X|■|||||||||||
| 1.5.1.3 | Piping system H2 | 53 |||||||||||||||||||||||||||||||||||||||||||||||||X|X|X|■|X||||||||||
| 1.5.1.3.1 | Boiled off gas compressor | 54 ||||||||||||||||||||||||||||||||||||||||||||||||||X|||■|||||||||
| 1.5.1.3.2 | Gas Valve Unit | 55 |||||||||||||||||||||||||||||||||||||||||||||||||X||||X|■||||||||
| 1.5.1.3.3 | Filling system | 56 |||||||||||||||||||||||||||||||||||||||||||||||||||||||■|||||||
| 1.5.2.1 | Piping system O2 | 57 ||||||||||||||||||||||||||||||||||||||||||||||||||||||||■||||||
| 1.5.2.2 | Separator system | 58 |||||||||||||||||||||||||||||||||||||||||||||||||||||||X||■|||||
| 1.5.2.3 | Humidifier | 59 ||||||||||||||||||||||||||||||||||||||||||||||||||||X||||X|X|■|||||
| 1.5.3.1 | Cooling system | 60 ||||||||||||||||||||||||||||||||||||||||||||||||||||||||||X|■||||
| 1.5.3.2 | Electrical system | 61 ||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||■|X|X|
| 1.5.3.3 | Fuel cell | 62 ||||||||||||||||||||||||||||||||||||||||||||||||||||||X||X|||X||■||
| 1.5.3.4 | Control system | 63 |||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||X|■|

Figure 5.12: Design Structure Matrix



| | | |
|---|---|---|
| 1.1.1.1 | Shore connection system DC | 1 |
| 1.1.1.2 | Generator connection | 2 |
| 1.1.2.1 | Transformer | 3 |
| 1.1.2.2 | Switchboard 1 | 4 |
| 1.1.2.2.4 | Control system (insulation monitor) | 5 |
| 1.1.2.3 | Switchboard 2 | 6 |
| 1.1.3.1 | batteries | 7 |
| 1.1.3.2 | Battery cooling/heat exchange system | 8 |
| 1.1.3.3 | Battery control system | 9 |
| 1.4.1.1 | LNG Tank | 10 |
| 1.4.1.2.1 | Filling system | 11 |
| 1.4.1.2.2 | De-earation system | 12 |
| 1.4.1.2.3 | Control system | 13 |
| 1.4.1.2.4 | Piping system LNG | 14 |
| 1.4.1.2.4.1 | Boiled off gas compressor | 15 |
| 1.4.1.2.4.2 | Gas Valve Unit | 16 |
| 1.4.1.2.4.3 | Gas conditioning system (expansion tank) | 17 |
| 1.4.1.3 | Vaporizer | 18 |
| 1.4.2.1.1 | Piping system fuel oil | 19 |
| 1.4.2.1.2 | Tank heating system | 20 |
| 1.4.2.2.1 | Service tank 1 | 21 |
| 1.4.2.2.3 | Overflow tank | 22 |
| 1.4.2.2.4 | Bunker tank 1 | 23 |
| 1.4.2.3.1 | Fuel oil pump system | 24 |
| 1.4.2.3.2 | Piping system | 25 |
| 1.4.2.3.3 | Filling system | 26 |
| 1.4.2.3.4 | De-earation system | 27 |
| 1.4.2.3.5 | Alarm system | 28 |
| 1.4.2.3.6 | Control system | 29 |
| 1.4.2.3.7 | Sounding system | 30 |
| 1.4.3.1 | Piping system lub oil | 31 |
| 1.4.3.1.1 | Filling system lubrication oil | 32 |
| 1.4.3.1.2 | De-earation system | 33 |
| 1.4.3.2 | Pumping system | 34 |
| 1.4.3.4.1 | Tank | 35 |
| 1.4.3.4.2 | Sludge | 36 |
| 1.4.3.4.3 | Oil drum filling | 37 |
| 1.4.3.4.4 | Sounding system | 38 |
| 1.4.3.6 | Dirty oil system | 39 |
| 1.4.4.1 | Piping system exhaust | 40 |
| 1.4.4.1.1 | Silencer | 41 |
| 1.4.4.1.2 | Drip tray | 42 |
| 1.4.4.1.3 | SCR unit | 43 |
| 1.4.5 | Diesel Generator | 44 |
| 1.4.5.1 | Electric engine system | 45 |
| 1.4.5.2 | Control system | 46 |
| 1.4.5.3 | Heat exchange system | 47 |
| 1.4.6.1 | Piping system air | 48 |
| 1.4.7 | Sludge/driptray system | 49 |
| 1.5.1.1 | Vaporizer H2 | 50 |
| 1.5.1.2 | Tank | 51 |
| 1.5.1.2.1 | Collection system of vaporized H2 | 52 |
| 1.5.1.3 | Piping system H2 | 53 |
| 1.5.1.3.1 | Boiled off gas compressor | 54 |
| 1.5.1.3.2 | Gas Valve Unit | 55 |
| 1.5.1.3.3 | Filling system | 56 |
| 1.5.2.1 | Piping system O2 | 57 |
| 1.5.2.2 | Separator system | 58 |
| 1.5.2.3 | Humidifier | 59 |
| 1.5.3.1 | Cooling system | 60 |
| 1.5.3.2 | Electrical system | 61 |
| 1.5.3.3 | Fuel cell | 62 |
| 1.5.3.4 | Control system | 63 |

Figure 5.13: DSM element definition with corresponding numbers

## 5.6. Working of the algorithm

The Matlab code which is used is made by R.E. Thebeau and is presented by Mortl [70] which was developed in December 2000. The method itself is usable and works but during the years improvements are made by other designers that refined the method. However, these improvements are made in individually owned programs and are not publicly available. For this reason the original Matlab code is used. Further improvements are possible to be made according to Fredrik Borjesson [43] and Damasi et al. [25]. This way the clustering is done to an optimum instead of the current situation which is based on an amount of improvements made. This means that the solution can be stuck on a local optimum and therefore the global optimum is not found. And due to time restrictions the code is not improved, but the code is run multiple times to find a general combination of clusters.

It is important to know that the solution of the algorithm is not necessarily the solution for modules. The input and physical design have a large influence on the feasibility for the clusters. This means that the result of the clusters give input for the potential modules but do not necessarily define the modules themselves. Therefore it is acceptable for the solution not to be optimal and multiple solutions might give more insight in the potential modules. For instance in one solution there could be a cluster made of 6 sub-systems where in another solution these 6 sub-systems can be divided into 2 clusters. In the definition of the modules due to the physical design the two clusters might be a better solution than the one.

The clustering which is done in the Matlab code is the work which is done in the DSM to analyse the results. The clustering is a form of partitioning analysis that reorders the rows and columns to group the sub-systems according to the objective to minimize interactions between clusters in order to obtain potential modules. Even though an important heuristic is to choose modules to be as independent as possible it is common in complex systems to have both modular and integrative sub-systems. Meaning that interactions cannot be excluded completely between modules.

**Clustering algorithm**

For the working of the clustering there is a number of functions and parameters. The functions describe the way the clustering works and the parameters are the values which are used in the functions to tune the functions in order to optimize the results. These parameters are elaborated in Appendix F. There are a number of functions which are used for the clustering meaning that they describe the actual mathematical working of the algorithm. These functions are the core of the algorithm and therefore do require some elaboration. To elaborate on the working of the functions, the flowchart of the algorithm is shown in Figure 5.14. Next to these functions there are also presenting functions which are used for plotting the new DSM including the potential clusters. However, these functions are not elaborated in this report.

Next to the functions simulated annealing is used to find the optimal solution for the DSM. The simulated annealing is defined by calculating the total coordination cost if the selected element would be included in a cluster with the highest bid. Meaning that the element is included in a cluster if it seems to be the best option after which the costs are calculated. After this at a random time, between 1 and 2 times the cluster size, a new coordination cost is chosen which is the second highest bid rather than the highest bid. This means a less then optimal cluster combination solution than the current solution. After which the optimization is continued where a new optimal solution can be found if possible. The combination of these two steps is the simulated annealing where the second part is implemented not to get stuck on a local optimum and therefore not reaching the optimal solution.

***Bid function***

The bid function shown in Equation 5.1 calculates the bids from an element to each of the possible clusters or groups of elements. Then for each element in the cluster where there is an interaction with the selected element, the number of interactions is added with the selected element. This number of interactions is then used to calculate the bid. This is done for off diagonal interactions as the elements cannot interact with themselves. Specifically it means that the interactions between the elements have different costs for being in a cluster or outside a cluster. These costs are calculated to calculate the 'bid' which is a suggested solution.

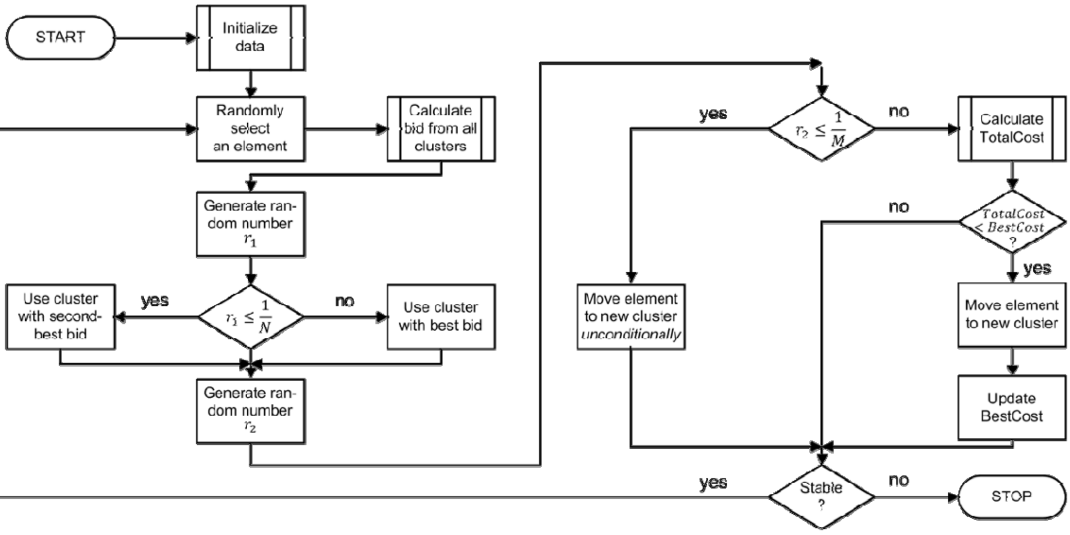


Figure 5.14: Flowchart of the original clustering algorithm used in Thebeau [92] shown in Fredrik Borjesson [43]

$$ClusterBid_j = \frac{(inout)^{powdep}}{(ClusterSize_j)^{powbid}} \tag{5.1}$$

| | | |
|---|---|---|
| *j* | = | *Cluster number* |
| *ClusterBid$_j$* | = | *Bid from Cluster j for the chosen element* |
| *inout* | = | *The sum of the DSM interactions of the chosen element with each of the elements in cluster j* |
| *powdep* | = | *Exponential to emphasize high interactions* |
| *powbid* | = | *Exponential to penalize size of large clusters* |

### ***Cluster function***

The cluster function is to cluster the elements of a matrix meaning to propose a solution of combined clusters. The objective is to find the solution which has the lowest costs. As elaborated in the parameters there are costs for interactions outside of clusters which are high and lower costs for interactions inside clusters. Also the costs of the cluster size are taken into account here. The clustering itself is done along the diagonal of the matrix to follow the elements in the DSM. After each bid an array is made to hold the cost history to be able to compare the costs.

### ***Coordination costs***

This function checks all the DSM interactions that are defined. It is possible for an interaction to be contained in more than one cluster. This means that this interaction between clusters has to be added. Also if an interaction is not contained in any cluster, a higher cost/penalty is assigned as the goal is to find all clusters instead of loose elements. This function also duplicates elements in the case that they are in more than one cluster. This means that the new matrix then has the same separate elements. However, this is done to be able to assign the penalty to the element. Finally the total costs of the clustering are calculated and stored. The mathematical functions used for the calculation are shown below in equations 5.2, 5.3 and 5.4 originating from Thebeau [92] based on Gutierrez [47].

For the interaction between element j and k within a cluster:

$$IntraClusterCost = (DSM(j,k) + DSM(k,j)) * ClusterSize(y)^{powcc} \tag{5.2}$$

For the interaction between element j and k outside of a cluster:

$$ExtraClusterCost = (DSM(j,k) + DSM(k,j)) * DSMSize(y)^{powcc} \tag{5.3}$$

Resulting in the total cost of:

$$TotalCost = \sum IntraClusterCost + \sum ExtraClusterCost \tag{5.4}$$

| | | |
|---|---|---|
| *TotalCost* | = | *Coordination Cost* |
| *IntraClusterCost* | = | *Cost of interaction which occurs within a cluster* |
| *ExtraClusterCost* | = | *Cost of interaction which occurs outside of any cluster* |
| *DSM(j,k), DSM(k,j)* | = | *DSM interactions between element j & k and k & j* |
| *ClusterSize(y)* | = | *Number of elements in the DSM* |
| *powcc* | = | *Parameter for penalizing the cluster size* |

***Delete Clusters function***

There is the possibility for duplicate clusters or clusters within clusters. This function deletes those clusters. In the case that clusters are equal or if one cluster is contained in another, the one contained is deleted. This function also deletes possible empty clusters.

***Find Cluster Matches function***

This function is to find matching clusters during different runs using the clustering algorithm.

***Get Match avg function***

The function to calculate bids from clusters for the selected element where each cluster bids for a selected element based on the defined parameters.

***Removal of entries or elements***

An important aspect in the working of the algorithm is that clusters are driven by entries or elements which have a high number of interactions between elements. The algorithm is made such that it allows for the removal of elements but for clustering purposes only meaning that these elements cannot be included in clusters. The elements are introduced again in the clustered DSM on the outside edges which means that the elements are included in the final result as the interactions do influence the results. The practical use for this is that a decision is made that certain elements should not be in a cluster based on the requirements for that element. For instance a switchboard can be seen as a system in itself and is a connection point to almost all systems. However, as it is such a central system it is not possible to include it in a cluster as it would either create an inclusive system which was chosen not to use. It would be inclusive as the minimization of interactions would result in including all the interacting elements of that element. This results in a cluster with a large number of elements which means an inclusive system. The other possibility is not to include connecting elements in the cluster and the interaction between the formed clusters then is not minimized which means that the modules will most likely not work or be come more complex.

**Outside cluster interactions**

The interaction outside clusters represent the interaction between clusters. This data is important as well as the interactions represent possible architecture decisions. Specifically it means that for these interactions it is possible to define or develop standard interfaces. Interactions between clusters are not owned by the cluster but the interactions represent the interface between two clusters or system elements. This means that they can cause conflicts between clusters and should be managed carefully for this reason. Again the purpose of clustering is to minimize external interactions between clusters or to even eliminate interactions. This means that after the clustering analysis should be done to understand the interactions and to be able to possible improve the design to improve or eliminate interfaces within a cluster.

### 5.6.1. Risk of using the algorithm

When using the DSM form all system information is put in one matrix together with the interactions. As stated in literature this is an expert method for which the input has to be reliable. However, the larger the matrix, the higher the chance of mistakes in the connections as well as input mistakes. This means that a mistake has a large influence on the results therefore requiring the evaluation of results as well as a thorough check of the input. This became apparent during evaluation of the first run results. Where in the first run there was a mistake in the input regarding a sub-system which meant that the matrix had to be adapted and connections had to be changed.

## 5.7. Analysis of the DSM input data

The results of the analysis of the clustering for the multiple configurations are shown in Appendix G. The first aspect that becomes clear when reviewing the results is that a selection of sub-systems is grouped in a cluster but not all elements are grouped besides the excluded ones. Based on the interactions the DSM clustering shows that a full clustering would give a less optimal solution. Without analyzing the results any further this would mean that the sub-systems in the vessel would not necessarily fit within a module. The aspect influencing the results of the clustering are based on the exclusion of sub-systems, the system configuration setup and the determination of the amount of runs.

### 5.7.1. Exclusion of sub-systems or elements

In running of the algorithm it is possible to exclude elements from the actual clustering as elaborated in the previous paragraph. The reason for excluding elements is that within the DSM there are elements which drive the integration of a cluster. This means that this element has a large number of interactions across the row or column or both which result in the making of a cluster based on this element alone. Specifically it means that one element with its interactions defines the cluster. Next to this it also often is that the other elements within these clusters have little or don't have any interactions with each other. For this reason the algorithm was modified by Thebeau [92] to be able to remove such elements. The addition to the code showed improved results on multiple areas which are elaborated in the work of Thebeau [92]. The results of the change were:

1. The likeness measurement increased for the clusters which means that the resulting clusters become more consistent.
2. The interactions increased within the clusters and the interaction outside or between clusters decreased.
3. The clusters became much more identifiable which means that the clusters became better potential modules. The identification is that the sub-systems could be grouped more understandably and technical feasible.

In this research a number of entries are removed from the clustering. These are Switchboard 1 and 2, the control and alarm systems. The numbers used for the elements which are used below are based on the DSM as shown in Figure 5.12 and 5.13. The removed elements below apply to all the cases in the clustering and the specific excluded elements are:

- Number 4 and 6 which are Switchboard 1 and 2. The reason for this is that these sub-systems are the connecting elements for multiple other elements which have no or almost no interaction with each other for which the exclusion was designed in the algorithm. This is based on the designed function for removal of elements as elaborated in Chapter 5.6

- Number 9 which is the battery control system. This element was excluded as this element can be seen as implemented in the battery modules themselves or to be seen as relatively separate. When using variable interactions this interaction could be used again using a low value interaction.

- Number 28 and 29, 46 and 63 which are the alarm and control system of the fuel oil system, the control system of the diesel generator and the control system of the fuel cell. Again these elements had a significant influence on the clustering due to the use of the binary interaction. As these connections are of low level and the high influence of these elements on the clustering they were excluded for the clustering. Again when using a variable interaction valuation these elements could be implemented in the clustering again.

Also already elaborated is that the power supply is not fully defined. Taking the example used in Thebeau [92] power supplies are represented as a single element as most sub-systems have their own power supply or share power supply with some other sub-systems. By implementing the power supply in a single element it is possible to reconfigure the power supply to meet the architecture of the clustering. Once clustering is finished power supply can be broken down more detailed to fit into clusters and each cluster can potentially have a section of the power supply. The main reason why the power supply was not included in the first place was that it caused clusters to form with elements that were not related or had only little interaction with each other. This also is similar to the motion controller and safety system which have interfaces with multiple elements. Important to know is that it is common practice to move DSM elements that have many entries to the outside of the DSM.

A visualization of the reasoning behind the exclusion is done using a simplified schematic drawing of the electrical system for the 9819 E3 ferry shown in Figure 5.15. In this figure the connections between the elements are shown by the lines connecting the elements. The main DC switchboard shows to have a significant amount of connections to separate sub-systems which have no interaction between the other sub-systems. By including the switchboard in the algorithm a module could be formed only based on the connections of the switchboard. However, as the sub-systems have no interaction it means that it is not an effective potential module due to the low level of interactions.

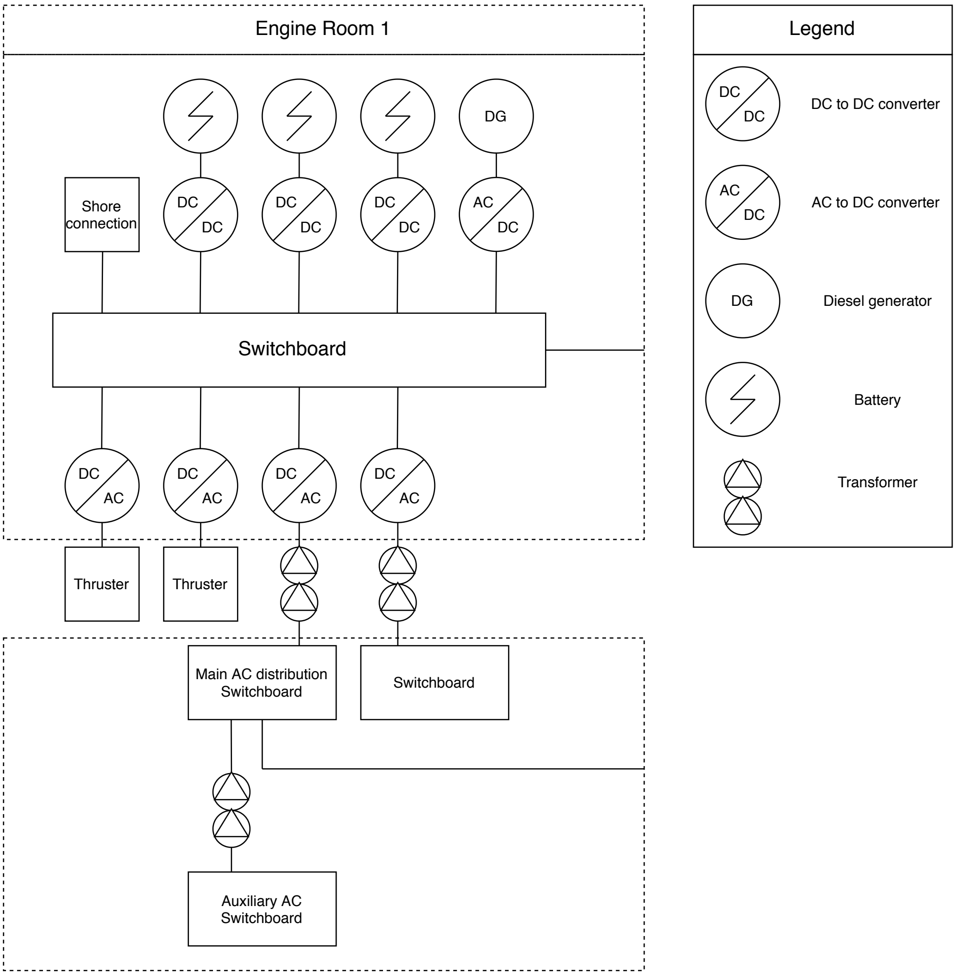


Figure 5.15: Simplified schematic single line diagram of the electrical system for the 9819 E3 ferry adapted from Ghiran [46]

### 5.7.2. Energy storage and conversion configurations

The Matlab code was run for 5 possible system configurations being the defined four configurations and a combination of all the configurations. With this approach the first configuration excludes the above defined elements. From there extra elements are excluded for the different configurations. The running of 5 configurations is done for two reasons.

The first reason being that there are multiple energy storage and conversion systems which cannot all be used in the same vessel. This means that each of the configurations can be used as a single solution in the vessel. Based on this reason it is possible to make different DSM's for all of the configurations. However, next to the configurations to be working separately it is also possible to implement the configurations in a parallel way. For instance a combination of the diesel configuration and the battery configuration. In this situation the module solutions have to work parallel and should not interfere with each other.

The second reason for the configurations is the future proof aspect in the design of the vessels. When designing modular the goal is to design modules as independently as possible[33] meaning that they don't affect other modules. This way when a system is changed to another configuration the effect of the change is technically feasible by changing only the modules for which the change is required and not influencing other modules. This is the advantage of modular design as changes to the system only affect the modules for which the change is required and redesigning or adaptions can be minimized. Specifically it means that modules can work together in parallel or even in series and when changes are made to a module it does not effect the other modules. Therefore the interchangeability of the modules is increased.

The implication of defining the modules as independently as possible is visualized in Figure 5.16. This figure shows a simplified diesel and battery configuration based on modules. When combining the two configurations in a hybrid configuration it shows that the switchboard module and the cooling systems overlap. When designing the modules completely independent it means that only these modules have to be changed and all the other systems can remain constant. However, this is only possible if the modules have the same boundaries for each of the configurations. And this is then the goal of using the different configurations and finding module solutions which are similar for all configurations.

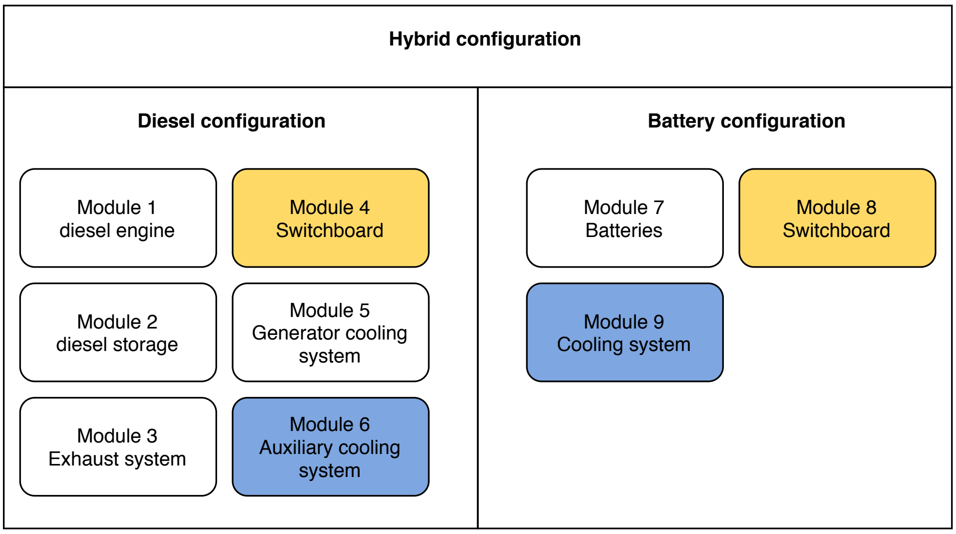


Figure 5.16: Simplified visualization of a combination of a diesel and battery configuration using modules combined into a hybrid configuration

The five configurations in combination with the specification for the excluded elements are:

1. The DSM which includes ***all the entries*** except for entries 4, 6, 9, 28, 29, 46 and 63. These items are the switchboards, control and alarm systems. As elaborated before the electric system of which these entries are part is not totally included in the DSM. Also as these systems can have a relatively flexible installation, the clustering would be affected when they are included. The switchboards are important systems that connect all the vessel systems. As these have a connection to all, they are seen as a basis and therefore are not included in the clustering.

2. The second configuration is a vessel configuration consisting of a ***diesel and battery configuration***. This is one of the possible vessel configurations which is built and could give other clustering possibilities. The assumption is this case is also that batteries are always required whether it is only for starting the systems or sailing on battery power. The elements which are now not included in the DSM are 4, 6, 9-18, 28, 29, 46 and 49-63.

3. The third configuration is the ***dual fuel engine together with batteries***. In this configuration LNG is added to the configuration with respect to the second configuration. The elements which are now not included in the DSM are 4, 6, 9, 28, 29, 46 and 49-63.
4. The fourth configuration is the combination of ***hydrogen and batteries***. This is a future configuration with the fuel cell and the batteries as support for peak shaving etc. The elements which are now not included in the DSM are 4, 6, 9-49 and 63.
5. The fifth configuration is the ***fully electric*** configuration where only batteries are included. In this configuration only the elements 1 to 9 are included where the rest is excluded.

### 5.7.3. Determination of amount of runs

As elaborated in Chapter 5.6 the algorithm is run multiple times for the different configurations. The determination of an amount of runs is required as the algorithm does not find the optimum solution but works by a defined amount of improvement iterations using random solutions. Based on the defined parameters the minimum amount of runs for one configuration is set to 5. However, for the minimum amount of runs there are conditions to the results which have to be met else the amount of runs is increased. The conditions are:

- The results of the configuration run show a similar cost result.
- The cluster result show no double elements in the results.
- The size of the clusters remain similar being that there are no large differences in the cluster composition results.

If the conditions are not met by the results an increase of the amount of runs is required. A first evaluation of the results is done by comparing the cost results of the solution. The algorithm works towards minimizing the cost of the clustering solution. Specifically this means the combination of sub-systems in groups which are called potential modules. If the costs of the results are similar it is likely that the results are similar. Often the higher costs are connected to the solutions with multiple double elements which is penalized by the algorithm and is elaborated in the second condition.

The second condition is the double elements in the solution. In the algorithm it is possible for an element or specifically a sub-system to be in two different modules. However, in practice this means that the sub-system is defined double meaning that there are two of that sub-system. This is not possible meaning that the result is not totally feasible. Therefore it is required to run the algorithm for more than the minimal amount of runs to increase the feasibility of the grouping results. This example is seen in Table 5.3 for cluster 2b and 3b.

For the third condition the size of the clusters is evaluated. In the situation that for instance a cluster is combined in one solution but not in the other means that there may be a difference in the grouping. This difference can be only once in many solutions or can be a more accepted result. For this reason extra runs are required to improve the quality of the results.

## 5.8. Potential clustering results based on the five configurations

Based on the 5 configuration possibilities for each of the configurations a grouping is made for the clusters. As the fifth configuration of a fully electric system did not result in feasible clusters the clustering results are based on the first four configurations. The cluster results are shown as numbers which are also shown in the DSM in Appendix D. For the grouping there were results where there was one large cluster and in other result showed the larger cluster into two or more smaller clusters which can be named sub-clusters.

The cluster results shown in the appendix are not the results from the Matlab algorithm but are made into tabular form for a better overview. To elaborate on the results from the algorithm three different solutions are showed.

Figure 5.17 is a solution which has large clusters with relatively little interactions. Taking into account that multiple elements are not taken into account as elaborated in Chapter 5.7. The little interaction between the clusters shows that the main interaction is inside the clusters.

The second figure is Figure 5.18 for the hydrogen with battery configuration. On the first glance it looks as a bad solution as there are many outside interactions and only 3 clusters. However, for this configuration even more elements are excluded which means that the result which is shown here is a good result.

Figure 5.19 shows the worst cost solution of all the runs. In this situation all the elements, besides the standard excluded ones, are included in the clustering. However, the interaction between clusters is significant. This is mainly due to the amount of double elements in the solution which are 4 elements in this run. These figures also show that based on the results alone no potential modules can be defined. For this reason a second level of decision making is required to be able to define potential modules.

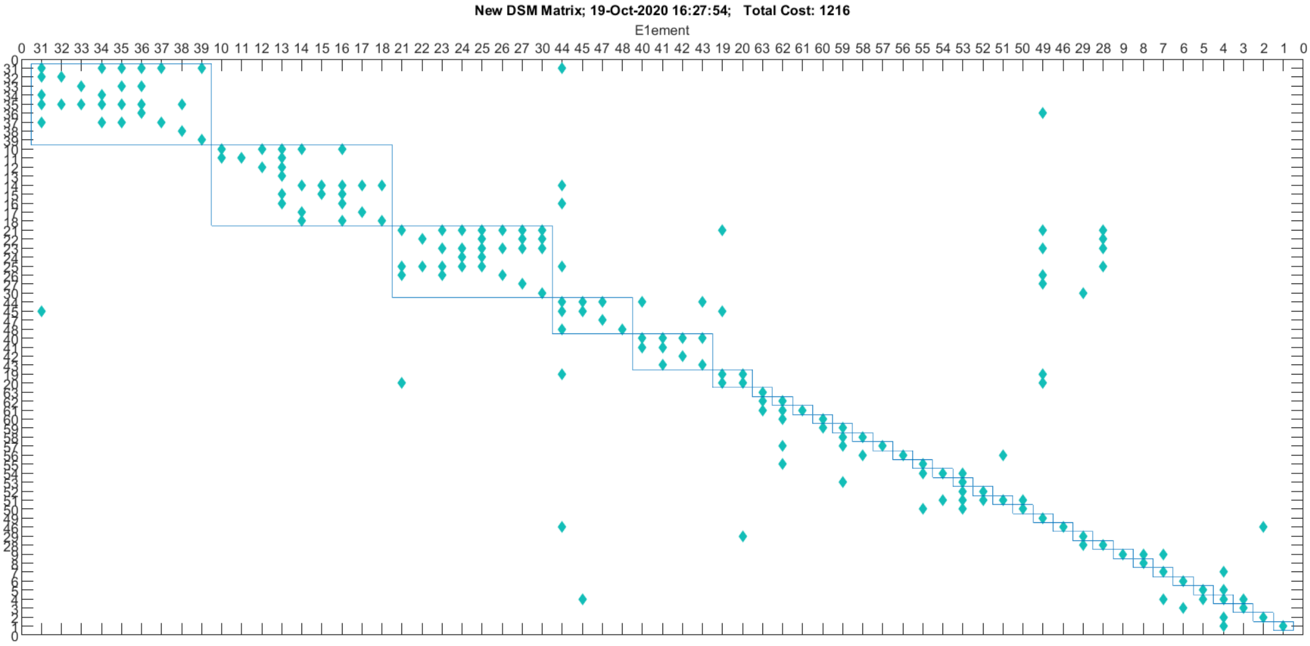


Figure 5.17: Run 18 using all the system configurations; having large clusters, little outside interactions and a total cost of 1216

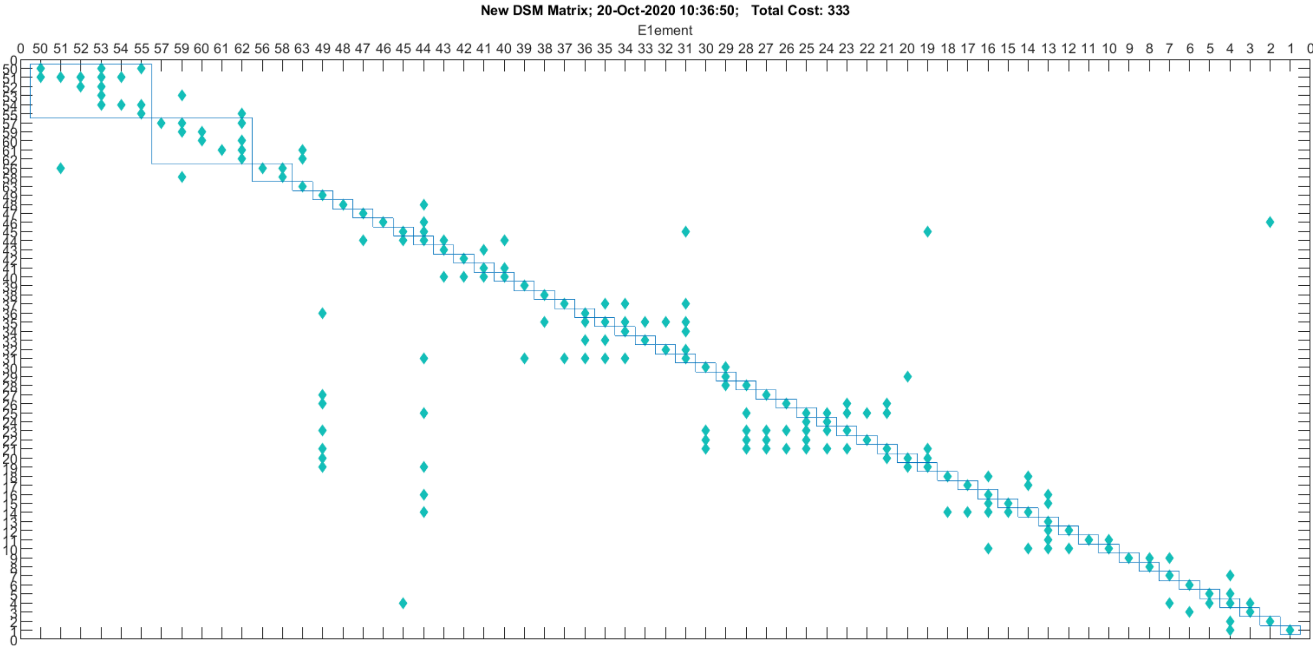


Figure 5.18: Run 20 using the battery with hydrogen system configuration; using having two main clusters, little outside interactions and a total cost of 333

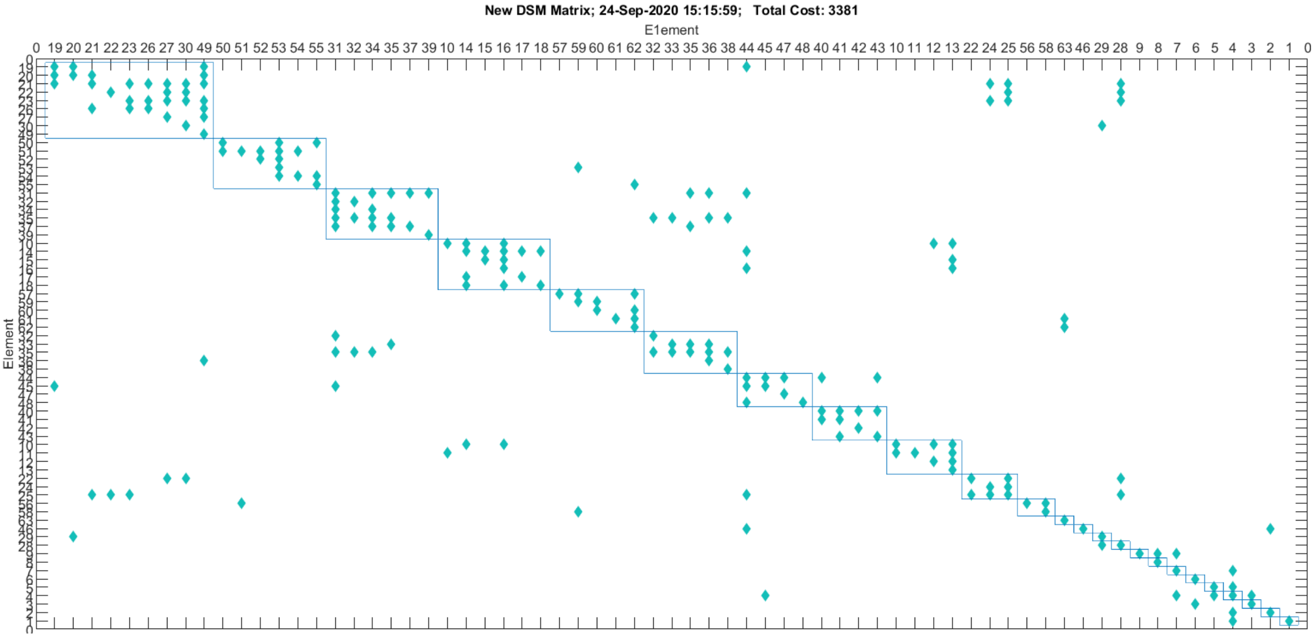


Figure 5.19: Run 2 using all the system configurations; having medium clusters, multiple outside interactions and a total cost of 3381

### 5.8.1. Clustering results

Potential sub-system groupings are all the clusters which are shown in Appendix G. From this selection it is possible to evaluate the clusters and to make a selection for the potential feasible clusters taking into account the workability for all configurations. A combination is made from the results into a smaller selection of potential modules which is also shown in Appendix G in Tables G.1 to G.3.

#### First result refinement

Table 5.3 shows the cluster results where there is the possibility for a sub-cluster. In this table there are orange values for the case that an element is found in two clusters. This is not feasible in reality but is in the clustering algorithm. Next to this multiple runs are done which means there are multiple cluster possibilities. The results shown in the table are a combination of these runs where the blue values are elements which are present in one run and absent in another. When determining feasible modules these elements can be omitted if this configuration would be better feasible. The specific clusters are all found in specific runs where below the cluster the run is defined in which the resulted cluster can be found. The overview of all the clustering results of the different runs is shown in Appendix G in section G.1 to G.4. The reduced potential modules shown in Table 5.3 is a combination of clusters based on section G.5. The reduced amount of clusters is a combination of all the generated results based on the different configurations. This is the first level of decision making and refining after acquiring the results.

Table 5.3: Clustering results based as a result of the clustering algorithm of Thebeau [92] and combining the four defined configurations using the DSM as shown in Figure 5.12 and 5.13

| **Cluster** | **1a** | **1b** | **2a** | **2b** | **2c** | **2d** | **3a** | **3b** | **3c** | **4** | **5** | **6a** | **7a** | **8a** | **6/7/8 b** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 10 | 10 | 21 | 22 | 21 | 19 | 31 | 32 | 31 | 44 | 40 | 50 | 57 | 56 | 56 |
| | 11 | 11 | 22 | 23 | 23 | 20 | 32 | 33 | 32 | 45 | 41 | 51 | 59 | 58 | 58 |
| | 12 | 12 | 23 | 24 | 26 | | 33 | 35 | 34 | 47 | 42 | 52 | 60 | | 59 |
| | 13 | 13 | 24 | 25 | 27 | | 34 | 36 | 37 | 48 | 43 | 53 | 61 | | 60 |
| **Elements** | 14 | | 25 | 30 | 30 | | 35 | 38 | 38 | | | 54 | 62 | | |
| | 15 | 14 | 26 | | 22 | | 36 | | 39 | | | 55 | | | 57 |
| | 16 | 15 | 27 | 21 | 24 | | 37 | 31 | | | | | | | 61 |
| | 17 | 16 | 30 | 23 | 25 | | 38 | 32 | 33 | | | | | | 62 |
| | 18 | 17 | 19 | 26 | | | 39 | 34 | 36 | | | | | | |
| | | 18 | 20 | 27 | | | | 37 | | | | | | | |
| | | | 49 | 49 | | | | 39 | | | | | | | |
| | | | | 30 | | | | | | | | | | | |
| **Run** | 13 | 15 | 3,4, 5 | 11 | 27 | 11, 26 | 18, 27 | 17, 16 | 10 | 15, 16 | 15, 16 | 20, 25 | 20, 25 | 20, 25 | 21 |

### 5.8.2. Interaction results

Based on these results it is not possible to evaluate combination of sub-systems. As elaborated in Chapter 4.3 the driving force of a module is the high interaction within the cluster and the minimized interaction between or outside clusters. For this reason the next step is to analyze the interactions which can also be found in the clustering figure results. To be able to assess the results as objectively as possible the decision is made to keep the results abstract and to not translate the numbers to the corresponding sub-systems. This way no value is attached to the results yet.

When analyzing the results the numbers 28, 29, 46 and 63 are excluded due to the low interaction influence as elaborated before. The second column in Table 5.4 are the number of interactions outside the cluster between other clusters or to individual elements. The third column in the table shows the interactions where overlapping interactions are combined to one interaction. Meaning that for instance within one cluster there is a connection between element 10 & 13, 11 & 13 and 12 & 13. In this situation this interaction is defined as one interaction as it might be possible to group these connections. However, this grouping does require proof of success. The specific interactions are elaborated in the appendix in Appendix G in Tables G.5 and G.6.

The interactions can be found in the DSM but are abstract and are not grouped making it hard to understand. The interactions between or outside clusters is shown in Figure 5.20. In this figure there are two clusters which have interactions. Based on the expected DSM results number 14 interactions would read that element 14 has input from number 44 and output to number 10. However, for the results the interactions are the other way around which means that number 14 has output to number 44 and input from number 10. This is important in reading and understanding the results.

Table 5.4: Interaction between and outside clusters

| **Cluster** | **Interactions** | **Interactions combined** |
|---|---|---|
| **1a** | 2 | 1 |
| 1b | 10 | 7 |
| **2a** | 10 | 6 |
| 2b | 21 | 16 |
| 2c | 22 | 13 |
| 2d | 5 | 5 |
| **3a** | 3 | 3 |
| 3b | 15 | 10 |
| 3c | 11 | 10 |
| 4 | 11 | 11 |
| **5** | 2 | 1 |
| **6a** | 3 | 3 |
| **7a** | 3 | 3 |
| **8a** | 2 | 2 |
| **6/7/8 b** | 7 | 7 |

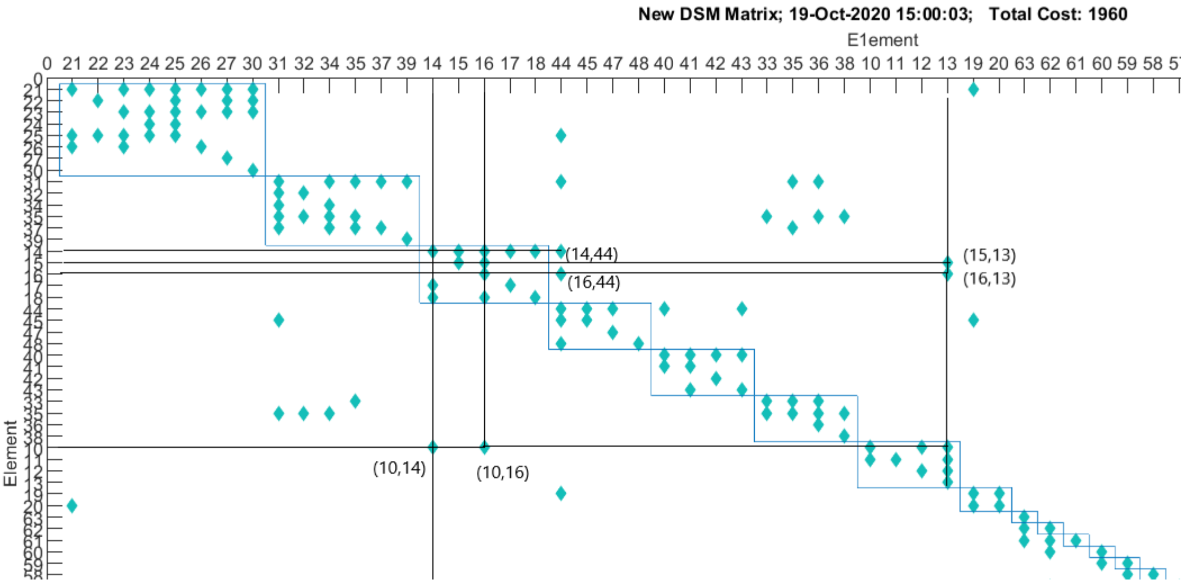


Figure 5.20: Elaboration of outside cluster interactions shown from section of clustering result of run 15 using the diesel and battery configuration

### 5.8.3. Translation and evaluation of cluster options based on technical feasibility

The first approach within this step is to translate the numbers to sub-systems to be able to understand the cluster groups which are the result of the algorithm. After this visualization the options with the lowest amount of interactions are evaluated in the first option for cluster possibilities. The technical feasibility is based on the complexity due to the size as elaborated in Chapter 4.2.2 and feasibility based on technical knowledge of the systems including the definition of system flows[57] elaborated in Chapter 4.3.

#### Space allocation and limitation

The starting point in the technical feasibility is the space allocation definition. Specifically it means the separation evaluation of the systems as there can be requirements with regard to the space in which a sub-system can be located. This is roughly visualized in Figure 5.21. This figure shows half of the General Arrangement (G.A.) of the 9819 E3 ferry of the tank top level. In this figure there are four main rooms in which sub-systems of the energy storage and conversion system are located. The vessel is symmetrical with regard to the engine room, battery room and switchboard room where there is a difference in machinery in the engine rooms with regard to non-redundant systems.

1. The battery room is a separate room from other systems which means that there is a physical separation with other systems as well as the other battery room. The separation of the two battery rooms is to provide redundancy in the case of an accident or malfunction for instance.
2. The switchboard room is also a separate room from other systems which also means a physical separation with other systems as well as the redundancy requirement of this system with a similar room at the other side of the vessel.
3. The engine room is designed redundant with regard to the diesel generator, the fuel oil storage and the exhaust systems. Other systems which require no redundancy are either located in the first or second engine room.
4. The final room is the machinery room in which lubrication oil, dirty oil and coolant are stored. The storage of these fluids is outside of the machinery room due to separation requirements of the systems.

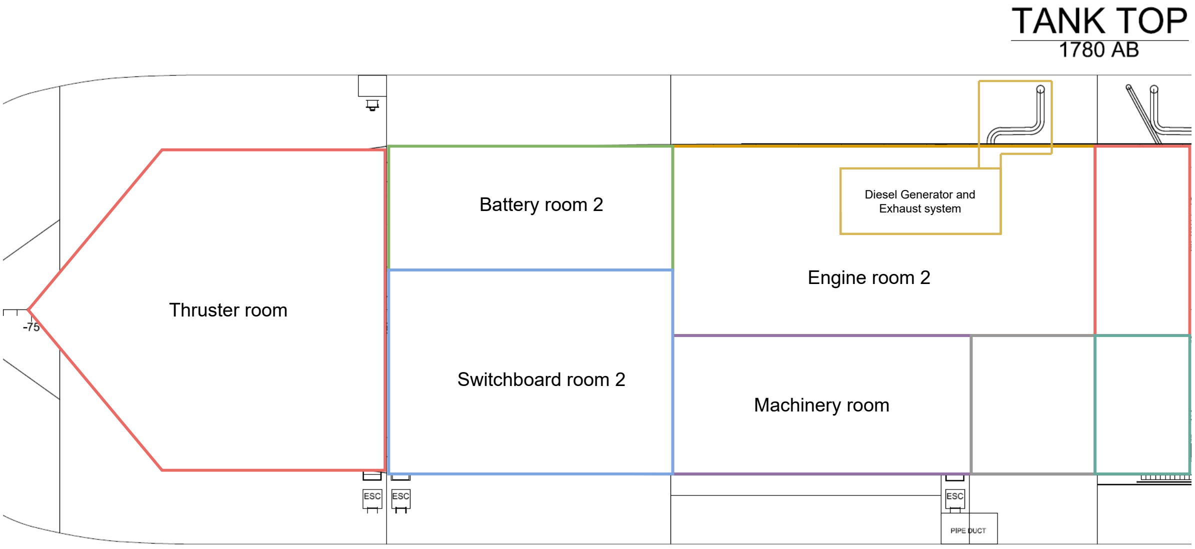


Figure 5.21: Space allocation in a General Arrangement drawing for different sub-systems

#### First option cluster possibilities

The interactions between or outside clusters should be minimized which means that based on minimizing the interactions of the potential clusters would give the best potential modules. Based on this approach the potential modules are made bold in the table. As clusters 6a,7a,8a and 6/7/8b do not variate significantly, both options are evaluated.

The first option in the cluster possibilities is a combination of clusters 1a, 2a, 3a, 5, 6a, 7a and 8a. Tables 5.5 and 5.6 show the potential modules when using the first option cluster possibilities minimizing the amount of clusters. Based on these results a number of observations can be made evaluating the clusters.

- When focusing on only minimizing the interactions between or outside modules the size of the modules themselves become larger. As a result the system decomposition groups are partly or sometimes whole becoming a module. This can be expected as the interactions between total decomposition groups are small.
- When running the results the diesel generator was kept in the clustering algorithm even though central elements or sub-systems were excluded such as the switchboard. As a result the module which included the Diesel generator has a significant amount of interactions which made the potential module fail. This was not done intentionally, but does prove the theory elaborated in the beginning of this chapter.
- Although the amount of interactions seem to be significant they can be explained. Firstly, there are 7 interactions with the diesel generator. Secondly, there are 6 interactions with control or alarm systems which are already defined as less significant due to their relative flexibility. And thirdly, there are 5 interactions with the sludge or driptray system which also is expected. The high amount of interactions mean that it might be possible to use or design standard interfaces for these sub-systems for a more optimal use and interaction of the interfaces.
- Also important to state is that the results of the clustering are to be used in the design phase of the vessel. The DSM uses the approach of the least interactions which means that overlapping systems could be in one cluster which might be less optimal in the building process.
- There are limitations in the connections between sub-systems. This is mainly regarding the piping system which is defined as one system. However, sometimes there is the connection between the generator to the SCR unit, the drip tray and the silencer. Between those sub-systems there is a connection using the piping system of the exhaust. However, to limit the amount of elements or sub-systems, the connection using piping is omitted in such a case and the piping system is only used once. A more detailed decomposition is possible but is unlikely to improve the results as the grouping or clustering is most likely to remain the same.
- Regarding the elements which are included in the clusters almost all elements are in clusters. Besides the elements which were excluded from the start the electrical part is not included in clusters due to the absence of the coupling elements which are the switchboards and control system. Besides this, the cluster which included the Diesel generator is excluded for this first solution due to the high amount of interactions. This means that the clustering algorithm works and includes all the elements which should be included.

Table 5.5: First option potential modules including the defined interactions outside the module part A

| **Module Elements** | | | **Interactions** | | | |
|---|---|---|---|---|---|---|
| **1a** | | | | **Output to** | | |
| 10 | 1.4.1.1 | LNG Tank | 14 | 44 | 1.4.5 | Diesel Generator |
| 11 | 1.4.1.2.1 | Filling system | 16 | 44 | 1.4.5 | Diesel Generator |
| 12 | 1.4.1.2.2 | De-earation system | | | | |
| 13 | 1.4.1.2.3 | Control system | | | | |
| 14 | 1.4.1.2.4 | Piping system LNG | | | | |
| 15 | 1.4.1.2.4.1 | Boiled off gas compressor | | | | |
| 16 | 1.4.1.2.4.2 | Gas Valve Unit | | | | |
| 17 | 1.4.1.2.4.3 | Gas conditioning system (expansion tank) | | | | |
| 18 | 1.4.1.3 | Vaporizer | | | | |
| **2a** | | | | **Output to** | | |
| 21 | 1.4.2.2.1 | Service tank 1 | 21 | 19 | 1.4.2.1.1 | Piping system fuel oil |
| 22 | 1.4.2.2.3 | Overflow tank | | 49 | 1.4.7 | Sludge/driptray system |
| 23 | 1.4.2.2.4 | Bunker tank 1 | | 28 | 1.4.2.3.5 | Alarm system |
| 24 | 1.4.2.3.1 | Fuel oil pump system | 22 | 28 | 1.4.2.3.5 | Alarm system |
| 25 | 1.4.2.3.2 | Piping system | 23 | 49 | 1.4.7 | Sludge/driptray system |
| 26 | 1.4.2.3.3 | Filling system | | 28 | 1.4.2.3.5 | Alarm system |
| 27 | 1.4.2.3.4 | De-earation system | 25 | 44 | 1.4.5 | Diesel Generator |
| 30 | 1.4.2.3.7 | Sounding system | | 28 | 1.4.2.3.5 | Alarm system |
| | | | 26 | 49 | 1.4.7 | Sludge/driptray system |
| 19 | 1.4.2.1.1 | Piping system fuel oil | 30 | 29 | 1.4.2.3.6 | Control system |
| 20 | 1.4.2.1.2 | Tank heating system | | **Input from** | | |
| 49 | 1.4.7 | Sludge/driptray system | 21 | 20 | 1.4.2.1.2 | Tank heating system |
| | | | 49 | 36 | 1.4.3.4.2 | Sludge |
| | | | | 19 | 1.4.2.1.1 | Piping system fuel oil |
| | | | | 20 | 1.4.2.1.2 | Tank heating system |
| **3a** | | | | **Output to** | | |
| 31 | 1.4.3.1 | Piping system lub oil | 31 | 44 | 1.4.5 | Diesel Generator |
| 32 | 1.4.3.1.1 | Filling system lubrication oil | 36 | 49 | 1.4.7 | Sludge/driptray system |
| 33 | 1.4.3.1.2 | De-earation system | | **Input from** | | |
| 34 | 1.4.3.2 | Pumping system | 31 | 44 | 1.4.5 | Diesel Generator |
| 35 | 1.4.3.4.1 | Tank | | | | |
| 36 | 1.4.3.4.2 | Sludge | | | | |
| 37 | 1.4.3.4.3 | Oil drum filling | | | | |
| 38 | 1.4.3.4.4 | Sounding system | | | | |
| 39 | 1.4.3.6 | Dirty oil system | | | | |

Table 5.6: First option potential modules including the defined interactions outside the module part B

| **Module Elements** | | | **Interactions** | | | |
|---|---|---|---|---|---|---|
| **5** | | | | **Input from** | | |
| 40 | 1.4.4.1 | Piping system exhaust | 40 | 44 | 1.4.5 | Diesel Generator |
| 41 | 1.4.4.1.1 | Silencer | 43 | 44 | 1.4.5 | Diesel Generator |
| 42 | 1.4.4.1.2 | Drip tray | | | | |
| 43 | 1.4.4.1.3 | SCR unit | | | | |
| **6a** | | | | **Output to** | | |
| 50 | 1.5.1.1 | Vaporizer H2 | 53 | 59 | 1.5.2.3 | Humidifier |
| 51 | 1.5.1.2 | Tank | 55 | 62 | 1.5.3.3 | Fuel cell |
| 52 | 1.5.1.2.1 | Collection system of vaporized H2 | | **Input from** | | |
| 53 | 1.5.1.3 | Piping system H2 | 51 | 56 | 1.5.1.3.3 | Filling system |
| 54 | 1.5.1.3.1 | Boiled off gas compressor | | | | |
| 55 | 1.5.1.3.2 | Gas Valve Unit | | | | |
| **7a** | | | | **Output to** | | |
| 57 | 1.5.2.1 | Piping system O2 | 62 | 63 | 1.5.3.4 | Control system |
| 59 | 1.5.2.3 | Humidifier | | **Input from** | | |
| 60 | 1.5.3.1 | Cooling system | 59 | 53 | 1.5.1.3 | Piping system H2 |
| 61 | 1.5.3.2 | Electrical system | | 58 | 1.5.2.2 | Separator system |
| 62 | 1.5.3.3 | Fuel cell | 61 | 63 | | |
| | | | 62 | 55 | 1.5.1.3.2 | Gas Valve Unit |
| **8a** | | | | **Output to** | | |
| 56 | 1.5.1.3.3 | Filling system | 56 | 51 | 1.5.1.2 | Tank |
| 58 | 1.5.2.2 | Separator system | 58 | 59 | 1.5.2.3 | Humidifier |
| **6/7/8b** | | | | **Output to** | | |
| 56 | 1.5.1.3.3 | Filling system | 56 | 51 | 1.5.1.2 | Tank |
| 58 | 1.5.2.2 | Separator system | 60 | 62 | 1.5.3.3 | Fuel cell |
| 59 | 1.5.2.3 | Humidifier | | | | |
| 60 | 1.5.3.1 | Cooling system | 57 | 59 | 1.5.2.3 | Humidifier |
| | | | 62 | 63 | 1.5.3.4 | Control system |
| 57 | 1.5.2.1 | Piping system O2 | | | | |
| 61 | 1.5.3.2 | Electrical system | | **Input from** | | |
| 62 | 1.5.3.3 | Fuel cell | 59 | 53 | 1.5.1.3 | Piping system H2 |
| | | | | 57 | 1.5.2.1 | Piping system O2 |
| | | | 61 | 63 | 1.5.3.4 | Control system |
| | | | 62 | 55 | 1.5.1.3.2 | Gas Valve Unit |
| | | | | 60 | 1.5.3.1 | Cooling system |

### Second option cluster possibilities

Analysing the results above shows that only focusing on minimizing the interactions between or outside modules results in modules which show similarities with the decomposition groups. Next to this the amount of interactions in the first results show that there are a significant amount of interactions to the same sub-systems being the diesel generator, alarm or control system and the sludge/driptray system. For these reasons also the second best option is analysed to see if this solution results in feasible modules. The results of the second option for cluster possibilities including the interactions are shown in Tables 5.8 and 5.9. The second best option of modules is combined of clusters 1b, 2c, 3c, 4, 5, 6/7/8 b. For this configuration of potential modules also multiple observations can be made.

- For this system module configuration the focus is less on the amount of interactions between or outside clusters. This means that the amount of clusters is higher than of the first potential solution. When referring to the second best solution all the first options are not taken into account and the amount of interactions becomes 45.

- As in the first solution also in this solution there are multiple connections to the less important or more flexible elements or sub-systems. This means that for instance there are 7 interactions with control or alarm systems which are already defined as less significant due to their relative flexibility. Next there are 5 interactions with the Diesel generator and finally there are 7 interactions with the sludge/driptray system. Again this high amount of interactions mean that the interactions with these systems could be optimized and standardized.

- In this configuration of potential modules almost all elements or sub-systems are included. Besides the excluded elements only the electrical sub-systems are not included in the potential modules. In contrary to the first option the cluster with the diesel generator is included as the focus is less on minimizing the amount of interactions.

- When analyzing cluster 3c it shows the inclusion of the pumping and piping system together with the filling, sounding and dirty oil system. However, the pumping and piping system is dependent on the flow requirements where the filling and sounding system are less or not influenced by it. This means that the cluster in practice is less than optimal to use as standard module. For this reason the third cluster option is also looked at which is 3b. The first cluster for this is the storage and control of the storage. The second cluster in this option is the piping and filling system which is connected and has more in common. The cluster result with interactions is shown in Table 5.7. What is remarkable for these clusters is that the interactions outside the two clusters are only to three different sub-systems where the rest of the interactions are between the two clusters. This means that there is the possibility to combine them into one cluster resulting in potential module 3a but resulting in a large system which is difficult to change. Or to standardize and optimize the interactions between the modules to be able to separate them.

Table 5.7: Cluster result 3b including interactions

| **Module Elements** | | | **Interactions** | | | |
|---|---|---|---|---|---|---|
| **3b** | | | | **Output to** | | |
| 32 | 1.4.3.1.1 | Filling system lubrication oil | 32 | 31 | 1.4.3.1 | Piping system lub oil |
| 33 | 1.4.3.1.2 | De-earation system | 35 | 31 | 1.4.3.1 | Piping system lub oil |
| 35 | 1.4.3.4.1 | Tank | | 34 | 1.4.3.2 | Pumping system |
| 36 | 1.4.3.4.2 | Sludge | 36 | 49 | 1.4.7 | Sludge/driptray system |
| 38 | 1.4.3.4.4 | Sounding system | | | | |
| | | | 31 | 35 | 1.4.3.4.1 | Tank |
| 31 | 1.4.3.1 | Piping system lub oil | | 36 | 1.4.3.4.2 | Sludge |
| 34 | 1.4.3.2 | Pumping system | | 44 | 1.4.5 | Diesel Generator |
| 37 | 1.4.3.4.3 | Oil drum filling | 37 | 35 | 1.4.3.4.1 | Tank |
| 39 | 1.4.3.6 | Dirty oil system | | | | |
| | | | | **Input from** | | |
| | | | 35 | 31 | 1.4.3.1 | Piping system lub oil |
| | | | | 37 | 1.4.3.4.3 | Oil drum filling |
| | | | 36 | 31 | 1.4.3.1 | Piping system lub oil |
| | | | | | | |
| | | | 31 | 32 | 1.4.3.1.1 | Filling system lubrication oil |
| | | | | 35 | 1.4.3.4.1 | Tank |
| | | | | 45 | 1.4.5.1 | Electric engine system |
| | | | 34 | 35 | 1.4.3.4.1 | Tank |

Table 5.8: Second option potential modules including the defined interactions outside the module part A

| **Module Elements** | | | **Interactions** | | | |
|---|---|---|---|---|---|---|
| **1b** | | | **Interactions with** | | | |
| 10 | 1.4.1.1 | LNG Tank | | **Output to** | | |
| 11 | 1.4.1.2.1 | Filling system | 10 | 14 | 1.4.1.2.4 | Piping system LNG |
| 12 | 1.4.1.2.2 | De-earation system | | 16 | 1.4.1.2.4.2 | Gas Valve Unit |
| 13 | 1.4.1.2.3 | Control system | | | | |
| | | | 14 | 44 | 1.4.5 | Diesel Generator |
| 14 | 1.4.1.2.4 | Piping system LNG | 15 | 13 | 1.4.1.2.3 | Control system |
| 15 | 1.4.1.2.4.1 | Boiled off gas compressor | 16 | 44 | 1.4.5 | Diesel Generator |
| 16 | 1.4.1.2.4.2 | Gas Valve Unit | | 13 | 1.4.1.2.3 | Control system |
| 17 | 1.4.1.2.4.3 | Gas conditioning system (expansion tank) | | | | |
| 18 | 1.4.1.3 | Vaporizer | | **Input from** | | |
| | | | 13 | 15 | 1.4.1.2.4.1 | Boiled off gas compressor |
| | | | 13 | 16 | 1.4.1.2.4.2 | Gas Valve Unit |
| | | | 14 | 10 | 1.4.1.1 | LNG Tank |
| | | | 16 | 10 | 1.4.1.1 | LNG Tank |
| **2c** | | | | **Output to** | | |
| 21 | 1.4.2.2.1 | Service tank 1 | 21 | 24 | 1.4.2.3.1 | Fuel oil pump system |
| 23 | 1.4.2.2.4 | Bunker tank 1 | | 25 | 1.4.2.3.2 | Piping system |
| 26 | 1.4.2.3.3 | Filling system | | 19 | 1.4.2.1.1 | Piping system fuel oil |
| 27 | 1.4.2.3.4 | De-earation system | | 49 | 1.4.7 | Sludge/driptray system |
| 30 | 1.4.2.3.7 | Sounding system | | 28 | 1.4.2.3.5 | Alarm system |
| | | | 23 | 24 | 1.4.2.3.1 | Fuel oil pump system |
| 22 | 1.4.2.2.3 | Overflow tank | | 25 | 1.4.2.3.2 | Piping system |
| 24 | 1.4.2.3.1 | Fuel oil pump system | | 49 | 1.4.7 | Sludge/driptray system |
| 25 | 1.4.2.3.2 | Piping system | | 28 | 1.4.2.3.5 | Alarm system |
| | | | 26 | 49 | 1.4.7 | Sludge/driptray system |
| | | | 27 | 49 | 1.4.7 | Sludge/driptray system |
| | | | 30 | 29 | 1.4.2.3.6 | Control system |
| | | | 22 | 27 | 1.4.2.3.4 | De-earation system |
| | | | | 30 | 1.4.2.3.7 | Sounding system |
| | | | 25 | 22 | 1.4.2.2.3 | Overflow tank |
| | | | | 23 | 1.4.2.2.4 | Bunker tank 1 |
| | | | | **Input from** | | |
| | | | 21 | 25 | 1.4.2.3.2 | Piping system |
| | | | | 2 | 1.1.1.2 | Generator connection |
| | | | 23 | 25 | 1.4.2.3.2 | Piping system |
| | | | 27 | 22 | 1.4.2.2.3 | Overflow tank |
| | | | 30 | 22 | 1.4.2.2.3 | Overflow tank |
| | | | 24 | 21 | 1.4.2.2.1 | Service tank 1 |
| | | | | 23 | 1.4.2.2.4 | Bunker tank 1 |
| | | | 25 | 21 | 1.4.2.2.1 | Service tank 1 |
| | | | | 23 | 1.4.2.2.4 | Bunker tank 1 |

Table 5.9: Second option potential modules including the defined interactions outside the module part B

| **Module Elements** | | | **Interactions** | | | |
|---|---|---|---|---|---|---|
| **3c** | | | | **Output to** | | |
| 31 | 1.4.3.1 | Piping system lub oil | 31 | 44 | 1.4.5 | Diesel Generator |
| 32 | 1.4.3.1.1 | Filling system lubrication oil | | 36 | 1.4.3.4.2 | Sludge |
| 34 | 1.4.3.2 | Pumping system | 35 | 33 | 1.4.3.1.2 | De-earation system |
| 37 | 1.4.3.4.3 | Oil drum filling | | 36 | 1.4.3.4.2 | Sludge |
| 38 | 1.4.3.4.4 | Sounding system | | | | |
| 39 | 1.4.3.6 | Dirty oil system | 33 | 35 | 1.4.3.4.1 | Tank |
| | | | 36 | 49 | 1.4.7 | Sludge/driptray system |
| 33 | 1.4.3.1.2 | De-earation system | | | | |
| 36 | 1.4.3.4.2 | Sludge | | **Input from** | | |
| | | | 31 | 45 | 1.4.5.1 | Electric engine system |
| | | | 35 | 33 | 1.4.3.1.2 | De-earation system |
| | | | 33 | 35 | 1.4.3.4.1 | Tank |
| | | | 36 | 31 | 1.4.3.1 | Piping system lub oil |
| | | | | 35 | 1.4.3.4.1 | Tank |
| **4** | | | | **Output to** | | |
| 44 | 1.4.5 | Diesel Generator | 44 | 40 | 1.4.4.1 | Piping system exhaust |
| 45 | 1.4.5.1 | Electric engine system | | 43 | 1.4.4.1.3 | SCR unit |
| 47 | 1.4.5.3 | Heat exchange system | 45 | 31 | 1.4.3.1 | Piping system lub oil |
| 48 | 1.4.6.1 | Piping system air | | 19 | 1.4.2.1.1 | Piping system fuel oil |
| | | | | **Input from** | | |
| | | | 44 | 25 | 1.4.2.3.2 | Piping system |
| | | | | 31 | 1.4.3.1 | Piping system lub oil |
| | | | | 14 | 1.4.1.2.4 | Piping system LNG |
| | | | | 16 | 1.4.1.2.4.2 | Gas Valve Unit |
| | | | | 19 | 1.4.2.1.1 | Piping system fuel oil |
| | | | | 46 | 1.4.5.2 | Control system |
| | | | 45 | 4 | 1.1.2.2 | Switchboard 1 |
| **5** | | | | **Input from** | | |
| 40 | 1.4.4.1 | Piping system exhaust | 40 | 44 | 1.4.5 | Diesel Generator |
| 41 | 1.4.4.1.1 | Silencer | 43 | 44 | 1.4.5 | Diesel Generator |
| 42 | 1.4.4.1.2 | Drip tray | | | | |
| 43 | 1.4.4.1.3 | SCR unit | | | | |
| **6/7/8 b** | | | | **Output to** | | |
| 56 | 1.5.1.3.3 | Filling system | 56 | 51 | 1.5.1.2 | Tank |
| 58 | 1.5.2.2 | Separator system | 60 | 62 | 1.5.3.3 | Fuel cell |
| 59 | 1.5.2.3 | Humidifier | | | | |
| 60 | 1.5.3.1 | Cooling system | 57 | 59 | 1.5.2.3 | Humidifier |
| | | | 62 | 63 | 1.5.3.4 | Control system |
| 57 | 1.5.2.1 | Piping system O2 | | | | |
| 61 | 1.5.3.2 | Electrical system | | **Input from** | | |
| 62 | 1.5.3.3 | Fuel cell | 59 | 53 | 1.5.1.3 | Piping system H2 |
| | | | | 57 | 1.5.2.1 | Piping system O2 |
| | | | 61 | 63 | 1.5.3.4 | Control system |
| | | | 62 | 55 | 1.5.1.3.2 | Gas Valve Unit |
| | | | | 60 | 1.5.3.1 | Cooling system |

## 5.9. Potential modules selection and interface definition

What becomes clear after evaluating the results of the potential modules is that every module is of a different part of the total energy storage and conversion system. The first selection of module definition is based on minimizing interactions using the DSM clustering. Using the solutions which had the lowest interaction "costs" the second step was to define potential clusters based on the amount of interactions. The third step is to define the interactions between and outside of the clusters continuing in to the final step where the interactions are evaluated.

When analyzing the potential modularity connections the connections of the modules are to other, different modules. The connections between and outside modules can be used in a next step to determine the feasibility of the modules. The next evaluation therefore is the standardization of the module interactions elaborated in Chapter 4.1 and 4.3. To be able to use the modules or the variants of a module for multiple configurations it is important to be able to standardize the interactions. This means a general interface definition. By elaborating on the requirements of sub-systems it is possible to elaborate on the feasibility of a module and the feasibility of standardizing the interface. The standardization is based on a number of interaction definitions for modularization which are based on Figure 4.7. For this final evaluation first the suggestion for interaction standardization is defined after which a short elaboration is given on why this interface would be optimal. The modularity interface possibilities in the table are:

1. Combinatorial modularity
2. Component-swapping modularity
3. Sectional modularity
4. Bus modularity

### 5.9.1. General interface definition and working elaboration of the suggested modules

The potential modules and the interface definition and discussion is elaborated below. This last step in the evaluation of potential modules elaborates on the interface of the modules. Meaning the definition of the interface of potential modules and the possibility to standardize this interface.

- Starting with the first part of the DSM list are the **electrical sub-systems** which are not included in the modules as elaborated before. However, although there are no potential modules at this point for this part it is possible to use the Bus modularity or Component-swapping connection based on the requirements of the system. When looking at the logical design there are two switchboards where one for instance has the output and input for the batteries or the propulsion. In the case that the same electrical cables can be used for the connection between the sub-systems the connection can be seen as the Bus modularity. When using different cables, it can be defined as component-swapping connection.

- **Module 1b** with interfaces 1 & 1
  *Module 1b$_1$ LNG storing module*
  There is interaction between the tank, the piping and the Gas Valve Unit system. This connection is the only one of its kind but can be standardized. Therefore it becomes the Combinatorial modularity for the first part.

  *Module 1b$_2$ LNG transport module*
  For the second part there is interaction between the piping and Gas Valve Unit and the Generator which is named Diesel generator in the model. Hydrogen is somewhat similar in the use and also requires a Gas Valve Unit and piping. For the future when using a generator which can handle hydrogen, the supply could be similar and the specific interaction to the generator could be similar. In this case again combinatorial modularity would be the solution. However, the interaction could be made standard in which this part would be interchangeable for both LNG and Hydrogen. However, this requires further research.

- **Module 2c** with interfaces 3 & 3
  *Module 2c$_1$ MGO storing module*
  The first potential module shows a number of interactions with the sludge/driptray system. This system

itself is not included in the modules as it is a connecting system which means that it even could be excluded from the clustering. However, the amount of interactions show the potential for standardization of the output from the modules to the sludge/driptray system. For the output of the sludge/driptray system it would be possible to use Sectional modularity. The interactions to the piping and pumping system can be standardized as there are more tanks. The first module in 2c might be used for more ship types which means that the interactions could be defined as Sectional modularity. This means that the output of these systems are standard to the piping and pumping system. Which is also possible for the interaction between the service and bunker tank and the overflow tank can also be standardized.

The interactions to the piping system and the generator might be different depending on the required capacity. For this reason the interaction from the storing to the piping system can be standardized using overdesign of the connections. This means a connection to the piping system which allows for a range of flow capacities while using the same storing module.

*Module 2c$_2$ MGO transport module*
The second cluster includes the piping system. This system is the connecting part which might have different requirements based on the capacity. This is the same for the fuel oil pump system which is also based on capacity requirements. For this reason the advice is to separate the piping and fuel oil pump system from the overflow tank. From this point it is possible to calculate if it is possible to standardize this part but does require extra research and calculations.

- **Module 3b** with interface 1
  *3b$_1$ Lubrication oil storing module*
  To make the potential modules smaller and thus less complex the cluster option 3b is used. The first potential module shows one interaction outside the two potential modules to the sludge/driptray system. As elaborated can this interaction be standardized.

  The interactions between the two clusters is based on the first part. For the interaction to the piping and pumping system it is possible to design standard interactions. However, again this is a unique system in the total system which means the interaction becomes Combinatorial modularity again.

  *3b$_2$ Lubrication oil transport module$^+$*
  The second potential module is focused on piping which connects the different sub-systems. As the in- and output of the system is known, the specific interaction point can be standardized. However, for the standard module design first a calculation or design should be made to determine the specifications of the system. Only after which it is possible to determine the possibility to standardize this module.

- **Module 5** with interface 1
  *Module 5 Exhaust module*
  This module only has input from the diesel generator which means that the interactions are low. This is perfect for a module which means that this module has high potential to succeed. The connection to this system can be standardized which means that again the connection is Combinatorial Modularity.

- **Module 6a**
  *Module 6a Hydrogen storing module*
  The next three modules form the hydrogen system which means that interactions are mainly between the three hydrogen modules.

  The potential module 6a is the hydrogen part of the system excluding the filling of the system. The output of this module can be standardized but might be difficult as for instance the piping system and the gas valve unit are highly dependent on the hydrogen requirement. However, it might be possible to design a setup which has a design supply flow whereas a higher required value would result in a second system which then would also satisfy the redundancy requirement.

- **Module 7a** with interface 1
  *Module 7a Fuel cell & oxygen module*
  This potential module includes the piping system of oxygen as well as the humidifier whereas the rest of the module is the fuel cell itself including the cooling which is connected to it as well as the electric generation part. It is expected that the required amount of oxygen is connected to the amount of hydrogen which means that module 6a and 7a could not be developed separately which is required in modular design. However, this should be verified. If it is connected and the influence of the oxygen

supply on the hydrogen supply is little or negligible it is possible to standardize the input connections of the piping system for hydrogen and the separator system using Combinatorial Modularity.

- **Module 8a** with interface 1
  *Module 8a Hydrogen filling module*
  The final module is the filling and separator system. These sub-systems can be designed separately from the other modules and based on set regulations. This means that the outputs can be standardized using again Combinatorial Modularity.

To visualize the results in a schematic way Figures 5.22 and 5.23 are added in the report. The results are divided in two parts to keep it organized. Where the first part involves a combustion engine and the second one a fuel cell. In the figures also the main connections between modules are shown. In the configuration that only MGO would be used a different engine is used than for the dual fuel configuration for the MGO and LNG configuration. In the schematic overview also an attempt is made to include the requirement of redundancy in the system where there are often two sub-systems for the redundant required systems.

### 5.9.2. Potential module interface conclusion

This last step also finalized the answer to the question "How can a general interface be defined between the systems for the vessel specification and the propulsion requirements?". The systems in the question are the sub-systems which are defined as modules at this point. Following the method it is possible to define modules based on some starting parameters for a vessel after which a configuration can be chosen. Using the proposed modules above a combination of these modules can be used to define a system. With for each module the defined interactions between and outside the module and therefore a general interface based on the different possible interface types. The potential modules which can be used in the design of a future proof modular vessel design are shown in Table 5.10.

Table 5.10: Potential modules

| Module | Description |
|---|---|
| 1b1 | LNG storing module |
| 1b2 | LNG transport module |
| 2c1 | MGO storing module |
| 2c2 | MGO transport module |
| 3b1 | Lubrication oil storing module |
| 3b2 | Lubrication oil transport module$^{+}$ |
| 5 | Exhaust module |
| 6a | Hydrogen storing module |
| 7a | Fuel cell & oxygen module |
| 8a | Hydrogen filling module |

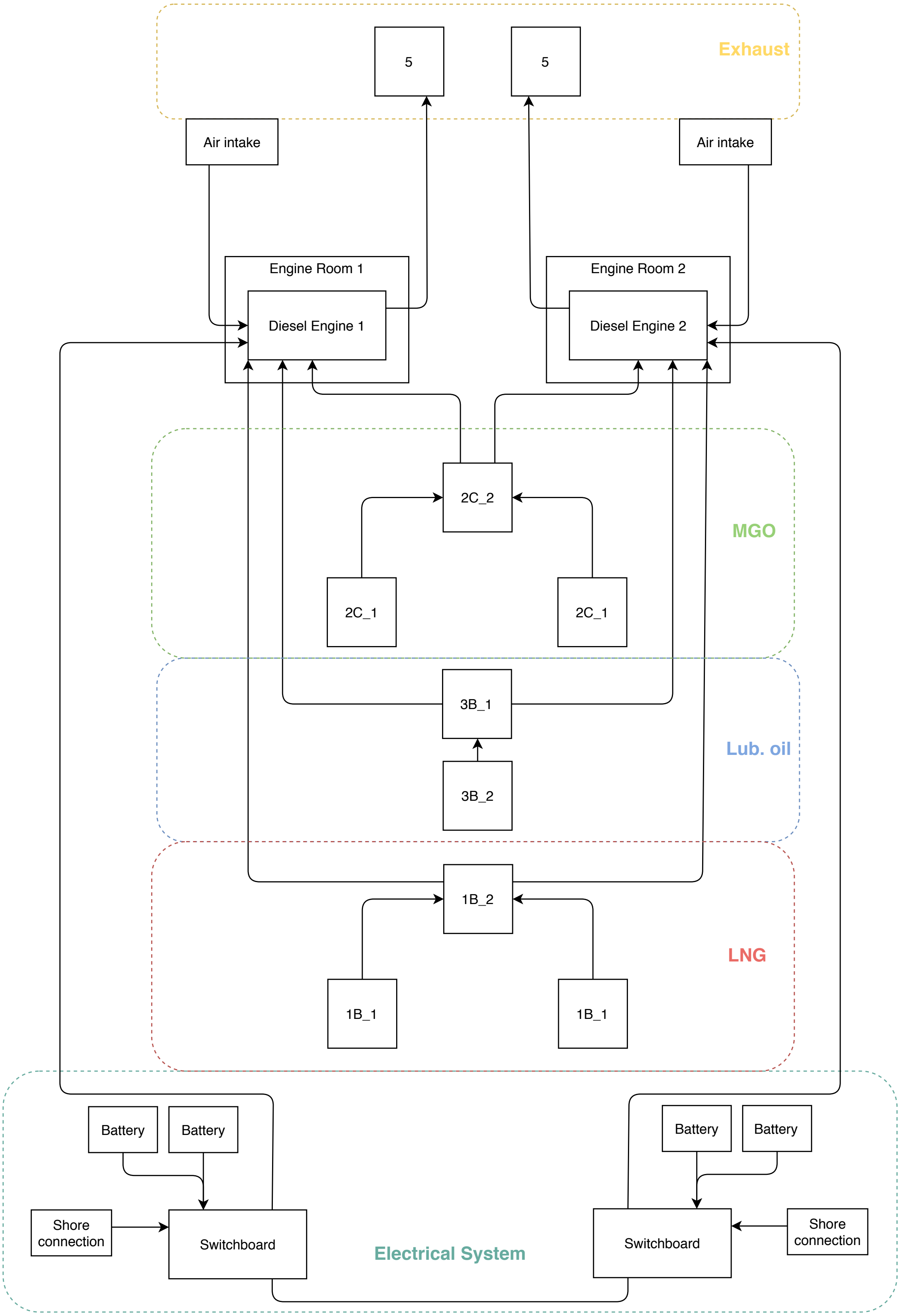


Figure 5.22: Visualization of the combination of suggested modules and their main interactions for the combustion engine with battery configuration

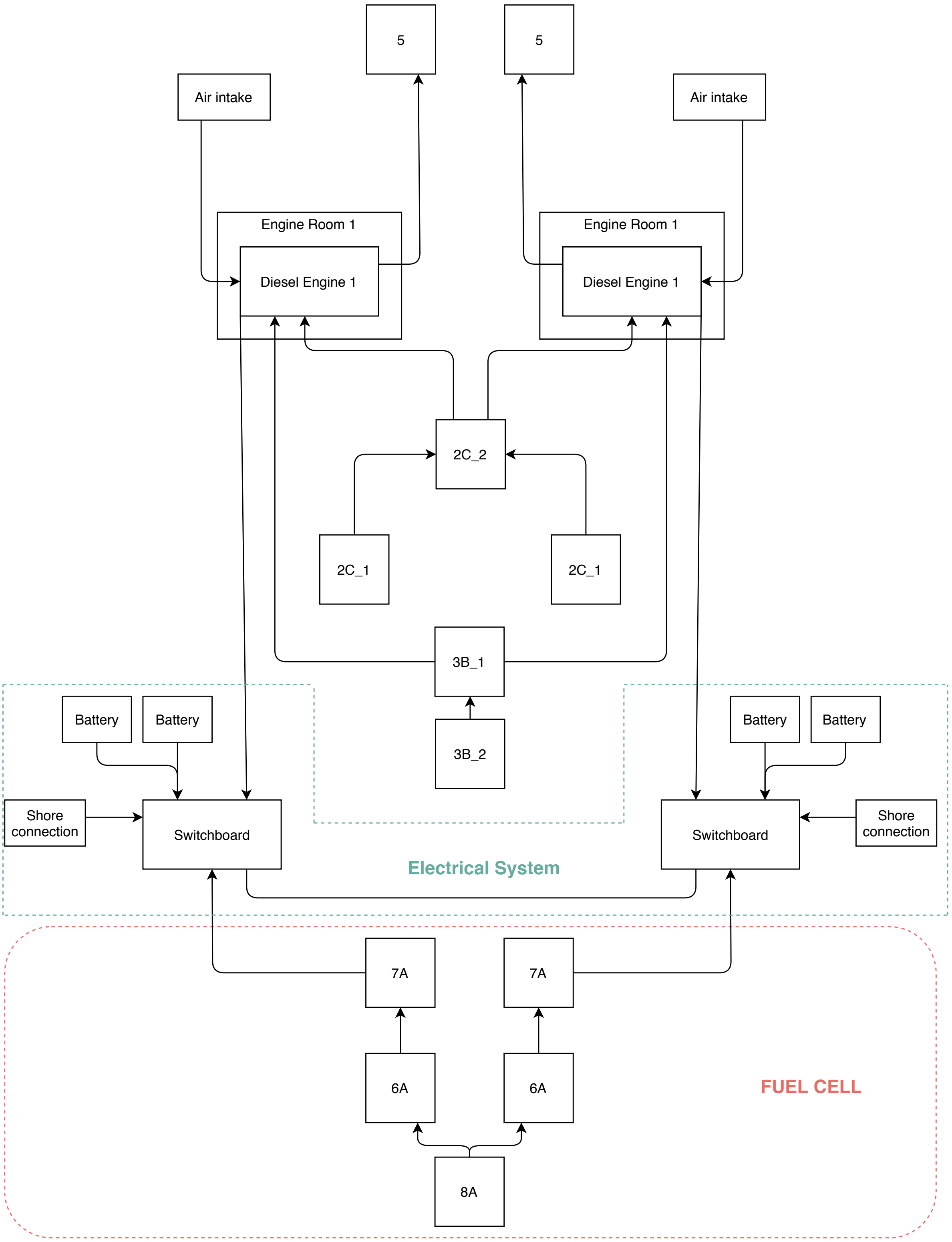


Figure 5.23: Visualization of the combination of suggested modules and their main interactions for the fuel cell with battery configuration

### 5.9.3. System design using modules

In addition to the module results there are two aspects which require elaboration. These are the determination of the common-core of the system as well as the future-proof properties of these modules.

#### Common-core and inclusive platform

After the design and evaluation of the modules it is possible to evaluate the system and the system approach. The common-core approach was used to reduce the complexity of the modules as well as to define a starting design basis. With regard to the reduction of the complexity it means that for instance a system is not fully included in a module but is divided into multiple modules. This results in modules consisting of fewer sub-systems and therefore the complexity of such a module is lower. The common-core can be elaborated as a connecting or central part in the system which is the basis or connecting basis for a number of systems. The common-core of the total system design in the energy storage and conversion system is the electrical system. This system is connecting all the different systems where more specifically the switchboards can be seen as the practical central point of the common-core. The switchboard is excluded from the DSM due to the amount of interactions to sub-systems. The next common-core is the diesel generator which is the result of the amount of interactions. This system also connects to a number of other systems where it is a central part of the system.

The visualization of the common-core is visualized in Figure 5.24. This figure shows the basic common-core as all the systems are to an extent connected with a power supply. The first building block shows the Diesel Generator which is the second common-core due to the connections to all the systems as well. This is further visualized in Figure 5.25 while using the visualization setup used in Figure 4.4.

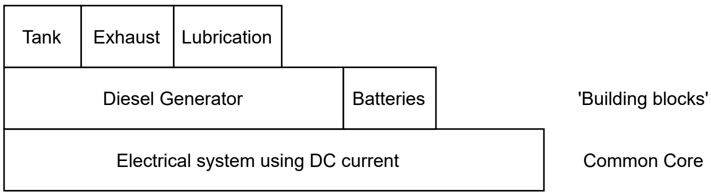
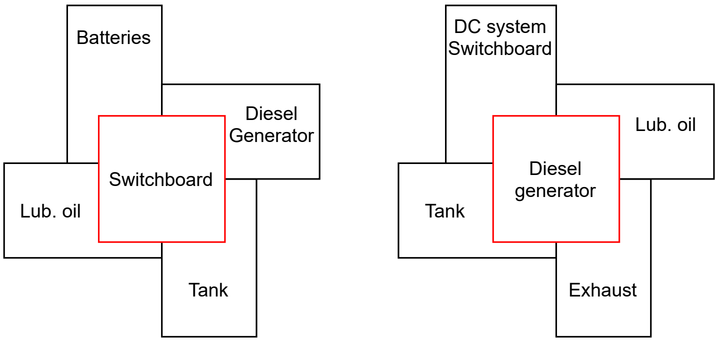


Figure 5.24: Common-core definition of the complete energy storage and conversion system based on Figure 4.4



Common core connected by the switchboard

First building block connected by the diesel generator

Figure 5.25: Practical application of the common-core approach with the main common core being the DC power supply visualized with the connecting DC Switchboard and the second common core being the conversion system visualized with the Diesel generator

#### Future proof

For the future proof design of the system it is helpful to design the system using the common-core approach. As visualized in the Figures 5.24 and 5.25 the basic common core system is the DC power system. Where a second common-core is the diesel generator system. As other systems can be used in the future such as a fuel cell, these will be a common-core setup as well as the diesel generator. This helps to understand what the basis of the design can be and will not change based on different energy carrier and conversion systems. Therefore by making the systems modular they can be designed to be connected to the DC current common-core. The common core will have the most significant influence on a design in case of a change. Therefore, by standardizing these common-cores in a modular way it is possible to increase the interchangeability of the modules connecting to the common-core while minimizing the requirement for changing the basic power distribution for instance. Resulting in the possibility to simplify the system design and also changes in the design with regard to future proof design which is less influenced by system changes.

### 5.9.4. Evaluation and discussion of potential modules

Starting with the set goal of the clustering for potential modules to find clusters based on minimal interactions. The minimal interactions resulted in larger clusters of sub-systems which had similarities to the decomposition made of the systems. When defining the decomposition of the systems these systems are made into groups. An example for this is the fuel system for the generator. This system has interactions with the diesel generator and can be seen as a separate system. For this reason when accepting large clusters the cluster algorithm shows that the optimal solution, based on clustering costs and minimized interactions, becomes this part of the decomposition. This result can be accepted as a solution but separate systems already are known and are therefore not a step forward towards modular design.

The clustering in this way can also be explained by the lack of full implementation of all the involved systems. As shown in the results the electrical part of the system is not fully implemented in the DSM. The main reason for this is that the algorithm uses binary connections at this point. If the electrical connections would be added in the DSM it would mean that for instance an electrical connection would be as significant as the connection between the diesel generator and the exhaust. The exhaust connection is significantly less flexible than the electrical connection which means that the clustering would be influenced by this implementation. In addition to this, literature advised to start a DSM with an amount of about 50 elements and from there reduce or extend the DSM where necessary. This resulted in the omitting of the water cooling system. In the decomposition there are two cooling systems where there is one for the auxiliary systems and one for the diesel generator. This cooling water system connects multiple systems and sub-systems as for instance the cooling of the batteries and lubrication oil. But could also for instance connect or be similar to cooling a generator and a fuel cell. This means that including the water cooling system could give more insight in combining sub-systems or clusters for the use of multiple fuel types.

The second part of the goal was to define the interactions between or outside the clusters. For this goal the DSM clustering algorithm works really well. The interactions are put in the matrix by the person using it, but using this approach the result is that the interactions between parts and potential modules is really clear and understandable. This means that the DSM analysis using clustering is fit for clearly showing potential modules and finding interactions between them.

More specific on the decision of the clusters some clusters are elaborated on. Starting with 2c which is chosen as the tank system is more separate than the total cluster shown in 2a. The fuel oil pump system including the piping system is also between other tanks which means that this cluster is too large and 2c is a better option for a potential module. However, 2c has the potential for separating the overflow tank and excluding it from the cluster. The overflow tank is something fixed in the vessel whereas the pump and piping system are more flexible and might be designed separately. Cluster 4 is still excluded from the overview as it is a connecting system to a lot of other sub-systems which makes it less fit for begin a module. Specifically the generator is the result of the high interactions which means that this system should not be included. And when looking at module 6a at this point it is clearly a separate system. However, as elaborated in potential module 1b there is the possibility of using hydrogen in combustion engines which means that the connections of the module could be standardized for using a fuel cell as well as a combustion engine and also the interchangeability becomes feasible.

Finally, the approach which is used is an abstract method where the sub-systems are translated to numbers and only translated back to sub-systems after the clustering and first analysis. This is done to ensure that the method is as objectively as possible. A question which can be asked then is: If objectivity is the important design decision for this approach, then why is there still such a large focus on technical approving modules based on knowledge? For instance module 2c2 where the overflow tank is included in the pump and piping system. At this point there is no technical proof yet to be able to state that it doesn't work. Thus based on the non biased approach this module could be feasible. However, this decision shows the combination of thrust in a method and technical knowledge of a system. As models have a level of simplification it is not possible to trust all results and technical evaluation is required.

### Risks of using the algorithm

With regard to the risk of using this algorithm there are multiple risks. As elaborated before there is a high possibility to make mistakes as the input is abstract which means that mistakes can go unnoticed until the analysis which means that the results have to be re-run. This risk is found to be true as in the first run a mistake was made and all the results had to be re-run. In Chapter 7 an analysis is made of the mistakes and also of the sensitivity of the algorithm and the influence of mistakes on the results.

An important conclusion in the usage of the algorithm is that now there are tools and possibilities to find the optimal solution. This means that when looking at minimizing the amount of interactions it also means that the possibility for larger clusters becomes higher. Elaborated in the elaboration of the clusters and specifically for Cluster_param.pow_bid the value of 2 and cluster_param.pow_dep the value of 4 was used to fine larger clusters. The more optimal solution then shows larger clusters. this means that for this case the bid function value could be lower to reduce the size of clusters. Meaning that when other tools or algorithms are used, the parameters become more important for a feasible solution with potential modules. In this version of the algorithm the real optimal solution is not found which means that there are multiple solutions. This also means that the analysis has to be done by the person executing the clustering and expertise is required to find the real potential solutions. This means that the solution alone of the DSM does not give final answers and can be worthless for someone who is not familiar to the method or systems.

### Advantage of the method

The advantage of using the RFLP approach and modular design is elaborated in Chapter 4.6. In addition to these advantages there are also a number of advantages for the method with respect to the determination of modules by experience.

- Combining sub-systems by experience is first of all labour intensive to find feasible combinations based on minimized interactions. Using the DSM clustering algorithm it is relatively easy to generate a large number of feasible solutions were parameters can be changed based on design variables.
- In the algorithm it is possible to implement decision variables and design decisions. These can for instance be the the size of the modules, the different interaction values between sub-systems and modules and the implementation to evaluate the influence of the implementation of alternative fuels or systems.
- The ability to design or adapt the input for the clustering algorithm without changing the other information also means that improvements can be made parallel to the existing systems.
- The practical next step in the usage of modular design is to design a physical module with the calculations and regulations supporting the design. Next to this, variations have to be designed which can be used in the modular design space. This means a number of things:
  - A systematic design approach is required to be able to manage the system data which is required to evaluate the modules and sub-systems. This is possible by following the changes using the functional and logical decomposition to evaluate the influences of the changes. Without these steps the data management and the influence of a change is difficult to follow.
  - The input and output data is required to be known which can be implemented in the definition of the sub-systems but also in the definition of the modules. The advantage of the latter is elaborated in Chapter 4.6.

# 6

# Methodological modular implementation of the energy carrier and conversion system

## 6.1. Method description for modular design implementing future proof systems

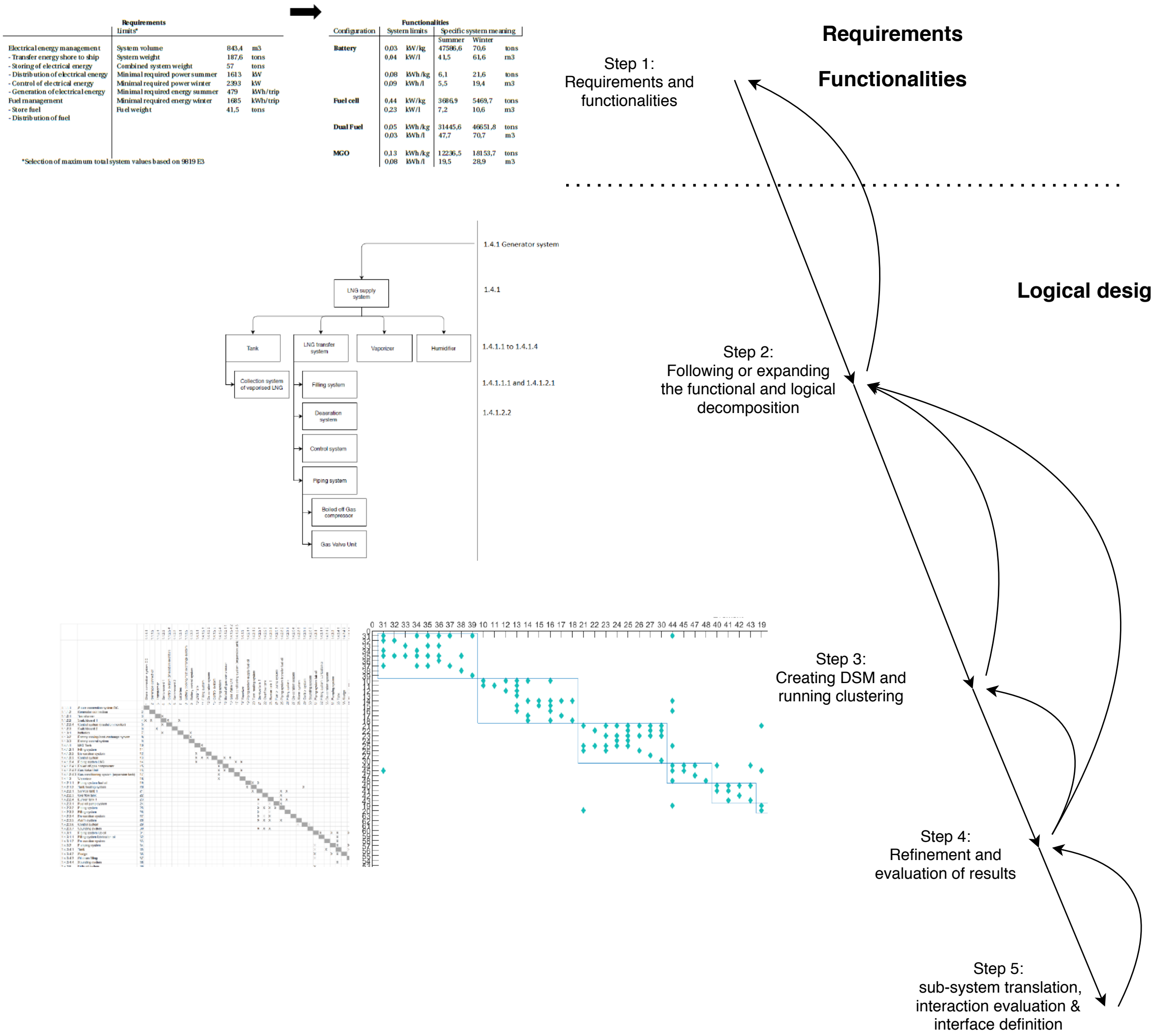
The previous chapter showed the results of using the Design Structure Matrix in order to obtain potential modules. Next to the usage of the DSM clustering algorithm, an amount of other different steps are used to suggest potential modules and to refine and evaluate the results of the clustering. This chapter is the combination of the specific approach and the potential usage of the method to be used as a continuous process to develop systems or modules.

The DSM clustering algorithm uses the main drivers for modularization. Resulting in the minimization of the interactions between clusters, a maximization of the interaction inside a cluster and the possibility to define different values of connections to take into account the importance of a connection. This means that the method itself is optimal to define potential modules. In addition to this, the decision is made to keep the clustering and potential module definition as objective as possible. This way it is better feasible to find new or better solutions which might be less common within the design process. Therefore, the approach is kept abstract for the large part and follows the theory to find optimal results based on minimal interactions and the lowest cluster combination 'cost'. Only after this analysis the numbers are translated back to actual sub-systems to be evaluated.

The original method is to implement one system which can be divided into modules based on minimizing interactions between modules. Meaning that modules are defined after which the next step is to develop or design variations of the modules that can be used and interchanged without changing the other modules. Practically, the chance is large that not only one module can be adapted, but the goal is to influence and change as few modules as possible. When mapping the interactions of the sub-systems and using the clustering modules it is possible to determine influences of design changes. Specifically it means that a change in propulsive power can be traced through the requirements and functionalities to the specific modules. Resulting in no additional required design for the parts which are not influenced by the change in design. When using this method it means that basic modules can be defined after which the variations still have to be designed according to the requirements of the specific sub-systems. This means that the potential modules can be used in a modular design although improvement of the setup and an increase in detail may lead to more feasible modules.

The additional step in this research is to not only include one system in the module definition but extending the method to include various system configurations. This is to include the future proofing of a vessel system design. Currently, the amount of configurations is 5 where 4 configurations resulted in potential modules. The extra step has the goal to be able to assess the influence of a system configuration design change. For this configuration change the same RFLP and DSM approach is used to be able to understand the change in system. This way it is possible to understand the specific implication of the change in configuration on the design including the weight and volume but also the usage of the interfaces to determine the potential of reusing one or more modules in the new design.

The method which will be described is visualized in Figure 6.1 with the corresponding RFLP steps next to it. It also shows the iteration or improvement potential based on feedback at different steps.



**Requirements**

| | Limits* | | |
|---|---|---|---|
| Electrical energy management | System volume | 843,4 | m3 |
| - Transfer energy shore to ship | System weight | 187,6 | tons |
| - Storing of electrical energy | Combined system weight | 57 | tons |
| - Distribution of electrical energy | Minimal required power summer | 1613 | kW |
| - Control of electrical energy | Minimal required power winter | 2393 | kW |
| - Generation of electrical energy | Minimal required energy summer | 479 | kWh/trip |
| Fuel management | Minimal required energy winter | 1685 | kWh/trip |
| - Store fuel | Fuel weight | 41,5 | tons |
| - Distribution of fuel | | | |

*Selection of maximum total system values based on 9819 E3

**Functionalities**

| Configuration | System limits | | Specific system meaning | | |
|---|---|---|---|---|---|
| | | | Summer | Winter | |
| **Battery** | 0,03 | kW/kg | 47586,6 | 70,6 | tons |
| | 0,04 | kW/l | 41,5 | 61,6 | m3 |
| | 0,08 | kWh/kg | 6,1 | 21,6 | tons |
| | 0,09 | kWh/l | 5,5 | 19,4 | m3 |
| **Fuel cell** | 0,44 | kW/kg | 3686,9 | 5469,7 | tons |
| | 0,23 | kW/l | 7,2 | 10,6 | m3 |
| **Dual Fuel** | 0,05 | kWh/kg | 31445,6 | 46651,8 | tons |
| | 0,03 | kWh/l | 47,7 | 70,7 | m3 |
| **MGO** | 0,13 | kWh/kg | 12236,5 | 18153,7 | tons |
| | 0,08 | kWh/l | 19,5 | 28,9 | m3 |

Figure 6.1: Method visualization of the steps based on the RFLP approach

## 6.1.1. First level of decision making using DSM clustering

### Step 1 - Requirements and functionality determination

The starting point of the approach are the requirements which are defined in Chapter 2.1 and 2.2. From Figure 2.3 at the basis a number of requirements can be used in the start of a design. The requirements for operational profile and speed are specific requirements for the specific logical design. However, the main requirements exclude or include functionality groups. For this research the speed for sailing is not included in the scope as the scope is focused on the energy storage and conversion system. This means that the speed of the vessel and the hull type already is defined. Therefore, the power consumption and required power is known at the start of this process. To include the power and energy requirements the calculations done in Chapter 2.2 can be implemented and used to include this step into the total approach. The class and statutory requirements are focused on emissions and safety. With regard to emissions it is possible to calculate emission values for instance for the 5 configurations such that emission values are known from the start. The innovation requirements are optional and are now specifically setup for this thesis but could also be used for client requirements as clients are requesting future proof vessels.

In this test case the requirements which have to be fulfilled are the energy and power requirements. As well as the charging feasibility, lifetime of systems and a specific vessel requirement for the weight and volume of the systems. The operational profile and speed are defined in the start of the project where an estimate or reference vessel can be used for the weight and volume determination.

The next requirement group is more related to the modular design process. This is the electrical energy management and the fuel management. An important aspect in this operational definition is that an electrical basis is used in the design. Meaning that there is no mechanical connection between the engine and thruster but there is an electrical connection. In these requirements a number of requirements are important as they are used to be able to determine the feasibility of a specific configuration. Table 6.1 shows the two main requirement groups from Figure 2.3 which are used in this process. In the next column the limits are shown which are related to the requirements. These are based on the previous calculations whereas the weight and volume calculation is based on the 9819 E3 ferry.

The next part of this step is to go to the functionality requirements where the four groups could be used as starting point for the different configurations. The configuration possibilities for the functional requirements being for a battery, fuel cell, combustion engine using dual fuel and a combustion engine using MGO configuration. For these possibilities there are the functional limitations of the systems where the next column combines the limitations to the specific vessel which shows the influence of the usage of a configuration on the weight and volume of a system. This can be a step before continuing to a configuration as it becomes possible to quickly determine if a configuration is possible for a vessel.

**Step 2 - Following or expanding the functional and logical decomposition**

For the decomposition of the functions a number of standard function descriptions are used as there are similarities between systems and the decomposition should be as consistent as possible. This way the decomposition is built up similarly for different configurations which means that adapting or adding parts can be done if the setup is understood. The standard functions being to: Transform, Transport, Store, Exchange, Control, Convert and Provide which is further elaborated in Figure 5.1. Next to these standard function descriptions there are more detailed function descriptions to decompose and describe the functions to the level of sub-systems. If the system needs to be expanded, it is possible to use the standard function descriptions to add these to the functional decomposition after which the following step to the logical decomposition can be followed.

Part two in this step is the logical decomposition. Using the original approach this should be done top-down which means that the system elements should be based on the functions only. However, as there are examples for systems and for instance P&ID drawings. Therefore the top-down and bottom-up approach are combined which means is that known and approved systems are used. The logical decomposition is divided in the same groups as the functional decomposition. In the logical decomposition the cooling water system is already included. It is not included at this point in the total method but can be used in an improvement of the module definition. Again as for the functional decomposition the systems are started from a main system and decomposed to sub-systems.

Part three in this step is the connection between the functional and logical decomposition. The reason for this is that the functional and logical decomposition preferably should have a 1 to 1 connection by preference. In practice this is not always possible and this requires elaboration on the decision why it is or is not further elaborated. For the case of a standard diesel engine the top-down and bottom-up method are used and combined. For this situation the approach seems double and the logical and functional decomposition are used to find missing elements. However, this process helps to use define alternative or new fuel types. This part also is the following step from the functional to logical step in the RFLP approach and connecting both steps with feedback.

Following the RFLP approach, the decomposition consists of two parts being the functional requirements based on the requirements which the technical solution has to fulfill. The connection between the two steps is visualized in Figure 6.2.

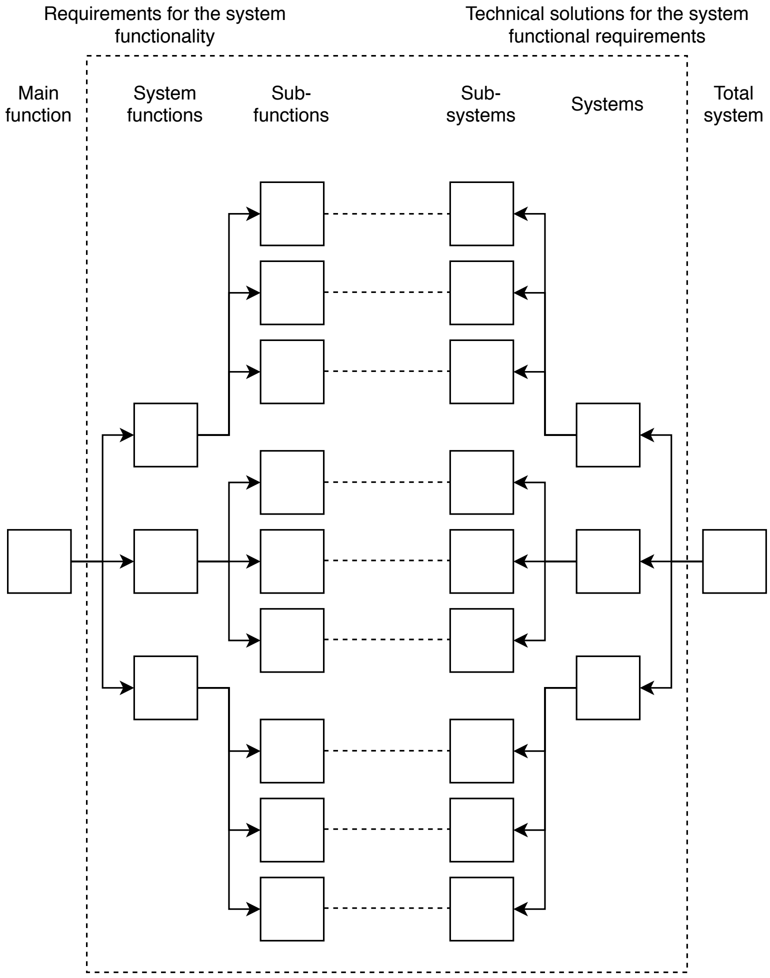


Figure 6.2: Schematic combination of the functional requirements and the logical or technical solutions

**Step 3 - Creating the Design Structure Matrix and using the clustering algorithm**

The DSM is not the same as the logical decomposition which is defined in a matrix form as well. For the decomposition all the elements are first included in the matrix for the full decomposition. The next step is to determine the sub-systems in the decomposition. This means that all the elements which are not sub-systems should be excluded from the DSM. Practically it means that the more describing elements are excluded. For instance when using the figure below as example the battery power, charging system, transform/control system and the storing system are all describing elements of systems and not sub-systems. This means that they should be excluded in the final DSM for clustering. As the describing elements are excluded, the different 'groups' become less separated. For this reason numbers are connected to the decomposition in the form of 1.4 for provide mechanical power in the form of a generator system. More towards sub-systems such as the LNG supply system 1.4.1 and 1.4.1.1 for the sub-system of the tank for LNG. This way the groups can be differentiated from others which is visualized in Figure 6.3.

The second step in the clustering algorithm is to define interactions between the sub-systems. The general connection is defined for this step where it is possible to start with the column or row. In this interaction defin it is possible to start with defining the 'input from' interaction between sub-systems after which the 'output to' can be defined. As the system consists of various interactions the matrix does not become symmetrical which means that it is important to approach the interaction definition from both sides. In addition to the interaction definition the interactions in the matrix have to be translated into data which can be used by the clustering algorithm. The code for this is shown in Appendix E.

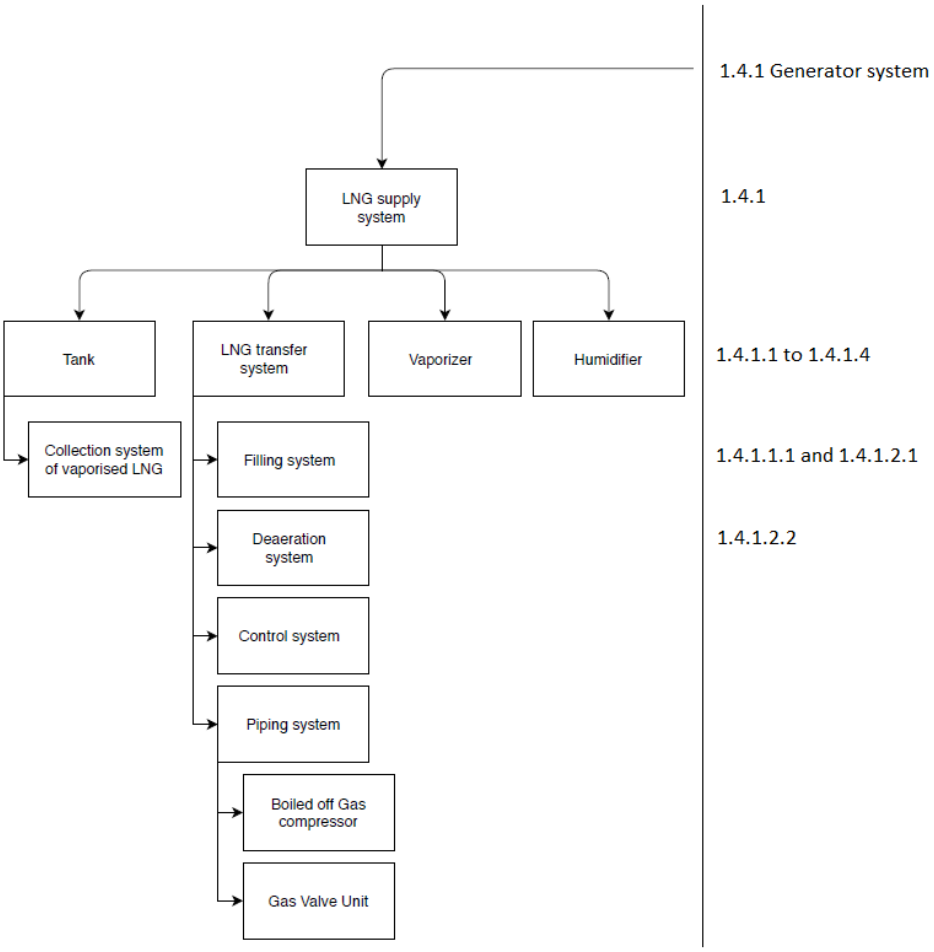


Figure 6.3: Elaboration of number allocation to different levels of elements

The third step is to run the algorithm using the predefined parameters as elaborated in Chapter 5.6 and Appendix F. The figures resulting from these runs can be saved to be processed and analysed.

### 6.1.2. Level 2 of decision making using modularity driving reasoning

**Step 4 - Refinement of results of the clustering algorithm**

Based on the first part there now are abstract results resulting from the clustering algorithm. First, a result refinement of the results is done before translating the results to specific sub-systems. After this the interactions are tracked to determine the amount of interactions outside the clusters.

A number of feasible cluster solutions is generated for each of the configurations from the total generated results. For this first refinement a combination is made from the different runs. In this refinement, if possible, double elements should be avoided as in practice this module is not feasible. Most likely the potential modules are largely similar where it is possible to find 1 or multiple potential clusters.

The second refinement is to combine the different configurations into one solution. At this point the focus lies on determining the difference in cluster results between the total solution and the other configuration options. Important to know it that it is possible to reduce the size of clusters, but much more difficult to increase the size of clusters. When increasing the clusters it has influence on the result costs of the clustering and new interactions have to be traced. When reducing the size of a cluster the interactions are known within and outside the cluster which means reducing is more feasible. Therefore, if there is a cluster solution which has one element less than another, the one with the extra solution can be reduced with a higher possibility for a feasible solution. A combination of all the results can be defined in one table with in this thesis clusters with a maximum of 4 variations per cluster while following the defined approach.

After the refinement for all the solutions the interactions are defined and shown for each of the potential clustering results. The interactions should be minimized as elaborated in the working of modules in Chapter 4.1. All interactions are counted including combined interactions for the situation that from one cluster there are multiple connections to another cluster. In this situation it might be possible to group these interactions which therefore can be optimized and the interactions have less influence on the design.

**Step 5 - Translating numbers to sub-systems**

At this point the translation can be made from numbers to sub-systems. The analysis that has to be done next is to determine if the size of the cluster makes sense. Meaning that in the case that clusters become large, they are becoming inclusive which means that they become more complex. For that reason clusters should be not too large which is elaborated in Chapter 4.2.2. The second part is to evaluate the interactions of the clusters. As elaborated in the creation of the DSM for instance the interaction to the alarm or control system is not as significant as for instance the connection from the diesel generator to the exhaust system with regard to flexibility. Besides this, the interactions are evaluated for technical feasibility to ensure that the modules make sense and are potentially feasible.

Based on these two evaluations the final suggestion for the modules is made where potential interfaces for the modules is defined. The description of the suggested modules elaborated on the potential can be used to design, to optimize and to standardize the specific modules, creating a variation of solutions. The next step outside this research is to continue with the development of the specific modules and design variants to a level at which they can be interchanged with each other based on the design requirements.

Table 6.1: Steps and a selection of limits for the requirements to the functionalities

**Requirements**

| | Limits* | | |
|---|---|---|---|
| Electrical energy management | System volume | 928 | m3 |
| - Transfer energy shore to ship | System weight | 206 | tons |
| - Storing of electrical energy | Combined system weight | 63 | tons |
| - Distribution of electrical energy | Minimal required power summer | 1613 | kW |
| - Control of electrical energy | Minimal required power winter | 2393 | kW |
| - Generation of electrical energy | Minimal required energy summer | 479 | kWh/trip |
| Fuel management | Minimal required energy winter | 1685 | kWh/trip |
| - Store fuel | Fuel weight | 46 | tons |
| - Distribution of fuel | | | |

*Selection of maximum total system values based on 9819 E3

**Functionalities**

| Configuration | System limits | | Specific system meaning | | |
|---|---|---|---|---|---|
| | | | Summer | Winter | |
| **Battery** | 0,03 | kW/kg | 47586,6 | 70,6 | tons |
| | 0,04 | kW/l | 41,5 | 61,6 | m3 |
| | 0,08 | kWh/kg | 6,1 | 21,6 | tons |
| | 0,09 | kWh/l | 5,5 | 19,4 | m3 |
| **Fuel cell** | 0,44 | kW/kg | 3,7 | 5,5 | tons |
| | 0,23 | kW/l | 7,2 | 10,6 | m3 |
| **Dual Fuel** | 0,05 | kWh/kg | 31,4 | 46,7 | tons |
| | 0,03 | kWh/l | 47,7 | 70,7 | m3 |
| **MGO** | 0,13 | kWh/kg | 12,2 | 18,2 | tons |
| | 0,08 | kWh/l | 19,5 | 28,9 | m3 |

## 6.2. Practical elaboration of the method

Two examples are used to elaborate the method and the influence on the design of the vessel. This way it is possible to elaborate on the influence of using modules in the design with regard to changing requirements or elements. The first example is a change in power requirement which results in a change of diesel generator. The second example is the change from using a combustion engine to a future change to use methanol in a dual fuel engine and in another configuration in a fuel cell.

### 6.2.1. New design using diesel battery configuration with changing power requirement

To start the first example for a diesel electric configuration the schematic visualization of the modules shown in Figure 6.4 is used. Starting with the example shown in Table 6.2 the difference between the two vessels is first of all the size of the two vessels and secondly the maximum speed. This change in power requirement can be solved in two ways. The assumption in this example and also in this thesis is that generators are used which transform chemical energy into electrical energy. This means that a direct drive configuration solution is not taken into account. Besides this the Azimuth thrusters are also not in the scope which means that the configuration from the electricity generation or storage to the thrusters is also not elaborated.

**Power requirement change option 1**

The first possibility is to use the method used for the 6819 E3 ferry as shown in the table. In this case the diesel generator sets are kept the same which means that the power generation to electric power is the same as the 9819 E3 ferry and only the battery capacity is changed. As the battery capacity is highly modular as also shown in Figure 6.4 this is the simplest adaption when starting with the designed propulsion system from the 9819 E3 vessel.

**Power requirement change option 2**

The second possibility is to change the diesel generator sets for another power requirement. As the length of the second vessel is 26.7 meters shorter than the first one. This means that the resistance of the vessel is less and therefore less propulsive power is required. Taking that into account there is a possibility to reduce the size of the generator sets. For this configuration all the modules shown in Figure 6.4 are used. To demonstrate the working of this possibility, two engines are used where the first engine is the CAT C18 565 ekW, 575V 60 Hz as defined in the vessel specifications in Table 2.3. The assumption is made that the second engine is the CAT C13 320-400 ekW, 380-415V 60 Hz[11]. When using modules it was elaborated that there is an over-dimensioning or over-design where systems or parts for instance have higher capacities than required.

When looking to the interactions of the generator to other systems based on the DSM Figure 5.12 the interactions are with the exhaust system, lubrication oil system, fuel supply system and the switchboard. For all these systems the effect is briefly discussed to show the influence of the change. Starting with the air intake ducting the main requirement with regard to the design which is influenced by a change in engine size is: "Piping diameter should be equal to or larger than the air cleaner inlet/outlet and the engine air inlet" and "keep maximum air velocity in the piping to 10 m/s"[10]. When designing the system for the larger engine it then is possible to keep the same air intake system for the smaller engine. This does mean that the intake is larger than the required size, but in theory can be used for both engines.

Next to the air intake is the exhaust system which is a module as well. Besides the placing requirements for this system there is the requirement: "Exhaust piping should be sized according to the maximum back pressure limit for the engine."[9] This again means that it is possible to design the exhaust system for one configuration where it might be less optimal for another system but remains within the maximum back pressure value. This means that this module can be kept the same as well.

Thirdly, the fuel transfer pump is discussed. When staying with this example the engines of CAT are engine driven[8]. This means that there is no pump in the connection from the tank to the engine which means that this system again can also be standardized. The limit for the design difference is that the fuel return line should be kept below 27 kPa for the return line for instance[8]. In this case again it is possible for the systems to be able to fulfill both the requirements of the engines and one system design can be used without change.

Storing modules have the main connection with the piping systems. This means that again it is possible to standardize the storing modules for in this case the MGO or lubrication oil where only the amount of storage should be checked. However, the design only can remain the same if the connections are standardized.

### Conclusion of the power requirement design

Taking the second option in power requirement adaption this approach shows that changing a power requirement has little influence on the system. If a system is designed not only fully for one specific design but is able to fulfill the requirements for the system configurations, the change only has influence on the engine itself and the connection to the sub-systems. A note to this approach is that no calculations are done to mathematically prove that using one system configuration is possible to use for both the engines. Besides this a size and weight calculation should be done to define the specific influence of applying this modular design. The example shows that the method provides a design support tool in order to objectively find modules based on the main modularity drivers. Using the method in this thesis and the defined modules it is possible to quickly see and map the change and the influence on other modules. By having a clear meaning of the limiting factors or requirements for a module it is possible to assess if a change in the generator has an influence on the design.

Table 6.2: Damen E3 ferry vessel specifications

| Ferry | 9819 E3 | 6819 E3 | |
|---|---|---|---|
| Length | 98.4 | 71.7 | m |
| Beam | 19.8 | 19.8 | m |
| Draught | 2.9 | 2.9 | m |
| Max. speed | 13.5 | 12 | kn |
| Propulsion | 2x 565 | 2x 565 | ekW |
| Battery | 4000 | 1800 | kWh |

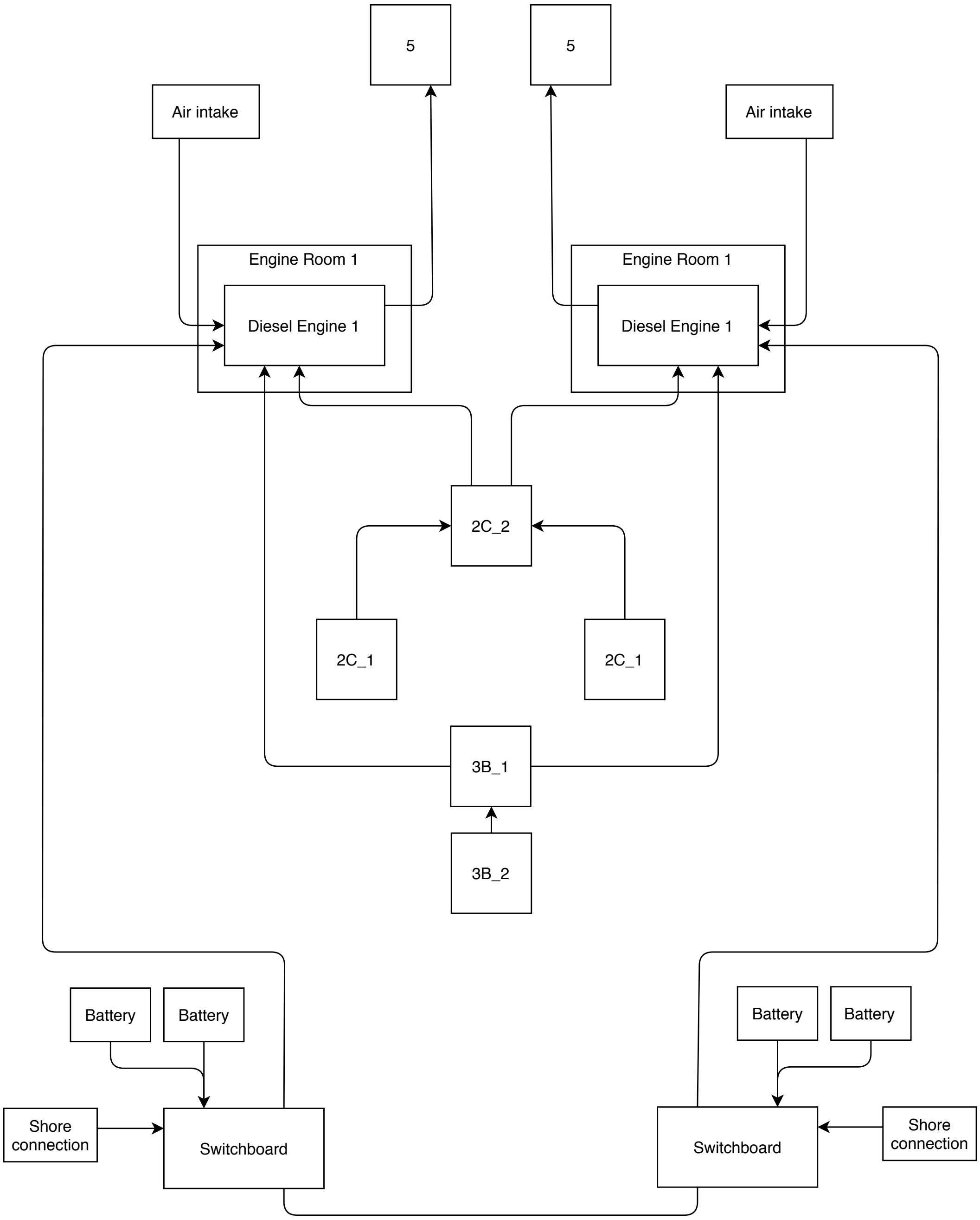


Figure 6.4: Visualization of the combination of suggested modules and their main interactions for diesel electric configuration

### 6.2.2. Double ended ferry refit in energy carrier and conversion system from diesel to methanol

The second example is more complex as the whole system is changed from a conventional combustion system to a fuel cell system. For this system there is a change from the configuration which is shown in Figure 6.4 to the configuration shown in Figure 5.23. This change in system shows a complete change in energy conversion system. This means that the diesel engine and modules 2, 3 and 5 are changed for modules 6, 7 and 8. The system change is from a conventional combustion system to a methanol propulsion system. The methanol propulsion system currently is not commercially available, but it is possible to elaborate on the potential implementation. Besides this it is possible to show the difference in systems which are included in the method where the steps are taken for RFLP and the impact it has on the design change. For the system change or refit there are two options in the implementation. Firstly, there is the possibility for the conversion to use a combustion engine and secondly there is the possibility for fuel cells. Both these situations can be further elaborated where there is a common base and a difference in the conversion system.

#### Diesel generator to methanol dual fuel engine

Starting with the original configuration shown in Figure 6.4 where the diesel generator system which is connected to the switchboard. In this situation the assumption is done that there are already batteries included in the system making the system a diesel electric ferry. The basic information to start with the design refit starts with the data shown in Table 6.1. As Methanol is not yet included in the method two extra tables are added for the basic information as shown in Table 6.3 and 6.4.

Table 6.3: System difference specification between MGO and Methanol based on Chapter 3.3 and 3.5

| | MGO | Methanol | | |
|---|---|---|---|---|
| | HS Diesel | Dual fuel | Fuel cell | |
| TRL | 9 | 8 | 5/6 | - |
| System specific weight | 0,13 | 0,05[1] | 0,44[2] | kW/kg |
| System specific volume | 0,08 | 0,03 | 0,23 | kW/l |
| Storage volume capability | 100% | 40% | 40% | % of MGO |
| Fuel capacity | 45,7 | 40,6 | 40,6 | tons |
| | 38,5 | 38,5 | 38,5 | $m^3$ |

Table 6.4: The system weight and volume change from diesel to methanol energy carrier and conversion system for the 9819 E3 ferry

| Configuration | | System limits | | Specific system meaning | | |
|---|---|---|---|---|---|---|
| | *Condition* | | | Normal | Winter | |
| Fuel cell | *System* | 0,44 | kW/kg | 3,7 | 5,4 | tons |
| | | 0,23 | kW/l | 7,2 | 10,6 | m3 |
| | *Storage* | | | | 87,5 | m3 |
| | *Total volume* | | | | 98,1 | m3 |
| Dual Fuel | *System* | 0,05 | kWh/kg | 31,4 | 46,7 | tons |
| | | 0,03 | kWh/l | 47,7 | 70,7 | m3 |
| MGO | *System* | 0,13 | kWh/kg | 12,2 | 18,2 | tons |
| | | 0,08 | kWh/l | 19,5 | 28,9 | m3 |
| | *Storage* | | | | 35,0 | m3 |
| | *Total volume* | | | | 63,9 | m3 |

As elaborated in Table 6.3 methanol requires 2.5 times more space for storage with the addition to this that the regular storage should be modified to accommodate for the low-flash point properties. The methanol does require a mix ignition to be used in a diesel cycle or a dual fuel engine should be used. Figure 5.23 shows the configuration for the fuel cell configuration. The refit to methanol is different than the elaborated and described cases. However, as the goal is to use the method for a future proof design an attempt is made to

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[1] The assumption is made that the system specification is similar to a dual fuel engine

[2] The assumption is made that the system specification is similar to a LT-PEM fuel cell

describe the adaptions to the system.

Starting with the transition from diesel electric to methanol using the dual fuel engine as the TRL for the duel fuel engine is 8 and 5/6 for the fuel cell. When looking at the available modules in the original situations the modules used are 2, 3 and 5. Module 2C_1 consists of the tanks, filling, de-aeration and the sounding system. Although the tanks can be used to store methanol the requirements for the storage are different and more strict than for MGO. With regard to module 2C_2 also there might be a different filling than the MGO. Module 3B_1 and 3B_2 can remain similar to the lubrication system for the engine where of course the lubrication requirements have to be checked using calculations and regulations. Module 5 could potentially be kept the same as well. Based on the specifications and requirements for the engine and the fuel types and specifically the fuel combination.

**Diesel generator to methanol fuel cell**

The second option is to transition from the diesel electric configuration to a fuel cell configuration. In this situation there is a total change of fuel type from MGO to methanol. In this situation the diesel generator, the MGO storing module (2C_1), MGO transport module (2C_2), Lubrication oil storing module (3B_1), Lubrication oil transport module (3B_2) and the Exhaust module (5) are not used anymore and need to be removed. However, lubrication oil is required for the thrusters which means that at least the lubrication storing module still is required but is outside the scope of this research. The change then becomes the storage from MGO to methanol where extra requirements are in place. Also the transport part to the fuel cell is unique as currently there is no other energy type which is transported from a 'diesel' tank to a fuel cell as liquid medium. Module 7a, Fuel cell oxygen module might be used but will require a change as the energy type is significantly different to LNG or Hydrogen.

**Conclusion of the diesel to methanol refit**

Concluding this part is that it is highly difficult to elaborate on the change in energy carrier and conversion systems if the systems are not commercially available. And therefore potential commonalities and differences are difficult to determine. Using the minimum amount of available information shows that the tanks for diesel can be used for methanol. For this transformation the note is that the range of the vessel decreases due to the energy and density difference of the two fuels. However, at this point it shows that the commercial availability is required to determine the requirements for the system as well as the functional and logical decomposition. The modular knowledge about the current system does help in identifying focus points for the refit towards the new system. The overall conclusion in addition to this example is that there is a significant difference between the examples. Where the first one is based and described according to the method, the second one is more not described. This shows that the usage of the RFLP approach and the usage of the DSM clustering including the refinements to the results result in the significant increase of usability of the results.

## 6.3. Discussion of the method and of the results

Defining the approach in a theoretical way resulted in multiple decisions which were made to be used in practice. One of the most important decisions was to use a modular-core platform which means that there is one core or basic module or core platform on which the other platforms are built on. This was visualized in Figure 4.4 and 4.5. Using the electrical setup of the vessel the core platform is the electrical connection. This means the electrical connection including the switchboards which are the connecting systems. However, in the practical elaboration using the DSM clustering in this situation it was not possible to implement the electrical connection due to the binary connection and more important the usage of the clustering method where connecting elements should be excluded from the clustering, elaborated in Chapter 5.7.1. Even though in theory the decisions are clear it is in this case difficult to couple it to the practical application. Outside of the clustering algorithm it is possible to define the module of the electrical system where the electrical connections from the switchboards to the (sub-)systems can be standardized.

**Platform decision**

The working of modular design became more clear after analyzing and using the results. Starting the approach, all methods are more abstract which means that it is difficult to determine the efficiency in practice. When evaluating the decision of using a modular-core platform instead of an inclusive platform it remains a good decision. When looking to the practical meaning of this the inclusive modules can be compared to the

First solutions in Chapter 5.8.1 where the modules are large and sometimes even consist of a whole system which means for instance the total fuel supply and storage system. The interactions than are minimized as is shown in the results but a change in requirement has a significant influence on the module which means that a change or improvement becomes complex and therefore time consuming.

**Solution method decision**

With regard to the potential methods which were possible to be used, the function decomposition which was used was required for the DSM. But more importantly it can be set up using standard function requirements. Meaning that it is possible to expand in a systematical way and it can be changed without changing other parts which is important in modular design. An important aspect in the usage or design of modules is the interaction and the interface between modules. First of all it is to be able to simplify connecting the modules to each other or to separate (sub-)systems. In addition to this and at least as important is that the setup of a DSM matrix maps the interactions between sub-systems. This means that the influence of a change in design or requirement can easily be followed to the effect on the modules and the interactions. This combines the two goals for the thesis for a modular and future proof design which can be implemented in the DSM.

MFD which was also proposed as option to determine modules and might still be an option to be used. However, the modularity drivers which are used are somewhat abstract that it would be necessary to work this method out before the effectiveness and feasibility of potential modules can be determined. These drivers in combination with the information that is used which is also abstract can make it even more difficult to use and interpret. For QFD the reason for not choosing this method remains the same as the goal is not to find one optimal solution at this stage but to have multiple solutions and to be able to evaluate the influence on using one solution over another. And next to this the influence of change which means the interactions between or outside clusters.

For both the functional and logical decomposition it is possible to improve them. The decompositions are based on the available information which could be found. This means that it might be more detailed and correct for the electrical and diesel configuration than it is for the LNG and hydrogen configuration. As for these last two configurations the specific class approved system drawings were not available which means that the decomposition is based on theoretical diagrams and not on approved P&ID drawings for instance.

It is also possible to reference the results and method to the idea for modularity named SYSMOD which is used by Damen. For this approach the core is the base system which is composed by one or more elements. A variation element only occurs in the case that a certain configuration is selected which is part of the variant. The point of variation can be seen as the docking point or interaction point. Specifically it means that a different propulsion train can be selected. In this case the propulsion train is the core and a variant then is a complete set of variant elements that varies the system. Translating this explanation of approach to this thesis the core is the different modules which together form the total system. For required modules variations can be developed which then is a variation element. A variation can be developed in the case that for instance a different engine is used which may result in different requirements for the fuel supply system. At this point the fuel supply module requires a variant for the propulsion train to work. In practice more modules will be influenced and require variant where a combination of these variants then is a complete set which varies the system.

## 6.4. Improvements on the DSM clustering method

**Non-binary input**

An important first decision which was made in the approach of Thebeau [92] that the interactions which are defined between functions and the logical elements are entered in the DSM with equal weight. In this decision is the assumption that the interface must be managed without much regard for the type of interaction which is taking place. However, this decision is questionable for some reasons. Firstly, there is a difference in the connections in systems. For instance, the connection between an engine and a gearbox is significantly more important than an electrical connection as it is often the case that electrical wire can be extended without much trouble. This means that there rather is a difference in connection level requirements. Secondly, the clustering results in the approach showed that members of clusters were not always highly similar and it occurred that the interaction level was not high. This resulted in clusters which were connected through interactions which should or could not be the the driving factor behind the design and clusters which were driven through indirect connections.

To resolve this problem a range of values for interactions was defined where a value of 0.5 was used for a weak interaction to a value of 2 for a strong interaction. Specifically the weak value could be used to define an electric or control interaction as these can be relatively flexible. However, for the first usage of this method, the decision is made to leave out other values than one to start the clustering algorithm. Also as it is possible to see and understand the influence of the different values and to start the method in a more controlled manner.

**Possible improvements to the elements and decomposition resulting in the DSM**

In the first attempt the water cooling system is not included in the clustering. This decision is made as the advise is to start with a smaller matrix due to the complexity and to be able to interpret the results. The inclusion of the water cooling system would mean more interconnections between systems. In the first logical decomposition the water cooling system is included in two parts where one part is for the generators and one part for the auxiliary systems. This means for instance for the batteries and switchboards, lubrication oil, etc. As the water cooling system would combine more systems together it also means that other clusters can be found which might be more optimal. The difference in inclusion of elements in this step is shown in Appendix C in the logical decomposition element list from version 2 to 3.

Secondly, the usage of a dual fuel system with a dual fuel engine and the hydrogen system using fuel cells are decomposed to more theoretical levels. This means that for the batteries and diesel generators there are specified P&ID drawings which work and are approved by class. However, as dual fuel and hydrogen with fuel cells are not yet used within Damen these decompositions are based on theoretical documents which means that the specification of the decomposition might not be complete. Nonetheless, the inclusion of these possible storage and conversion systems is an important aspect. As the clustering shows possible modules which means that the interchange of these systems can be determined based on the clustering.

Thirdly, the electrical system is not defined completely in the decomposition. Where the main components of the electrical system are taken into account the electrical connection between the systems in not defined in the DSM matrix. This counts for the electrical system including the control of systems and alarms. However, these sub-systems might have an influence on the clustering which means a numbered clustering would be a possibility. In this DSM setup the connections are defined by numbers between for instance 0.5 and 2 instead of binary connections. In this case a value of 2 would be a strong and important connection where a value of 0.5 would be a less important connection. In this way it is possible to include less important connections such as electrical which are more flexible than for instance a tank and filling system.

Finally, with regard to the drip tray it is defined as a sub-system but is not really connected. There is piping and storage for the drip tray, however, in some systems the drip tray is just a drip tray without the piping which means that for instance the dirty oil has to be collected manually. The drip tray system therefore is not seen as a connecting system but as a part of the system it is attached to.

**Algorithm improvement**

With regard to improvements possible for the clustering algorithm there are improved versions. These versions find the optimized result which means that after one run the solution is found. However, as seen it is not always the case that the best solution with regards to costs is also the best solution for feasible modules. But when using the optimized algorithm the parameters would become the values to 'play' with. This means that the parameters Cluster_param.pow_bid for penalizing cluster sizes and Cluster_param.max_cluster_size could be changed to influence the size of the clusters. It is expected that the amount of results can then be reduced which means that running the algorithm for new solutions becomes faster and more efficient.

# 7

# Verification and validation of the method

A mathematical model is a system of equations with related mathematical expressions that describe the problem using decision variables, an objective function, constraints and parameters. The objective function is the goal of the function and therefore the decision variables, the constraints are restrictions on these variables and the parameters are inputs[28]. Continuing with this definition the verification and validation is elaborated. This is more difficult as "A model is not verifiable directly by experiment. For all models are both true and false. Almost any plausible relation amongst aspects of nature is likely to be true in the sense that it occurs (although rarely and slightly)." and "All models leave out a lot and are in that sense false, incomplete, inadequate. The validation of a model is not that it is 'true' but that it generates good testable hypotheses relevant to important problems."[61]

Therefore, for the verification and the validation of the method the paper from K. Pedersen et al.[36] is used as it describes a method to verify and validate a design method which is used in this thesis. According to this paper normally validation refers to internal consistency which is for instance a logical problem. Verification refers to justification of knowledge claims. However, in modeling these terms are used the other way around. Thus, verification refers to internal consistency and validation to justification of knowledge claims[3]. Specifically it means[28]:

- **Verification:** The implemented model is according to the mathematical model. Meaning: Is the the model right?
- **Validation:** The mathematical model is fit to provide answers on questions regarding the real world problems. Meaning: Is it the right model for the problem?

Engineering design primarily involves open problems which involve objective and subjective elements where there is no single right answer or solution. Meaning that a logical validation only based on experience which is strictly formal cannot be used as the results are often not either true or false. Also Relativist validation cannot be used alone. Here validation is used as a gradual process of confidence building in the usefulness of the generated new knowledge. The objective of this validation and verification approach therefore is not based on relativist or logical experience validation as there are no specific right or wrong answers to the problem. Besides this, many heuristics are involved and less or non-precise representations are common. Formal and quantifiable validation can be applied to a design method's internal consistency. This means that the validation is based on the logic of the method. However, the external relevance is not proved by this validation which means that the usefulness of the method is not validated. For this reason the purpose of the method should be elaborated including a set of example problems which can prove the usability of the method. The examples can be analyzed to prove whether they support the theory to prove the usefulness of the design method.

The validation and verification itself is following the V-cycle and is specified in Figure 7.1. The specific verification and validation steps are coupled to the different stages of verification and validation defined in the V-cycle.

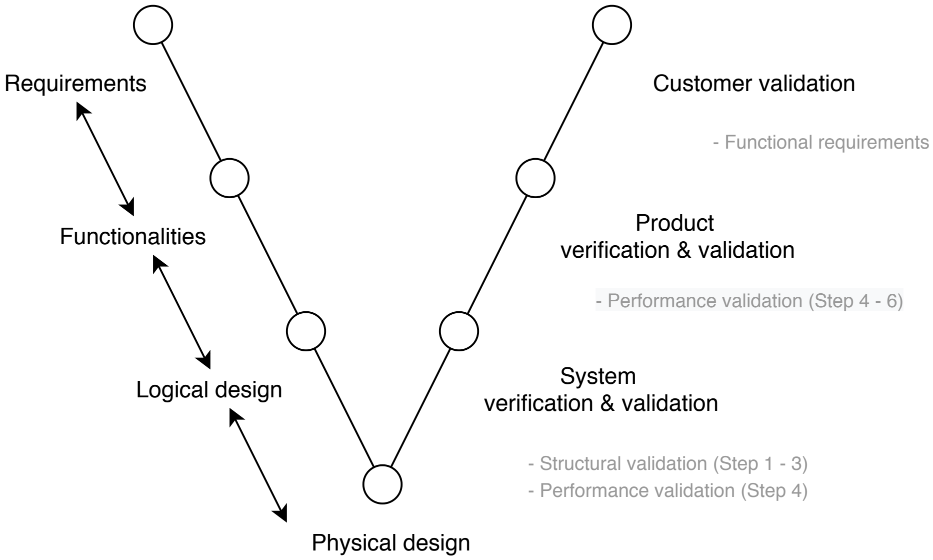


Figure 7.1: V-cycle verification and validation using the second half of the V-cycle adapted from Figure 1.7[85]

## 7.1. Validation and Verification using the Validation Square

The steps for the validation can be divided into two parts. These are the structural validation and the performance validation. The two parts are divided into 6 steps which have to be taken and are shown in Figure 7.2. The first step is focused on individual validity, step 2 on integrated validity and the third step for the validity of the example problems which are used to test the method. In the fourth and fifth step respectively the usefulness of the method for the example and the usefulness achieved by the application of the method is demonstrated. Finally, step 6 elaborates on the generality of the method.

### 7.1.1. Part 1 - Structural Validation

**Step 1** Accepting the individual constructs forming the method and thereby accepting its validity:

For this confidence in the validity of the method it is suggested to use literature. The constructs in this method are the mathematical formulas and the specific usage of them for the clustering algorithm. The acceptance of the method will be based on literature and the application of the clustering method. If the clustering method and code is used as benchmarking for new constructs they can be demonstrated as highly accepted and valued.

The method used in this thesis is the Design Structure Matrix method and specifically the mathematical clustering algorithm. The DSM is used for a long time[70] where the different approach is the usage of the mathematical analysis for the clustering in the DSM. The DSM itself is accepted in design and processes and is researched at multiple universities[69]. In the report the code made by Thebeau [92] is used that thesis builds further on the work of Gutierrez [47] who connects clustering with DSM. The clustering algorithm is based on a previously developed algorithm from Idicula [51]. This means that the combination of the clustering and the DSM method are combined for the first time in the method of Gutierrez [47] and both the clustering and DSM method are not new.

Where the first setup of the approach was elaborated for a less complex system the thesis of Thebeau [92] uses it for a more complex and integrative system. And based on this work new improvements are made for instance by Fredrik Borjesson [43] and Damasi et al. [25]. Based on the history of both the clustering and the DSM method and the usage of the combined algorithm in Thebeau [92] on which new methods are built the individual constructs or the method is accepted. Therefore the validity of this method is accepted.

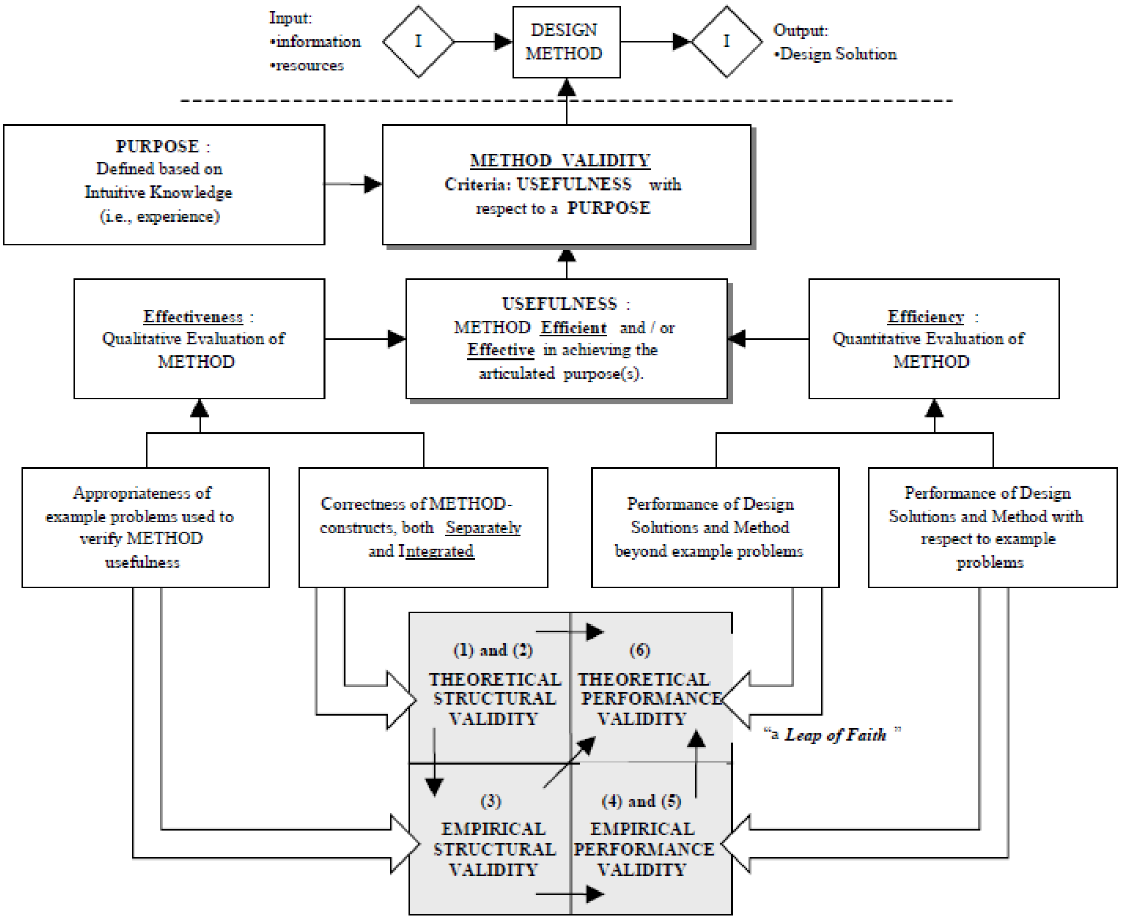


Figure 7.2: Design method validation by using the Validation Square[36]

**Step 2** Accepting the internal consistency of the way the constructs are combined in the method:

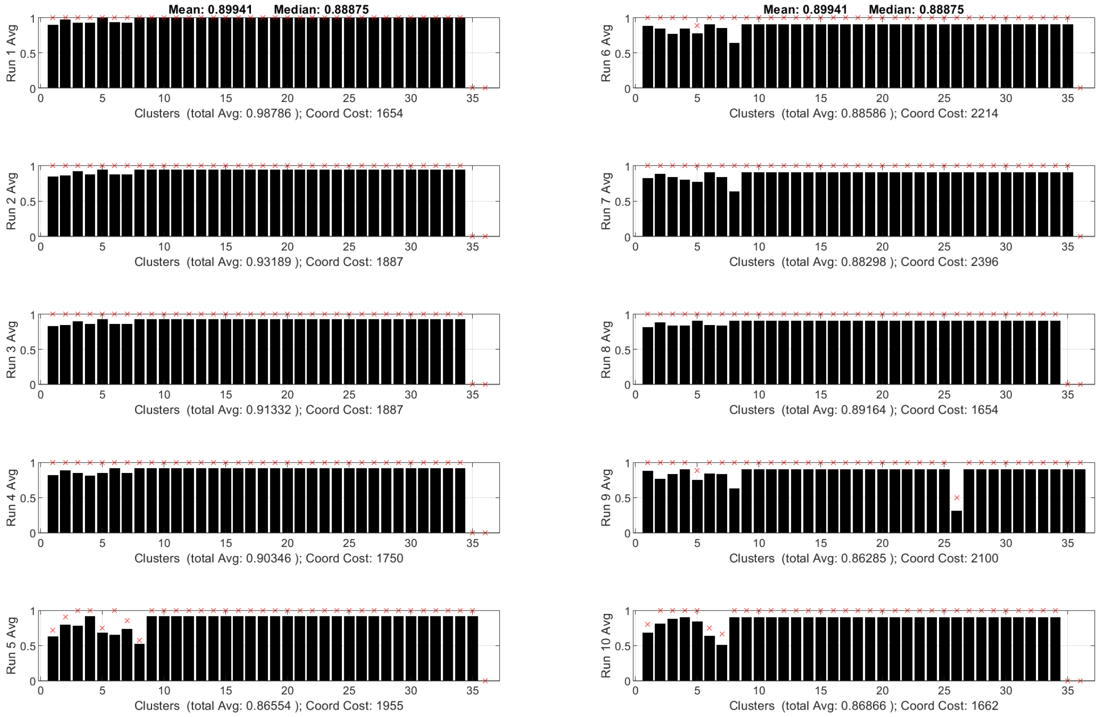
The confidence in the constructs combined in the method, being the internal consistency, is suggested to use a focus on the information flow. By using a flowchart visualization it is possible that for each step the input can be verified to be adequate as well as for the output. in addition to this the identification of the in- and output information shows what information is available to be able to compare it to reality. Inconsistency in the method is defined by the generation of information which is unnecessary or inadequate and the assumptions which are invalid which influence the method results.

The flowchart of the method to find clusters is shown in Figure 5.14. The input for the clustering algorithm is based on the input of the DSM and the parameters which are used for the functions. To build confidence in the internal consistency and to verify the out- and input of the method three steps are taken. The first two steps are for the output where the last step is for the input data.

1. The *stability and the validity range* of the solutions is elaborated. This means that the results are analyzed for feasibility or the results.
2. The *what-if analysis* where other scenarios or different assumptions are used in the method.
3. A *sensitivity analysis* where parameters over a range can be varied to find the most critical or sensitive ones. This means the determination of the influence of change in parameters or input on the results.

**Stability of the results**

The stability of the output of the results can be elaborated by using the likeness of the results as described in Appendix F. This likeness can be calculated for each of the configurations but is now only done for the dual fuel and battery configuration. The likeness of the cluster results are shown in Figure 7.3. This likeness improved when changing the parameters to the values as described in Chapter 5.6. The results show that over 10 runs there is a high likeness of elements being in the same cluster. With a mean of 0.899 it shows that the results are very consistent even though the 'optimal' solution is not necessarily found. As the 10 runs are different runs than the ones shown in the results and appendix the average cost results are compared where the average costs of the runs in the report is 1923 and for the likeness calculation 1920. This means that the likeness calculation is really comparable to the cost results used in the results. Besides this, the consistency is shown in the clustering and the simulated annealing. The working and consistency of the simulated annealing which is used is also shown in Figure 7.4. This figure shows the amount of different clustering suggestions where a lowest cost is reached and once every 2 times the DSM size a less optimal solution is used to potentially lead to a better solution. The figure shows that the process is repeated multiple times according to the defined parameters and the final solution is the solution with the lowest cost. Again this is one example shown where the working is clear. For the other runs the working also shows the same consistency.



(a) Average likeness of clustering results dual fuel batter configuration 1 to 5 (b) Average likeness of clustering results dual fuel batter configuration 6 to 10

Figure 7.3: Average likeness of 10 clustering runs for the dual fuel battery configuration

**The what-if analysis**

This analysis focuses on different configurations where there is a different input due to other energy storage and conversion systems. This analysis is already applied in the analysis of the results in Chapter 5.7 and is shown in the results of the different configurations where the cluster results combination is shown in Appendix G in G.5. The results show large overlapping of clustering results. As is expected there are differences in clusters due to elements being removed in the clustering of different configurations. However, the overall clustering results are relatively similar.

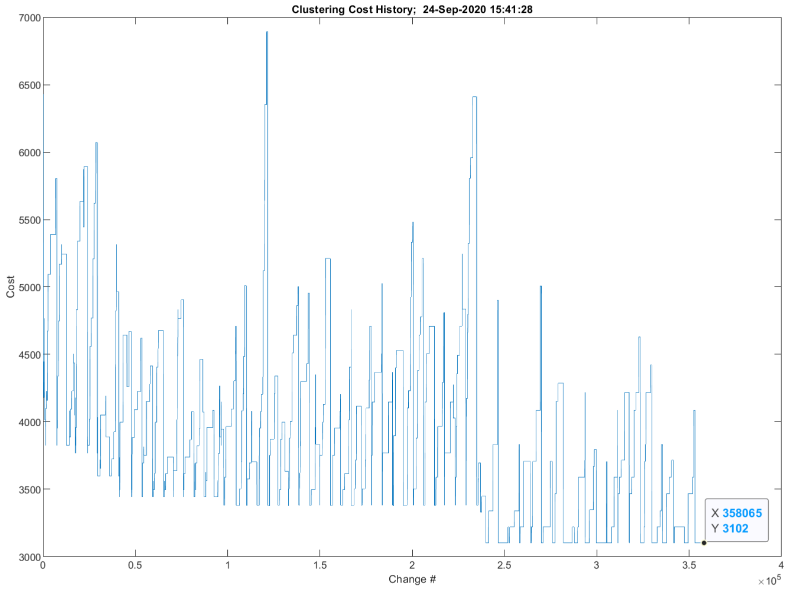


Figure 7.4: Cost evaluation using the simulated annealing in combination with the random clustering with data originating from run 4

**Sensitivity analysis**

The input for the clustering method can be verified by using a sensitivity analysis. By changing parameters or input values it is possible to show the influence on the results. Only two parameters are tested which are the Cluster_param.times and the Cluster_param.stable_limit parameter. The original values for this parameter were set to 2 and 2 where the final parameters were set to respectively 25 and 5. The parameter change specifies the increase in attempts to find a better cost solution which means that the result should be better. Using the example it was shown that the change in parameters showed a better optimization of the costs which specifically meant that lower cost solutions were found. The likeness of the cluster elements does not change significantly where the mean of the respectively '25,5' parameters was 0.899 is the mean for the original '2,2' parameters 0.859. However, the average cost of a solution went to 2647 instead of 1923.

The input verification for the two clusters shows that firstly, an improvement is made with regard to the solution which is expected based on the simulated annealing. And secondly, the consistency of the elements in the clusters remains high meaning that the clustering algorithm is consistent. No other changes or tests are done in changing parameters which means that the input is not fully tested. Cluster_param.pow_cc and Cluster_param.pow_bid could be changed in order to have influence on the size of the clusters. However, this would be mainly relevant in the situation that the optimal solution is found where the different results now already showed different cluster sizes. Therefore, these parameters were kept constant and the testing of the values was accepted from Thebeau [92]. Finally, there is the cluster parameter Cluster_param.pow_dep for the interaction focus. Also this parameter is not tested for influence on the clusters. As the interactions are defined as '1' or '0' the value of the interaction is the same. Implying that it would be more interesting to change the value of this parameter in the case that a variable interaction is used and defined at which the influence of this parameter could be shown. Therefore, also for this parameter the value provided by Thebeau [92] is accepted for this research.

In addition to the parameter variation the influence of input change is elaborated as well. When the DSM input was generated two mistakes were made. The first mistake was the deleting of an element which was not implemented correctly in the input data for the clustering algorithm. This is shown in Table 7.1 where the fist column is the right version. The middle values in the fault version where the order of the numbers is put in wrong. As the input for the DSM is abstract this mistake is only found when the results are analyzed. This mistake specifically was not significant as element 63 was not included in the clusters. Changing this input connection from 'input from' to 'output to' in this situation therefore meant no change in the clusters but only in the change in direction of the input. This is also shown in Figure 7.5.

Table 7.1: Fault DSM input and change for the clustering algorithm specified in data snapshot

| Changed version | | Fault version | |
|---|---|---|---|
| DSM(59,60) | = 1; | DSM(59,60) | = 1; |
| DSM(60,60) | = 1; | DSM(60,60) | = 1; |
| | | | |
| DSM(**61,61**) | = 1; | DSM(**61,61**) | = 1; |
| DSM(**62,61**) | = 1; | DSM(**61,62**) | = 1; |
| DSM(**63,61**) | = 1; | DSM(**61,63**) | = 1; |
| | | | |
| DSM(55,62) | = 1; | DSM(55,62) | = 1; |
| DSM(57,62) | = 1; | DSM(57,62) | = 1; |
| DSM(60,62) | = 1; | DSM(60,62) | = 1; |
| DSM(62,62) | = 1; | DSM(62,62) | = 1; |

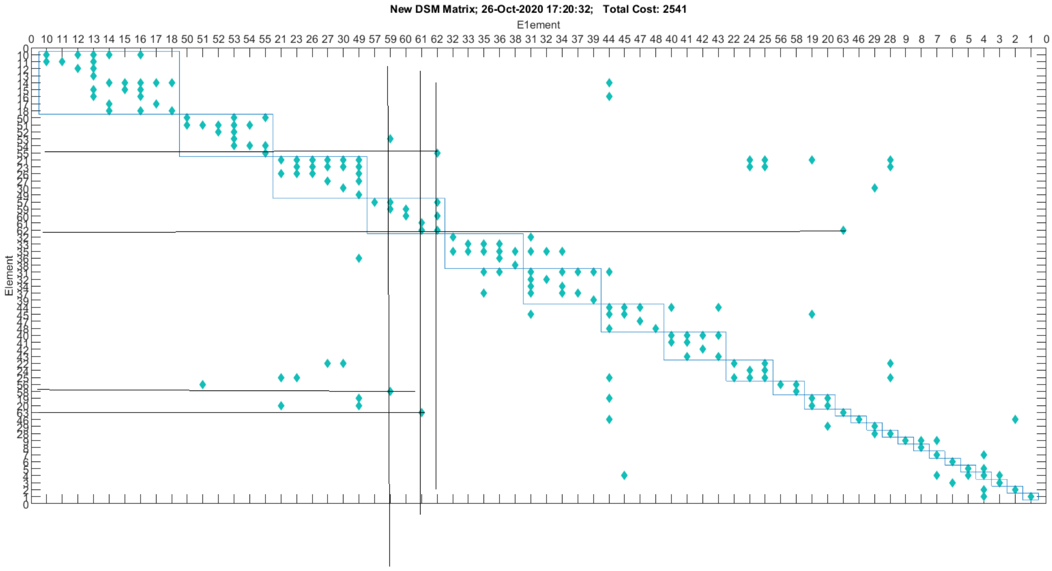


Figure 7.5: Change interaction direction for element 63 based on a fault of DSM input data

In another situation an element was deleted from the input as it was not correct. The result for this was that the element was included in a cluster where it is not possible to state that the cluster configuration would have the same form in the case that the element was not included. The results from this first run overview is shown in Table 7.2 where in the first cluster the mistake is shown. This mistake shows that the results are highly sensitive for faults and faults are difficult to find due to the abstract input.

Table 7.2: Clustering results fault version including element 39

| | Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 | Cluster 7 | Cluster 8 | Cluster 9 |
|---|---|---|---|---|---|---|---|---|---|
| A | 31 | 22 | 51 | 56 | 45 | 14 | 41 | 10 | 19 |
| | 34 | 24 | 52 | 58 | 48 | 15 | 42 | 11 | 20 |
| | 37 | 25 | 53 | 59 | 49 | 16 | 43 | 12 | 21 |
| | **39** | | 54 | 60 | | 17 | 44 | 13 | |
| | 40 | | | | | 18 | | | |
| B | 32 | 23 | 55 | 57 | 2 | | | | |
| | 33 | 26 | 50 | 61 | 46 | | | | |
| | 35 | 30 | | 62 | | | | | |
| | 36 | 21 | | | | | | | |
| | 38 | 27 | | | | | | | |

**Step 3** Accepting the appropriateness of the example problems that will be used to verify the performance of the method:

To build confidence in the appropriateness of the examples used to verify the method, performance documentation in stages is suggested. The first step in the documentation is to elaborate on the similarity between the example which is elaborated and the purpose problem for which the method is already generally accepted. The second step is to prove that the elaborated example represents the defined problem for which the method is intended to be used. This means that the goal of the research and working of the tool is compared to the example to prove that the example fits within the working of the method.

The example problem is about an elevator system to prove and elaborate on the method of combining DSM with clustering for more complex systems. In the example which is used to apply the method in the research of Thebeau [92] there are mechanical and wiring parts, control systems and different kind of interactions. In addition to this, there are different levels of importance with regard to the connections/interactions. The problem shows one system configuration where modules have to be designed to be able to meet the system performance for multiple variations of the design. With the second goal to have standard and optimized interfaces such that the modules can be used for multiple models.

This setup for a problem is focused on one system where there are variations on modules to be able to meet requirements of different designs. For which the alternatives can be connected by a standard and optimized connection. In the basis this is also the goal for this problem. Elaborating the example of a diesel electric configuration where there is the system for which the clustering algorithm can be run. The systems, which form the energy storage and conversion system, are divided into clusters based on the interactions in order to find and define modules with standardized interactions or interfaces. Besides this, the decision was made to use the RFLP approach which is also used in the research of Thebeau [92] in order to work to the elements of the DSM for input for the clustering algorithm. The combination of the goal and the approach which was used in the example of Thebeau [92] the comparison can be made between the two examples which means that this method can be applied to the example or problem in this thesis.

### 7.1.2. Part 2 - Performance Validation

**Step 4** Accepting that the outcome of the method is useful with regard to the purpose for chosen examples:

The usefulness of the method is also proven by the examples which are representative to build confidence in the method. The outcome can then be evaluated in terms of its usefulness. With this the purpose of the method can be included to clarify and therefore be able to elaborate on the usefulness.

The goal for the DSM as defined in the report is: "To find clusters for possible modules that remain constant in configurations by searching for the minimum interaction between clusters. And next to this the goal of the DSM clustering is to define the interactions between and outside clusters to be able to standardize those interactions."

The results elaborated in Chapter 5.8 show that there is a number of solutions as the result for this algorithm is not necessarily giving the optimal result. Due to the use of random cluster solutions in combination with simulated annealing. This is further elaborated in Chapter 5.6. Therefore, an extra level of decision making is required to find if the results are useful with regard to the purpose of the examples. When elaborating and visualizing the results of Table 5.3 the results show: Clusters that have little interactions (shown in Table 5.4), acceptable size of clusters and technical feasible clustering groups (elaborated in Chapter 5.8.3). In order to further analyze the results the potential working of the clusters is evaluated and the interface is determined to ensure that the suggested modules have a high feasibility potential (elaborated in Chapter 5.9. These steps alone do show that the outcome is useful as the goal as described above is reached. However, the requirement for minimum interaction could be improved by using the variable input for the DSM where the interactions are quantified. This way it is possible to specify the interaction even better. Resulting in the possibility for improvement with regard to the minimum interaction but based on the input the results are useful for the purpose. The evaluation of the results can be done using the V-cycle steps with regard to:

- System verification and validation
- Product verification and validation
- Customer validation

**System verification and validation**
The system verification and validation of the hybrid system configuration is designed and approved by class. Therefore, the design of this system can be used to evaluate the modules and the combinations of the modules while the system itself does not need additional evaluation. To prove the usefulness of the results of the method the technical feasibility of the modules have to be correct. For the feasibility there are a number of questions to assess the modules:

1. Do the sub-systems fulfill a single functionality?
2. Are the interactions logically and technically feasible?
3. Are the sizes of the modules feasible regarding the common-core design?

The first step is to validate if the sub-systems are correct and feasible. Figure 5.22 and 5.23 show a schematic overview of the system configurations and the main interactions. The interactions of these modules are discussed in Chapter 5.9.1. The evaluation of the connection between the functional and logical solution is elaborated in Chapter 5.4 and visualized in Appendix C. More specifically the analysis can be done using a single system and taking Figure 5.8 as an example. The functional requirements matched to the technical solution can be seen in Table 7.3. It shows that the same functionality description is used for different sub-systems. Where it is possible to connect general limitations or requirements to the functionalities it shows that a more defined functional description can be made for this system. Therefore, a more refined functional requirement decomposition is required. However, due to time limitations and the application of the DSM for the logical solution this is accepted for now. As the logical solution is used in the DSM it means that no logical elements are lost and therefore the solution is not compromised.

Table 7.3: Functionalities and system solution coupling for the lubrication oil system

| | **Functional requirement** | **Logical solution** |
|---|---|---|
| 1. | Fill oil storage | Lubrication oil filling system |
| 2. | Manage oil | Oil exhaust system |
| 3. | Convert chemical to electric energy | Diesel generator |
| 4. | Transport internally | Lubrication oil piping system |
| 5. | Manage oil | Dirty oil system |
| 6. | Transport lubrication oil | Lubrication oil pumping system |
| 7. | Control lubrication oil | Lubrication de-aeration system |
| 8. | Store lubrication oil | Lubrication oil storage system |
| 9. | Manage oil | Sludge system |
| 10. | Fill oil storage | Lubrication oil drum filling system |

Table 7.4: Boundaries of the sub-systems defined by interaction

| | **Logical solution** | **Interaction type** |
|---|---|---|
| 1. | Lubrication oil filling system | Flow of the fuel to the storage of the fuel |
| 2. | Oil exhaust system | Gas form of exhaust |
| 3. | Diesel generator | Transformer of fuel to electrical energy |
| 4. | Lubrication oil piping system | Flow of oil without change |
| 5. | Dirty oil system | Change of ’medium’ from oil to dirty oil |
| 6. | Lubrication oil pumping system | Changing of the oil flow |
| 7. | Lubrication de-aeration system | Aeration of the oil system |
| 8. | Lubrication oil storage system | Storage of the oil, therefore no flow |
| 9. | Sludge system | Change of ’medium’ from oil to sludge |
| 10. | Lubrication oil drum filling system | Storage of the oil, therefore no flow |

The second question is if the interactions are technically feasible and logical. For this question the same figure is used of the lubrication oil system. The main rule for this evaluation is to determine if the interactions are feasible based on a change in the flow or interaction. Table 7.4 shows that a boundary of a sub-system can also be determined in the change of a medium or the change in flow. Implying that no sub-system is cut within the function or change of flow and therefore makes the sub-system more technically feasible.

The third question is based on the cluster size which is answered in Chapter 5.8.3. By evaluation of the cluster size with the common-core design approach it is possible to evaluate the size and feasibility of the clusters. Combining these three evaluations verify and validate the results and the approach for the system.

**Product verification and validation**

The translation from system to product verification and validation is done by translating the logical solutions back to the functional requirements. The functional requirements consisting of two parts. Firstly, if the system solutions fulfill all the functional requirements. Secondly if the specific functional requirements of the ferry are met by the system solution.

The first part of the product V&V is elaborated in Chapter 5.4. This chapter elaborates and visualizes the connection between the system solutions or logical solutions and the functional requirements for the systems. Elaborated in that chapter there are improvements to be made to the functionalities as there are sometimes multiple sub-system solutions to a single functional requirement. This means that improvement and iteration of the functional requirements design is needed. The visualization of the interactions which show the evaluation of the interactions between the requirements and system solutions is shown in Table 5.4 as well as Appendix C.

The second part of the product V&V is evaluated by the results shown in Table 7.5 with a specified calculation for the storage volume estimation in Table 7.6. The top level of the functional requirements for the energy storage and conversion system defined in Chapter 3.1 require:

- A minimal power requirement of 2394 kW
- Refuelling in 10 minutes and an energy storage and delivery capability of 1685 kWh per sailing cycle
- The ability to handle power fluctuations with regard to the operational profile and sailing conditions
- Minimization of the emissions from the conversion system

The power and energy functional requirement is elaborated in the tables below. The approach for the evaluation of the system configurations is based on the power and energy requirement and the effect it has on the system weight and volume. Specifically it means that based on the required power and energy the weight and volume of the system configurations are calculated. The weight and volume then have to be lower than the current hybrid configuration to be feasible. A note to this approach is that the current hybrid design uses a diesel generator and battery configuration. Where the combined configuration was the result of a redundancy requirement from the client, the other systems are based on a single conversion system. However, using only the configurations elaborated in the tables the results show that the solution is feasible to fulfill the functional requirements. In addition, it is required for the system weight and volume to be less than the maximum values. The reason for this is that the real idea of modularity is found in the variation of modules[44], elaborated in Chapter 4.3. Specifically this means that modules can be used to fit different system requirements. Meaning that one variation of for instance the exhaust system can be used to the limits of the exhaust system but also for systems which might require a smaller exhaust system due to a 'smaller' engine. Therefore, variation design space and weight is required to be able to include that potential extra weight and volume for which the calculation results are shown in Table 7.5. The design using the hybrid, battery or MGO system configuration in itself has no influence on the power, weight or performance of the vessel. However, due to variations of modules design space is required to allow for the over-design of modules which can have a negative influence on the weight and volume. The calculations in the table show that there is a difference in the weight and allowable weight as well as the volume and allowable volume of the systems. Concluding that the elaborated systems except for dual fuel allow for modular design and the over-design using module variations.

The third and fourth functional requirement is elaborated in Chapter 3.1 and 3.3. For the minimization of the emissions alternative fuels are a much better option than the current diesel configuration which is included in the solutions as well. However, the approach is a road towards minimization of the emissions which means that it is accepted for now where the system potentially can be refitted as elaborated in Chapter 3.6. This way an environmentally friendly energy type can be used.

Table 7.5: Volume and weight results based for different configurations for the 9819 E3 ferry

| **System configuration** | **Weight [Tons]** | **Volume est. m$^3$** | **Notes** |
|---|---|---|---|
| Hybrid (current config.) | 206 | 928 | $^1$*Including lubrication oil and switchboards,*<br>*Excluding fresh water and cooling system* |
| Battery$^1$ | 108 | 658 | $^2$*Excluding storage and storage managing systems* |
| MGO | 186 | 586$^3$ | $^3$*Assuming the same volume for switchboard*<br>*room as the hybrid version* |
| Dual fuel$^4$ | 214 | 648 | $^4$*Assuming the same fuel weight for dual fuel as MGO* |
| Fuel cell | 43$^{1,2}$ | 554 | |

Table 7.6: Configuration storage volume determination specification

| **Volume determination** | | **Notes** |
|---|---|---|
| Hybrid | | |
| 166.8 | m$^3$ | Based on the 9819E3 ferry |
| 26.2 | tons | |
| Batteries | | |
| 449.9 | m$^3$ | Based on the winter conditions |
| 70.6 | tons | specified in Table 2.3 |
| LNG | | |
| 47.8 | m$^3$ | 5 times the volume of fossil fuel (Chapter 3.3)<br>Assuming 60% usage of LNG vs MGO |
| Hydrogen | | |
| 543.6 | m$^3$ | Assuming compressed hydrogen with<br>space requirement of 10-15 times of HFO (Chapter 3.3) |

In order to show the usefulness at an extra level which is less abstract, two examples are elaborated to visualize the results in Chapter 6.2. By elaborating on two practical examples it is shown that and how the design method of the combination of DSM and clustering can be used to design a modular future proof design. Where the design in this thesis is the energy storage and conversion system for multiple configurations. This extra step in using the results in a practical situation shows the usefulness of the method and the results for the two examples.

**Step 5** Accepting the achieved usefulness is linked to the applied method:

This step focuses on building confidence that the usefulness of the problem is linked to applying the method. For this it is suggested to evaluate contributions to usefulness from each construct individual. Practically this is done by comparing the solutions with and without the construct. Thus with and without using the clustering for the modular application method. In addition solutions should be compared to the solutions which are found with existing design approaches. This means by using other theories. However, this additional comparison is difficult for the project for this is the first application of a method for the modular design. This means that there is no ‘rival’ method is used to define modules and to be able to future proof the designs based on interactions.

This step is difficult as within Damen there are no mathematical methods used in defining modular clusters. Besides this it is the first modular design approach for future proofing systems which means that not only systems which are currently used are implemented in the method but also other feasible systems. These other systems are new and also newly researched which means that no reference approach is available. This means that at this point with the available data it is not possible to build confidence in the method by using other results. The adaption which is done that is somewhat similar to a modular design change is the design of the 6819 E3 ferry as shown in Chapter 6.2.1.

However, there are differences in the approach towards module definition which is relevant. Currently within Damen the development of modules is already started where it is done using theory and experience. Besides using experience I believe that there are significant improvements possible as well as extra insight when using this method in combination with the experience and knowledge. Firstly, this is based on that defining modules based on experience is not the best option. For instance when someone outside of the program or a new engineer wants to use it, it does require more time to understand and use. Secondly, if the approach is manually, changes in the the case study can have a large effect. Meaning for instance the effect in the case that the module definition has to be applied to other vessels which are different than the basis. Having defined decisions manually would mean that these have to be checked and possibly changed. And Finally, the design documentation tracking is important. Using manual module definition the considerations and decisions are captured in organization principles. For analyzing and the second level of decision making this is a good idea. However, in my opinion the clustering itself should be done as objective as possible based only on fundamental modular ideas.

**Step 6** Accepting that the usefulness of the method is beyond the elaborated examples:

Based on the previous steps generality is claimed for the usage of the method for the tested examples and beyond these problems. By going through the Validation Square, circumstantial evidence is facilitated to facilitate a leap of faith. This acceptance is external validity or generalization and refers to validity of the approach to other problems or situations. For this acceptance it is avoided to treat the case studies as sampling units but as separate problems. If two or more cases are elaborated which support the theory of the method, repetition may be claimed.

Generality for the method the elaborated examples show that the method works for more than the specific problem of module definition. Where multiple examples can be found where the method can be applied to evaluate the influence of a change, define modules and find variations and to find new potential energy storage and conversion systems. The step beyond the defined model then also is to combine multiple systems. Where the example of Thebeau [92] describes a single system and the interactions within the system it is also possible to extend the potential of this method. This next step is done in this thesis where multiple systems are implemented in the DSM and are grouped by the clustering algorithm.

The additional step in this research is extending the method to include various systems. What makes it different and beyond the original example is that five configurations are elaborated where the five configurations are different systems which not always can be combined. This can be seen as the combination of five different systems where there can be combinations of systems and interactions. By using the function to remove elements from the clustering algorithm it is possible to define the configuration and therefore also the potential combination of systems. In the clustering algorithm the 5 configurations can be applied where the result shows potential modules which can be used over the range of configurations. This means that the modules not only have a potential to work for variants of one system but also with variants of systems. As the method follows the defined approach of RFLP the input is systematic and can be expanded to be able to elaborate on new solutions. The original example did focus on improvements to the system and input for the DSM where this method shows the potential to increase the solution space. Using the method and the systematic approach it is possible to understand the specific implication of the change in configuration on the design including the weight and volume but also the usage of the interfaces to determine the potential of reusing one or more modules in the new design.

Specifically the improvement or change in method allows for the iterations in input and input improvements. It allows for straightforward evaluation of different configurations to be able to compare the different potential modules in order to increase the modularity and standardization of modules. And it allows for the implementation of future energy storage and conversion systems without having to change the input and setup of the original input. This alone is the usage of modular design where parallel development is possible. Specifically the application of this input extension would allow for configurations such as the fuel cell which runs on methanol. This way the future proofing of designing systems remains up to date and future proof. And finally the description of the second level of decision making increases the usability of the results and translates the results to information which is less abstract and can be understood. This extra step has the goal to be able to assess the influence of a system configuration design change.

# 8

# Conclusion

In the energy transition from fossil fuels towards zero emission fuels there is a shift towards energy carrier and conversion systems which are or will be developed in the coming years. Where it is possible to design a commercially available system, it is important to allow for design changes for the alternative fuels. In addition, improvements are made to the system design with regard to standardization which allows for optimizing the system while allowing for variation. The combination of these two improvements is found in the EU H2020 NAVAIS project which focuses on customer tailored vessels in combination with a standardized and modularized approach. Based on these two problems the main question for this research is defined: *“How can the energy carrier and conversion system of a ferry be made environmentally friendly and modular and how does the inclusion of low emission and modularity objectives impact the power supply and total design of the ferry?”*

To answer this question six sub-questions are defined to answer this question. Starting with the first part which answers the question “What are the vessel and system requirements of the Damen 9819 E3 ferry?”. For this vessel specific requirements are defined as well as research requirement which are important for this thesis. The requirements being: Firstly, the energy carrier and conversion system is future proof which means that an environmentally friendly or zero emission energy carrier is used or can be used which is commercially available. Secondly, the energy carrier and conversion system require the ability to be refitted by environmentally friendly energy carriers. Thirdly, the energy carrier and conversion system has to be modular. Fourthly, the defined operational profile of the vessel has to be fulfilled by the systems. And finally, all the used systems are technically feasible systems which means that they are commercially available for the marine industry and can be used for the test case vessel.

The second part answers the question "What are feasible environmentally friendly energy carrier and conversion possibilities?" Based on the requirements the feasibly solutions are: a battery system, a diesel generator using MGO and a dual fuel engine using LNG and MGO. In addition a fuel cell is implemented in the solutions where this is not yet commercially available, but will be a feasible solution with regard to the system requirements in a limited amount of years.

Based on the definition of the requirements for the vessel and the determination of the feasible energy storage and conversion systems the next part answers the question: "How can the energy storage and conversion system be defined using modules?". The reason for modularity is as the next step in standardization which allows for diversification using standardized modules, it increases design efficiency and supports the configuration process. For this approach two platform based approaches are used. These are the top-down approach which is based on the RFLP approach and supports modularity. Secondly, the common-core approach is used where multiple modules can be combined and connected to the common-core in order to define a system. The definition of modules in this thesis is based on the research of Fuchs and Golenhofen [44] where the modules implement one or more functional elements and interfaces which are not coupled but require a clear definition. For this interaction there are the possible interactions of a combinatorial modularity, a component-swapping modularity, a sectional modularity and a bus modularity which can be used in the module interaction definition. The method to define the modules in the system starts with a function decomposition. After this, the function tree or decomposition is connected to the logical design components and finally the Design Structure Matrix tool is used to group functionalities for possible modules. Based on the interactions groups can be formed in between there is minimized interaction.

The fourth part answers the question: "How can a general interface be defined between the systems for the vessel specification and the propulsion requirements?" By following the described RFLP approach in combination with the Top-down approach and the Design Structure Matrix with the clustering algorithm a number of results are generated. As the results are abstract and based on a specific system configuration the first step is refinement of the results. This means that a combination is made from the different sub-system clustering results into a table with a maximum of three variants per cluster as shown in Table5.3. Next, the clusters are evaluated based on the amount of interactions and the potential for grouping. Based on the technical feasibility and knowledge of the system a choice is made for the best module suggestions. After which the modules are evaluated based on the potential to standardize the interaction interface of the modules. Besides the electrical systems for which the interaction can be standardized as bus modularity, all the other modules are standardized using combinatorial or sectional modularity.

The suggested modules for the energy storage and conversion system are storing and transport modules for LNG, MGO and lubrication oil, an exhaust system module and hydrogen storing, fuel cell and oxygen and hydrogen filling module. The module definition to the level of general interface definition can be done for 10 groups of sub-systems into modules while excluding some sub-systems. The determination of the general interface hence is based on the DSM clustering algorithm while using the platform approach, the refinement of the results and the evaluation of the modules. Based on the evaluation of the modules the basic common-core of the system is defined being the electrical system using DC current. A practical application of this common-core is the switchboard which is the connecting system to almost all the systems within the energy storage and conversion system. The second common-core is the diesel generator at this point which is the basis and connecting system as a first building block of the electrical system. The common-core is determined to help understand the basis of the system to be able to design standard, modular systems.

After this, step sub-question five is: "How can energy carrier and conversion systems be modular implemented using a method that fulfills the requirements and functionalities of the vessel?" This is a description and elaboration of the method which is applied for the previous questions in order to not only use the results, but also use the method to generate new and improved results. The described method is divided into two parts where there is a first level of decision making using the DSM clustering which includes the functional and logical decomposition.

The second part of the method description is the second level of decision making using modularity driving reasoning. This means that the evaluations and refinements are based on the methods included in the platform approach as well as the technical knowledge of the system and a modular evaluation of the interfaces. Due to the use of DSM clustering algorithm the main drivers for modularization and DSM allow for an objective approach for module definition. In the method an abstract approach is used to find optimal results based on minimal interactions and the lowest cluster combination ‘costs’ without evaluating the physical sub-systems. This way it is possible to keep the quality and objectivity of the results as high as possible without implementing personal choices. Using this approach it is possible to find or improve clustering results but also to include new alternative fuels to be able to find the interactions between the systems. In which the commonalities and interactions can lead to improved modules and more generally used clusters.

The final part answers the sub-question: "How can this method be verified?". The result is the description and usage of a method and not of specific results making it impossible to validate and verify in a standard way. Therefore, the validation is done by proving the internal consistency of the method and the verification is performed by proving the internal consistency and validation of the results using the approach of et al. [36]. The validation square in this method uses 6 steps where the structural validation is proven by various works on the method and clustering algorithm. The internal consistency is proved by elaborating the stability and validity range, the what-of analysis and a sensitivity analysis. The evaluation of these steps show a stability of the clustering results of 90%, a constant working of the algorithm based on the defined parameters and consistent results for change of input and parameters. The appropriateness of the example is elaborated by comparing the two goals and examples for which the DSM and clustering is used. The usefulness of the outcome of the method is elaborated by the evaluations of the results and the elaboration of the two examples as described in Chapter 6.2.

System verification and validation shows that the functional requirements match with the technical solutions but a more refined functional requirement decomposition is required. However, the interaction and feasibility of the modules based on the technical solution which is used for the module design is feasible. Next, the product verification and validation show that the module configurations all fit within the requirement limits while allowing for variation of modules. The design using the hybrid, battery or MGO system configuration in itself has no different influence on the power, weight or performance of the vessel with regard to designing without modules. However, due to variations of modules design space is required to allow for the over-design of modules which can have a negative influence on the weight and volume. Meaning that the variation of modules is accountable for over-design of modules. This implies that the design space is required within the system requirements. The specific usefulness is not proven as the physical modules with variations are not designed and calculated. However, the results do show the design space which allows for the variations proving the usefulness of the methods. As a result of the previous steps, the last step to accept the usefulness of the method to be generally acceptable beyond the examples is proved by elaborating on the multiple configurations and the potential for extending the solution space.

The main question *"How can the energy carrier and conversion system of a ferry be made environmentally friendly and modular and how does the inclusion of low emission and modularity objectives impact the power supply and total design of the ferry?"* can now be answered. By supplying a number of potential energy carrier and conversion systems which are now commercially available and others in the near future. Whereas the modular approach is answered by the approach of using and applying DSM in combination with a clustering algorithm based on the defined platform approach. After which refinement and evaluation steps result in feasible module solutions with a general interface. By combining conventional solutions with alternative and more environmentally friendly energy carrier and conversion systems it is possible to design a future proof design. Where the combination is found in the modular energy storage and conversion system. The implication of designing modular shows a better understanding of the energy carrier and conversion system and its interactions. The initial module design has no different influence on the system weight and volume with respect to designing without modules. However, the variations of the modules do have a negative influence on the weight and volume of the systems. Concluding that the power supply can be delivered but extra design space is required due to the module variation design.

## 8.1. Recommendation

- The first recommendation is to use the module results in order to verify the feasibility and usability of these modules. This way it is possible to visualize potential problems with the solutions which can be adapted in the method.
- Another recommendation is to review and improve the input of the DSM to a level which is more complete. Specifically it is possible to add the water cooling system which may have influence on the module definition as this system is combining multiple sub-systems. As the cooling system is connected to multiple sub-systems it might be possible that the water cooling system can be standardized in a module and be used for multiple configurations. Next to this also the system specifications and the design for a LNG and hydrogen should be improved and better specified. As there are potential combinations more detailed specifications are required.
- The other recommendation for input improvement is to change the input of the DSM to a variable instead of binary. Where the results and inputs required extra refinements due to the binary input of interactions it is possible to improve the results by defining the interactions as a variable. However, this means that consistence is required in the values for which clear definitions have to be defined.
  Another possibility is to use multiple matrices for the different type of interactions which is also used in other clustering algorithms. However, this is not advised as the level of abstractness then increases significantly and the result refinement and evaluation also become more difficult to interpret.
- It was found that the input translation from the matrix which was made in Excel into the Matlab format resulted in some mistakes. As this was done manually it is recommended that a tool is developed to translate Excel data into the specific Matlab code which can be used in the algorithm. This way the potential mistakes are minimized.

## 8.2. Personal reflection

The size of the project and the complexity is something I looked up against and was exited for at the same time at the start of the project. I like to be challenged by difficult projects and this was a good challenge to prove it. Looking back I liked the complexity of the subject but also found it difficult to explain the knowledge and literature I have learned to people which are involved to a lesser extent. The challenge therefore was to simplify all the complex knowledge and apply it to my specific research. Besides this I learned a lot from setting goals and planning the project due to the length of this thesis.

Starting this thesis I had an interest in innovation, sustainability and complex systems. These three subjects could be included in the research into the modular and future proof design of the energy storage and conversion system. Sustainability is becoming a more important topic every day although I found it difficult in the beginning how to apply it in the system design. Especially the translation step from current systems to systems which are commercially available in a number of years. In addition to this, the personal understanding of modularity was a process where I started with a simplistic idea of modularity. During my research while combining theoretical literature to some practical examples I started to understand modularity more clearly. However, the real understanding and ability to translate the ideas to modular design of systems remains a challenge.

After forming a conclusion for feasible alternative fuel types and approach for modular design. Using a method which I did not understand fully at the start was difficult. However, it also gave the opportunity for a new approach which in the end is quite effective in my opinion. The process of understanding the method and evaluating results which are generated by the method is very educational and enjoyable. Therefore I am satisfied with the research and also the things I have learned with regard to technical and methodological knowledge. And no less important I have learned to better plan, set goals, interact with experts and colleagues and my research capabilities have improved. After this research I have become even more enthusiastic about the feasibility to implement alternative fuels and the advantages of using modular design and I remain exited for complex projects.

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# List of Figures

# List of Tables

# A

# Functional Decomposition

The functional decomposition of the four configurations is a single total decompositions. However, due to the size of the decomposition it is cut into three parts with the first part being a functional description of the battery power and the fuel cell power. The second part is the provision of the energy carrier with regard to the combustion engine. Both LNG and MGO are included in the energy provision. The third part is the conversion of the energy carrier into electrical energy using the combustion engine.

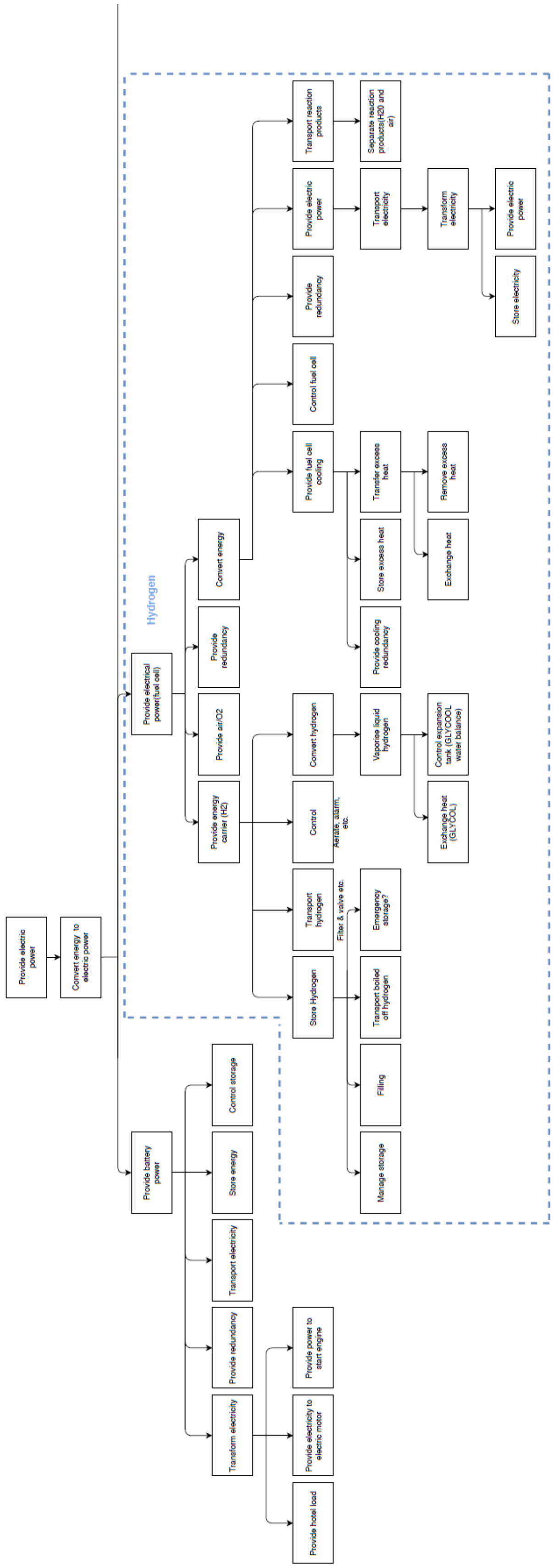


Figure A.1: Functional decomposition part 1

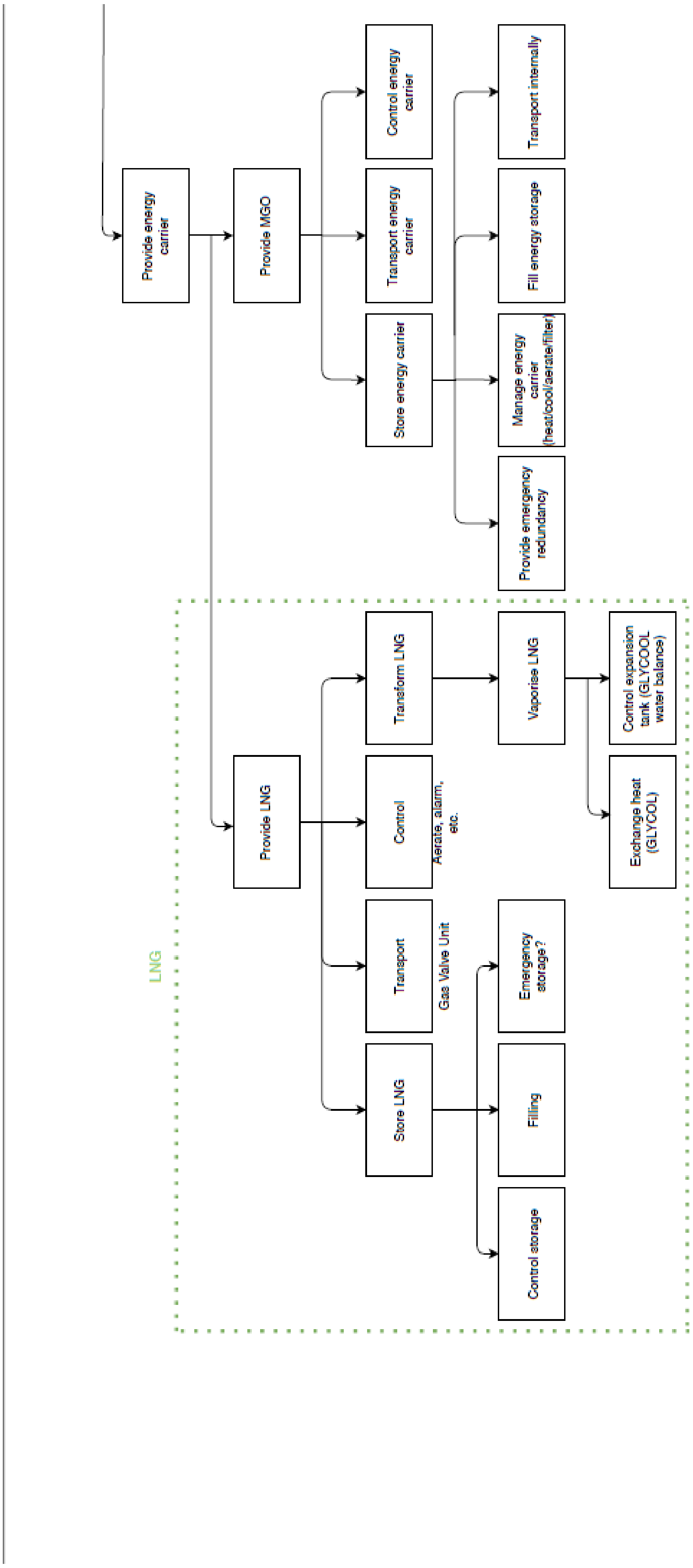


Figure A.2: Functional decomposition part 2

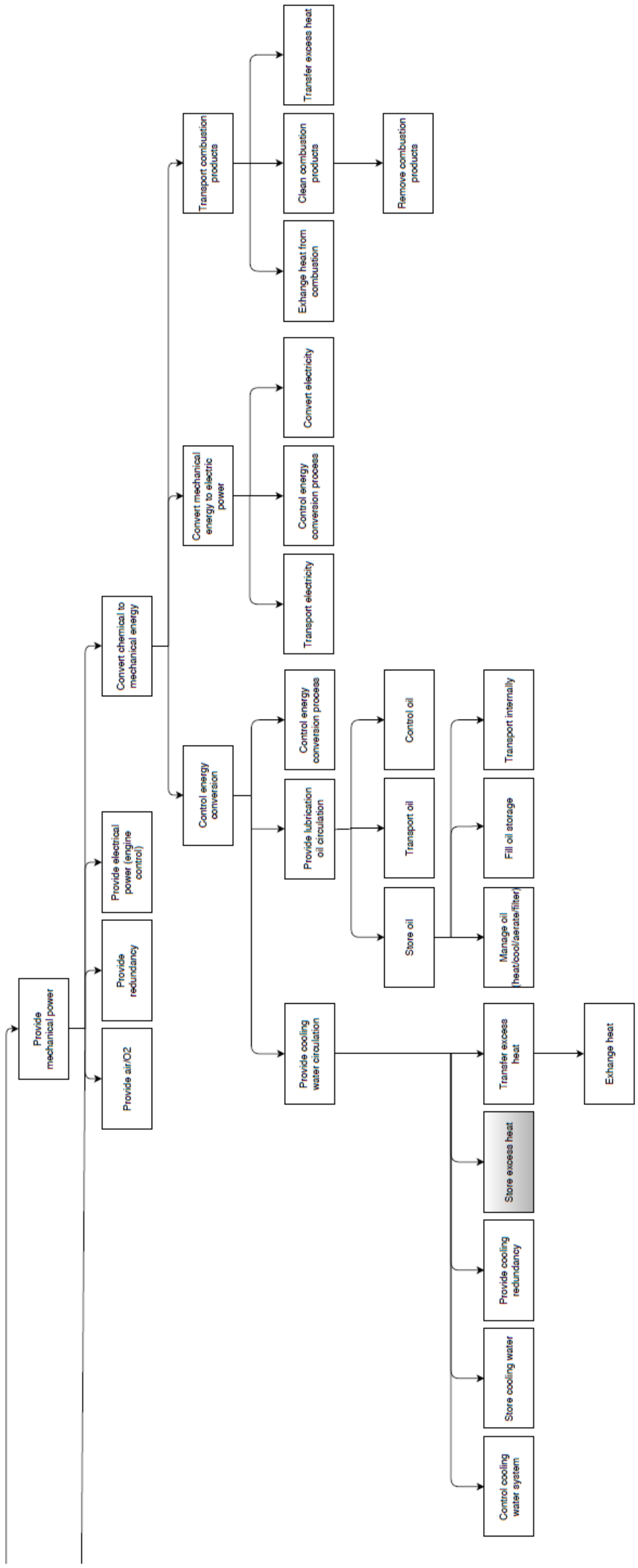


Figure A.3: Functional decomposition part 3

# B

# Logical Decomposition

The logical decomposition shows the decomposition of the configurations which means the technical solution for the functional requirements. Due to the size of the decomposition it is cut into six parts. The first part being the battery power system, the second part the cooling water system for the generators, the third part the cooling water system for auxiliary systems, the fourth and fifth part show the combustion engine or generator system including the LNG and MGO supply system and the sixth part shows the PEM-fuel cell system.

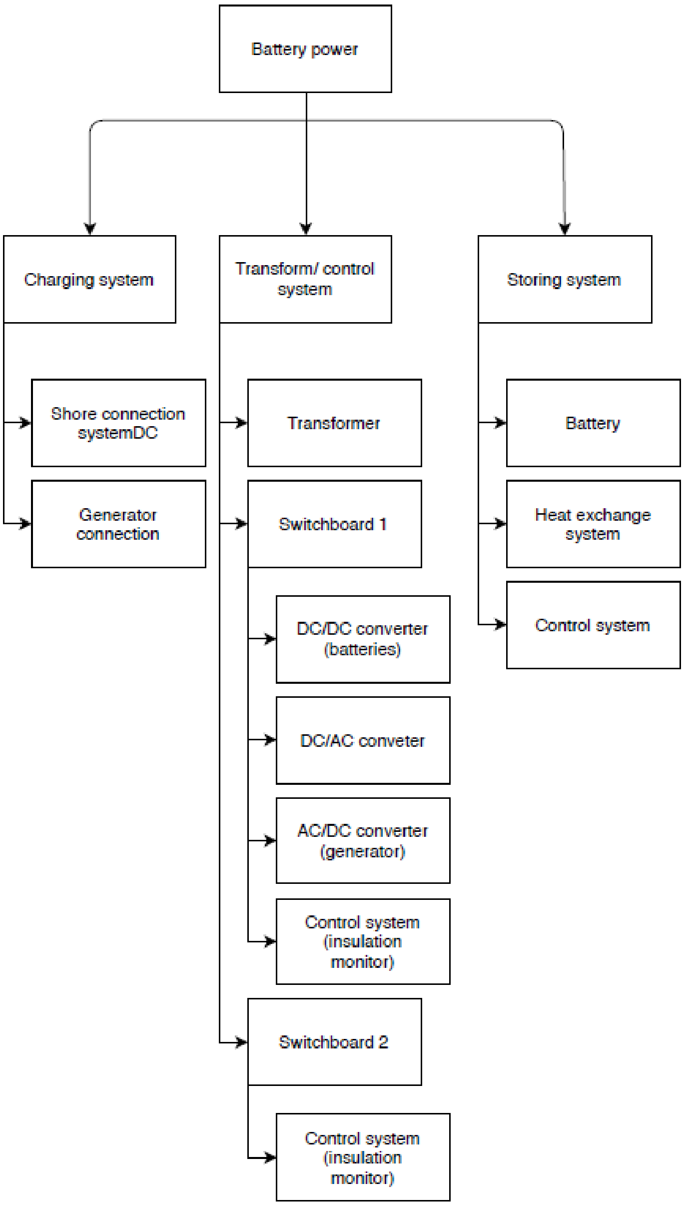


Figure B.1: Logical decomposition part 1

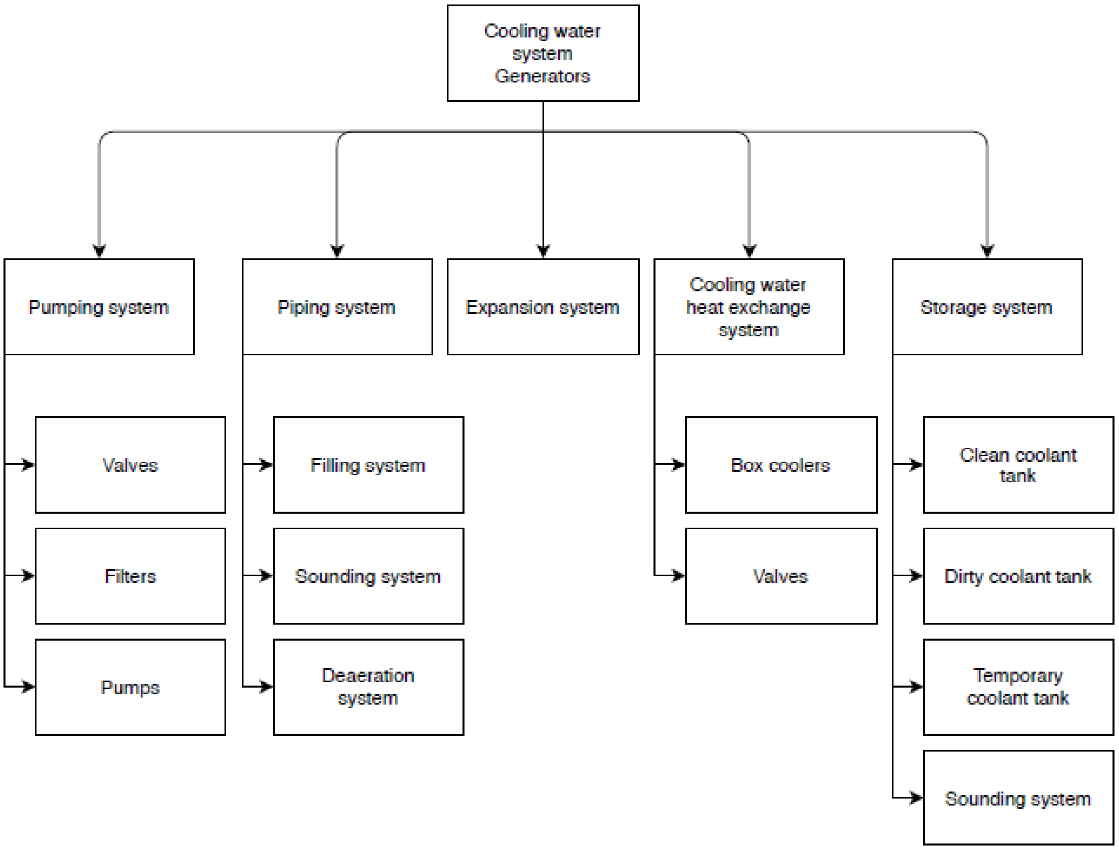


Figure B.2: Logical decomposition part 2

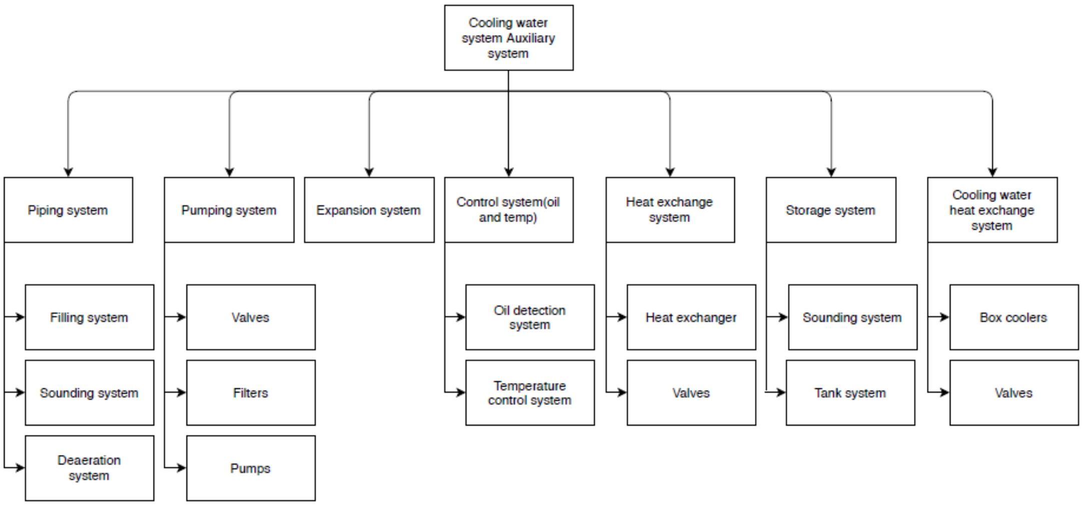


Figure B.3: Logical decomposition part 3

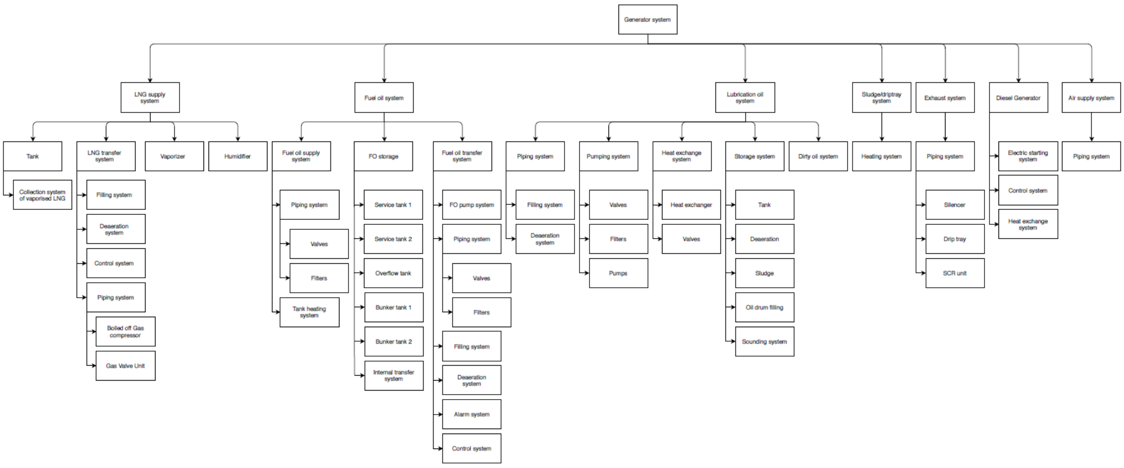


Figure B.4: Logical decomposition part 4 and 5 combined

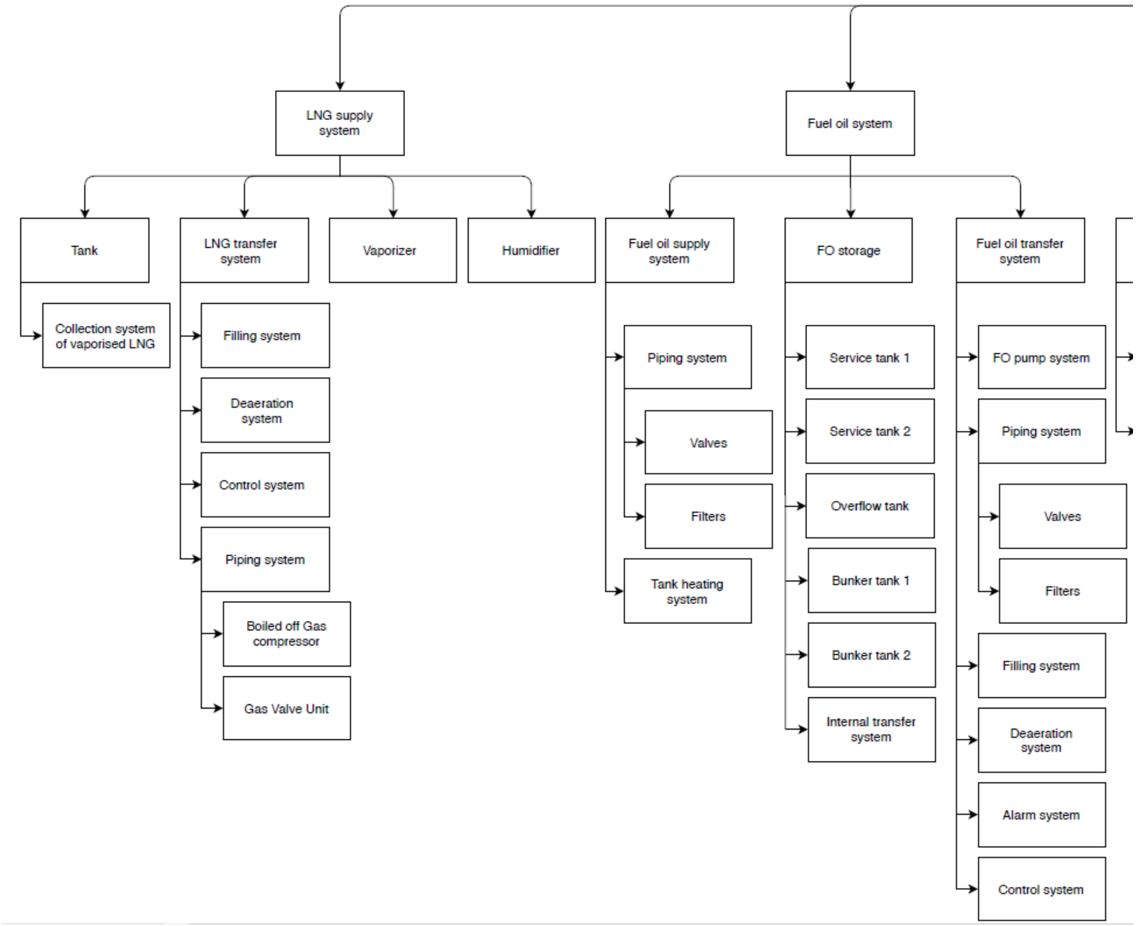


Figure B.5: Logical decomposition part 4

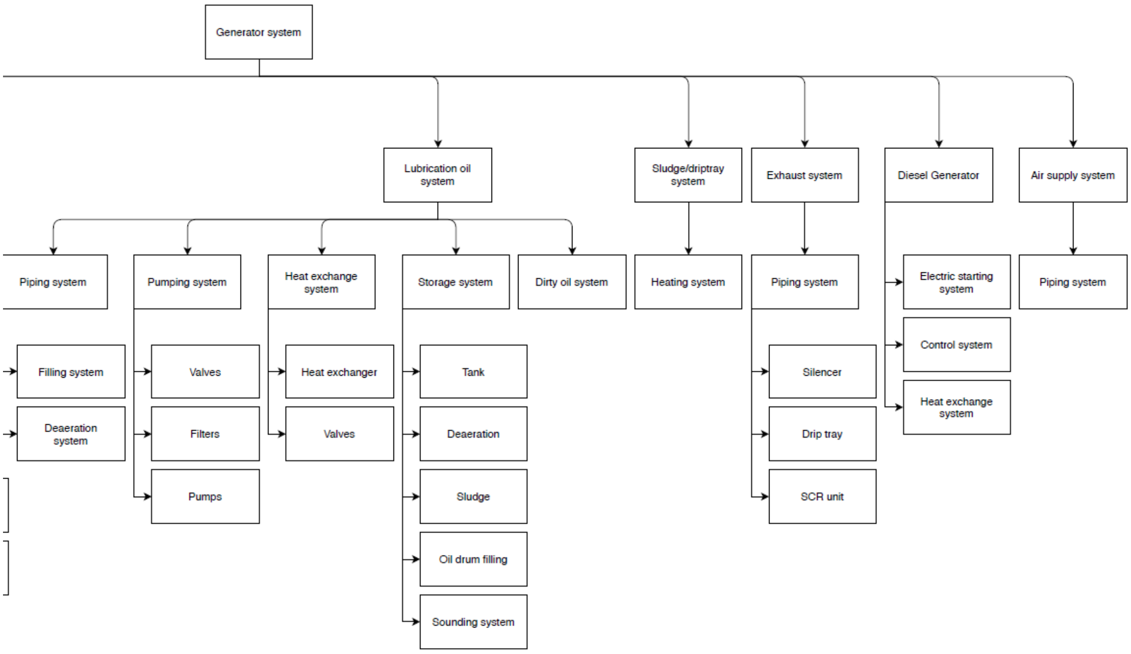


Figure B.6: Logical decomposition part 5

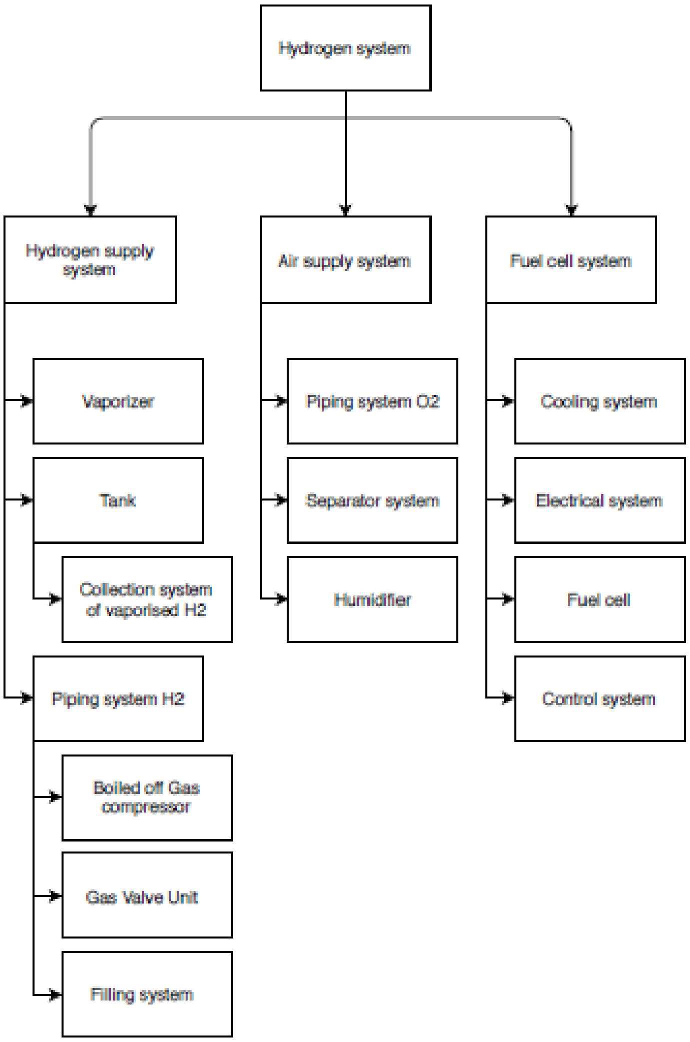


Figure B.7: Logical decomposition part 6

# C

# Function to Logical mapping

This appendix shows the connection of the functional decomposition to the logical decomposition in a matrix form. This form of matrix is the Design Structure Matrix setup where the functional requirements are connected to the logical or technical solutions which can fulfill the requirements. Next to this the refinement of the decomposition in table form is added to visualize the changes required and performed to reach the final logical and functional decomposition.

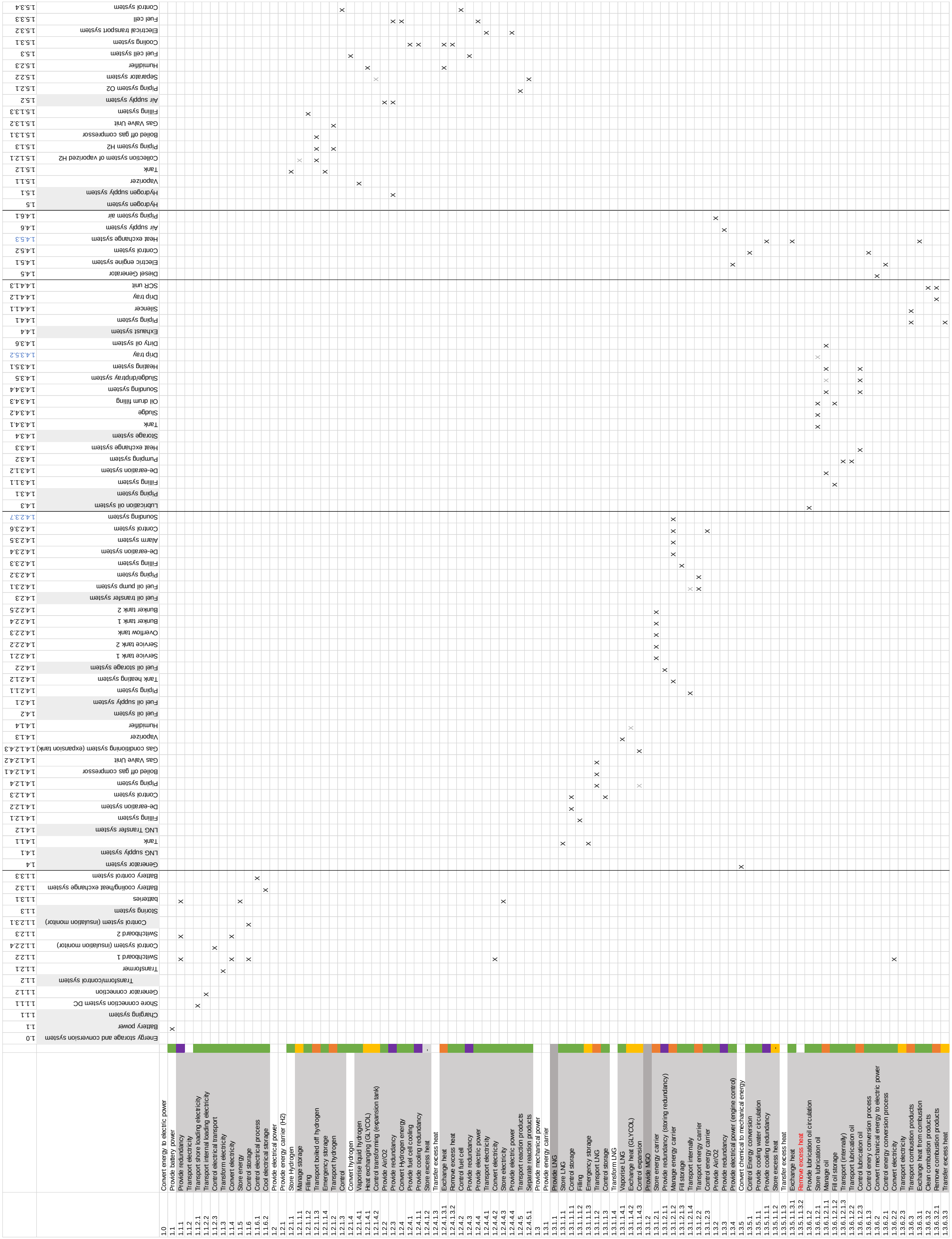


Figure C.1: Functional decomposition mapping to logical decomposition

Table C.1: Functional decomposition list based on Appendix A

| | |
|---|---|
| 1.0 | Convert energy to electric power |
| 1.1 | Provide battery power |
| 1.1.1 | Provide redundancy |
| 1.1.2 | Transport electricity |
| 1.1.2.1 | Transport shore loading electricity |
| 1.1.2.2 | Transport internal loading electricity |
| 1.1.2.3 | Control electrical transport |
| 1.1.3 | Transform electricity |
| 1.1.4 | Convert electricity |
| 1.1.5 | Store energy |
| 1.1.6 | Control storage |
| 1.1.6.1 | Control electrical process |
| 1.1.6.2 | Cool electrical storage |
| 1.2 | Provide electrical power |
| 1.2.1 | Provide energy carrier (H2) |
| 1.2.1.1 | Store Hydrogen |
| 1.2.1.1.1 | Manage storage |
| 1.2.1.1.2 | Filling |
| 1.2.1.1.3 | Transport boiled off hydrogen |
| 1.2.1.1.4 | Emergency storage |
| 1.2.1.2 | Transport hydrogen |
| 1.2.1.3 | Control |
| 1.2.1.4 | Convert hydrogen |
| 1.2.1.4.1 | Vaporise liquid hydrogen |
| 1.2.1.4.1 | Heat exchanging (GLYCOL) |
| 1.2.1.4.2 | Control transforming (expansion tank) |
| 1.2.2 | Provide Air/O2 |
| 1.2.3 | Provide redundancy |
| 1.2.4 | Convert Hydrogen energy |
| 1.2.4.1 | Provide fuel cell cooling |
| 1.2.4.1.1 | Provide cooling redundancy |
| 1.2.4.1.2 | Store excess heat |
| 1.2.4.1.3 | Transfer excess heat |
| 1.2.4.1.3.1 | Exchange heat |
| 1.2.4.1.3.2 | Romove excess heat |
| 1.2.4.2 | Control fuel cell |
| 1.2.4.3 | Provide redundancy |
| 1.2.4.4 | Provide electric power |
| 1.2.4.4.1 | Transport electricity |
| 1.2.4.4.2 | Convert electricity |
| 1.2.4.4.3 | Store electricity |
| 1.2.4.4.4 | Provide electric power |
| 1.2.4.5 | Transport reaction products |
| 1.2.4.5.1 | Separate reaction products |
| 1.3 | Provide mechanical power |
| 1.3.1 | Provide energy carrier |
| 1.3.1.1 | Provide LNG |
| 1.3.1.1.1 | Store LNG |
| 1.3.1.1.1.1 | Control storage |
| 1.3.1.1.1.2 | Filling |
| 1.3.1.1.1.3 | Emergency storage |
| 1.3.1.1.2 | Transport LNG |
| 1.3.1.1.3 | Control storage |
| 1.3.1.1.4 | Transform LNG |
| 1.3.1.1.4.1 | Vaporise LNG |
| 1.3.1.1.4.2 | Exchange heat (GLYCOL) |
| 1.3.1.1.4.3 | Control expansion |
| 1.3.1.2 | Provide MGO |
| 1.3.1.2.1 | Store energy carrier |
| 1.3.1.2.1.1 | Provide redundancy (storing redundancy) |
| 1.3.1.2.1.2 | Manage energy carrier |
| 1.3.1.2.1.3 | Fill storage |
| 1.3.1.2.1.4 | Transport internally |
| 1.3.1.2.2 | Transport energy carrier |
| 1.3.1.2.3 | Control energy carrier |
| 1.3.2 | Provide Air/O2 |
| 1.3.3 | Provide redundancy |
| 1.3.4 | Provide electrical power (engine control) |
| 1.3.5 | Convert chemical to mechanical energy |
| 1.3.5.1 | Control Energy conversion |
| 1.3.5.1.1 | Provide cooling water circulation |
| 1.3.5.1.1.1 | Provide cooling redundancy |
| 1.3.5.1.1.2 | Store excess heat |
| 1.3.5.1.1.3 | Transfer excess heat |
| 1.3.5.1.1.3.1 | Exchange heat |
| 1.3.5.1.1.3.2 | Remove excess heat |
| 1.3.5.1.1.4 | Control cooling water system |
| 1.3.5.1.1.5 | Store cooling water system |
| 1.3.6.1.2 | Provide lubrication oil circulation |
| 1.3.6.1.2.1 | Store lubrication oil |
| 1.3.6.1.2.1.1 | Manage oil |
| 1.3.6.1.2.1.2 | Fill oil storage |
| 1.3.6.1.2.1.3 | Transport (internally) |
| 1.3.6.1.2.2 | Transport lubrication oil |
| 1.3.6.1.2.3 | Control lubrication oil |
| 1.3.6.1.3 | Control energy conversion process |
| 1.3.6.2 | Convert mechanical energy to electric power |
| 1.3.6.2.1 | Control energy conversion process |
| 1.3.6.2.2 | Convert electricity |
| 1.3.6.2.3 | Transport electricity |
| 1.3.6.3 | Transport combustion products |
| 1.3.6.3.1 | Exchange heat from combustion |
| 1.3.6.3.2 | Clean combustion products |
| 1.3.6.3.2.1 | Remove combustion products |
| 1.3.6.3.3 | Transfer excess heat |

Table C.2: Logical Decomposition version 1

| | |
|---|---|
| 1.0 | Energy storage and conversion system |
| 1.1 | Battery power |
| 1.1.1 | Charging system |
| 1.1.1.1 | Shore connection system DC |
| 1.1.1.2 | Generator connection |
| 1.1.2 | Transform/control system |
| 1.1.2.1 | Transformer |
| 1.1.2.2 | Switchboard 1 |
| 1.1.2.2.1 | DC/DC converter |
| 1.1.2.2.2 | DC/AC converter |
| 1.1.2.2.3 | AC/DC converter |
| 1.1.2.2.4 | Control system (insulation monitor) |
| 1.1.2.3 | Switchboard 2 |
| 1.1.2.3.1 | Control system (insulation monitor) |
| 1.1.3 | Storing system |
| 1.1.3.1 | batteries |
| 1.1.3.2 | Battery cooling/heat exchange system |
| 1.1.3.3 | Battery control system |
| 1.2 | Cooling water system generators |
| 1.2.1 | Pumping system |
| 1.2.1.1 | Valves |
| 1.2.1.2 | Filters |
| 1.2.1.3 | Pumps |
| 1.2.2 | Piping system |
| 1.2.2.1 | Filling system |
| 1.2.2.2 | Sounding system |
| 1.2.2.3 | De-earation system |
| 1.2.3 | Expansion system |
| 1.2.4 | Cooling water heat exchange system |
| 1.2.4.1 | Box coolers |
| 1.2.4.2 | Valves |
| 1.2.5 | Storage system |
| 1.2.5.1 | Clean coolant tank |
| 1.2.5.2 | Dirty coolant tank |
| 1.2.5.3 | Temporary coolant tank |
| 1.2.5.4 | Sounding system |
| 1.3 | Cooling water auxiliary system |
| 1.3.1 | Piping system |
| 1.3.1.1 | Filling system |
| 1.3.1.2 | Sounding system |
| 1.3.1.3 | De-earation system |
| 1.3.2 | Pumping system |
| 1.3.2.1 | Valves |
| 1.3.2.2 | Filters |
| 1.3.2.3 | Pumps |
| 1.3.3 | Expansion system |
| 1.3.4 | Control system (oil & temp) |
| 1.3.4.1 | Oil detection system |
| 1.3.4.2 | Temperature control system |
| 1.3.5 | Heat exchange system |
| 1.3.5.1 | Heat exchanger |
| 1.3.5.2 | Valves |
| 1.3.6 | Storage system |
| 1.3.6.1 | Sounding system |
| 1.3.6.2 | Tank system |
| 1.3.7 | Cooling water heat exchange system |
| 1.3.7.1 | Box coolers |
| 1.3.7.2 | Valves |
| 1.4 | Generator system |
| 1.4.1 | LNG supply system |
| 1.4.1.1 | Tank |
| 1.4.1.2 | LNG Transfer system |
| 1.4.1.2.1 | Filling system |
| 1.4.1.2.2 | De-earation system |
| 1.4.1.2.3 | Control system |
| 1.4.1.2.4 | Transport system |
| 1.4.1.2.4.1 | Boiled off gas compressor |
| 1.4.1.2.4.2 | Gas Valve Unit |
| 1.4.1.3 | Vaporizer |
| 1.4.1.4 | Humidifier |
| 1.4.2 | Fuel oil system |
| 1.4.2.1 | Fuel oil supply system |
| 1.4.2.1.1 | Piping system |
| 1.4.2.1.1.1 | Valves |
| 1.4.2.1.1.2 | Filters |
| 1.4.2.1.2 | Tank heating system |
| 1.4.2.2 | Fuel oil storage system |
| 1.4.2.2.1 | Service tank 1 |
| 1.4.2.2.2 | Service tank 2 |
| 1.4.2.2.3 | Overflow tank |
| 1.4.2.2.4 | Bunker tank 1 |
| 1.4.2.2.5 | Bunker tank 2 |
| 1.4.2.3 | Fuel oil transfer system |
| 1.4.2.3.1 | Fuel oil pump system |
| 1.4.2.3.2 | Piping system |
| 1.4.2.3.2.1 | Valves |
| 1.4.2.3.2.2 | Filters |
| 1.4.2.3.3 | Filling system |
| 1.4.2.3.4 | De-earation system |
| 1.4.2.3.5 | Alarm system |
| 1.4.2.3.6 | Control system |
| 1.4.2.3.7 | Sounding system |
| 1.4.3 | Lubrication oil system |
| 1.4.3.1 | Piping system |
| 1.4.3.1.1 | Filling system |
| 1.4.3.1.2 | De-earation system |
| 1.4.3.2 | Pumping system |
| 1.4.3.2.1 | Valves |
| 1.4.3.2.2 | Filters |
| 1.4.3.2.3 | Pumps |
| 1.4.3.3 | Heat exchange system |
| 1.4.3.3.1 | Heat exchanger |
| 1.4.3.3.2 | Valves |
| 1.4.3.4 | Storage system |
| 1.4.3.4.1 | Tank |
| 1.4.3.4.2 | De-earation system |
| 1.4.3.4.3 | Sludge |
| 1.4.3.4.4 | Oil drum filling |
| 1.4.3.4.5 | Sounding system |
| 1.4.3.5 | Sludge/driptray system |
| 1.4.3.5.1 | Heating system |
| 1.4.3.5.2 | Drip tray |
| 1.4.3.6 | Dirty oil system |
| 1.4.4 | Exhaust system |
| 1.4.4.1 | Piping system |
| 1.4.4.1.1 | Silencer |
| 1.4.4.1.2 | Drip tray |
| 1.4.4.1.3 | SCR unit |
| 1.4.5 | Electric starting system |
| 1.5 | Hydrogen system |
| 1.5.1 | Hydrogen supply system |
| 1.5.1.1 | Vaporizer |
| 1.5.1.2 | Tank |
| 1.5.1.2.1 | Collection system of vaporized H2 |
| 1.5.1.3 | Transport system |
| 1.5.1.3.1 | Boiled off gas compressor |
| 1.5.1.3.2 | Gas Valve Unit |
| 1.5.2 | Air supply system |
| 1.5.2.1 | Transport system |
| 1.5.2.2 | Separator system |
| 1.5.2.3 | Humidifier |
| 1.5.3 | Fuel cell system |
| 1.5.3.1 | Cooling system |
| 1.5.3.2 | Electrical system |
| 1.5.3.3 | Fuel cell |

Table C.3: Logical Decomposition version 2 with less elaborate system decomposition

| | |
|---|---|
| 1.0 | Energy storage and conversion system |
| 1.1 | Battery power |
| 1.1.1 | Charging system |
| 1.1.1.1 | Shore connection system DC |
| 1.1.1.2 | Generator connection |
| 1.1.2 | Transform/control system |
| 1.1.2.1 | Transformer |
| 1.1.2.2 | Switchboard 1 |
| 1.1.2.2.4 | Control system (insulation monitor) |
| 1.1.2.3 | Switchboard 2 |
| 1.1.2.3.1 | Control system (insulation monitor) |
| 1.1.3 | Storing system |
| 1.1.3.1 | batteries |
| 1.1.3.2 | Battery cooling/heat exchange system |
| 1.1.3.3 | Battery control system |
| 1.2 | Cooling water system generators |
| 1.2.1 | Pumping system |
| 1.2.2 | Piping system |
| 1.2.2.1 | Filling system |
| 1.2.2.2 | Sounding system |
| 1.2.2.3 | De-earation system |
| 1.2.3 | Expansion system |
| 1.2.4 | Cooling water heat exchange system |
| 1.2.5 | Storage system |
| 1.2.5.1 | Clean coolant tank |
| 1.2.5.2 | Dirty coolant tank |
| 1.2.5.3 | Temporary coolant tank |
| 1.2.5.4 | Sounding system |
| 1.3 | Cooling water auxiliary system |
| 1.3.1 | Piping system |
| 1.3.1.1 | Filling system |
| 1.3.1.2 | Sounding system |
| 1.3.1.3 | De-earation system |
| 1.3.2 | Pumping system |
| 1.3.3 | Expansion system |
| 1.3.4 | Control system (oil & temp) |
| 1.3.4.1 | Oil detection system |
| 1.3.4.2 | Temperature control system |
| 1.3.5 | Heat exchange system |
| 1.3.6 | Storage system |
| 1.3.6.1 | Sounding system |
| 1.3.6.2 | Tank system |
| 1.3.7 | Cooling water heat exchange system |
| 1.3.7.1 | Box coolers |
| 1.3.7.2 | Valves |
| 1.4 | Generator system |
| 1.4.1 | LNG supply system |
| 1.4.1.1 | Tank |
| 1.4.1.2 | LNG Transfer system |
| 1.4.1.2.1 | Filling system |
| 1.4.1.2.2 | De-earation system |
| 1.4.1.2.3 | Control system |
| 1.4.1.2.4 | Piping system |
| 1.4.1.2.4.1 | Boiled off gas compressor |
| 1.4.1.2.4.2 | Gas Valve Unit |
| 1.4.1.2.4.3 | Gas conditioning system (expansion tank) |
| 1.4.1.3 | Vaporizer |
| 1.4.1.4 | Humidifier |
| 1.4.2 | Fuel oil system |
| 1.4.2.1 | Fuel oil supply system |
| 1.4.2.1.1 | Piping system |
| 1.4.2.1.2 | Tank heating system |
| 1.4.2.2 | Fuel oil storage system |
| 1.4.2.2.1 | Service tank 1 |
| 1.4.2.2.2 | Service tank 2 |
| 1.4.2.2.3 | Overflow tank |
| 1.4.2.2.4 | Bunker tank 1 |
| 1.4.2.2.5 | Bunker tank 2 |
| 1.4.2.3 | Fuel oil transfer system |
| 1.4.2.3.1 | Fuel oil pump system |
| 1.4.2.3.2 | Piping system |
| 1.4.2.3.3 | Filling system |
| 1.4.2.3.4 | De-earation system |
| 1.4.2.3.5 | Alarm system |
| 1.4.2.3.6 | Control system |
| 1.4.2.3.7 | Sounding system |
| 1.4.3 | Lubrication oil system |
| 1.4.3.1 | Piping system |
| 1.4.3.1.1 | Filling system |
| 1.4.3.1.2 | De-earation system |
| 1.4.3.2 | Pumping system |
| 1.4.3.3 | Heat exchange system |
| 1.4.3.4 | Storage system |
| 1.4.3.4.1 | Tank |
| 1.4.3.4.2 | Sludge |
| 1.4.3.4.3 | Oil drum filling |
| 1.4.3.4.4 | Sounding system |
| 1.4.3.5 | Sludge/driptray system |
| 1.4.3.5.1 | Heating system |
| 1.4.3.5.2 | Drip tray |
| 1.4.3.6 | Dirty oil system |
| 1.4.4 | Exhaust system |
| 1.4.4.1 | Piping system |
| 1.4.4.1.1 | Silencer |
| 1.4.4.1.2 | Drip tray |
| 1.4.4.1.3 | SCR unit |
| 1.4.5 | Diesel Generator |
| 1.4.5.1 | Electric engine system |
| 1.4.5.2 | Control system |
| 1.4.6 | Air supply system |
| 1.4.6.1 | Piping system air |
| 1.5 | Hydrogen system |
| 1.5.1 | Hydrogen supply system |
| 1.5.1.1 | Vaporizer |
| 1.5.1.2 | Tank |
| 1.5.1.2.1 | Collection system of vaporized H2 |
| 1.5.1.3 | Piping system H2 |
| 1.5.1.3.1 | Boiled off gas compressor |
| 1.5.1.3.2 | Gas Valve Unit |
| 1.5.1.3.3 | Filling system |
| 1.5.2 | Air supply system |
| 1.5.2.1 | Piping system O2 |
| 1.5.2.2 | Separator system |
| 1.5.2.3 | Humidifier |
| 1.5.3 | Fuel cell system |
| 1.5.3.1 | Cooling system |
| 1.5.3.2 | Electrical system |
| 1.5.3.3 | Fuel cell |
| 1.5.3.4 | Control system |

Table C.4: Logical Decomposition version 3 with the cooling water system omitted

| | |
|---|---|
| 1.0 | Energy storage and conversion system |
| 1.1 | Battery power |
| 1.1.1 | Charging system |
| 1.1.1.1 | Shore connection system DC |
| 1.1.1.2 | Generator connection |
| 1.1.2 | Transform/control system |
| 1.1.2.1 | Transformer |
| 1.1.2.2 | Switchboard 1 |
| 1.1.2.2.4 | Control system (insulation monitor) |
| 1.1.2.3 | Switchboard 2 |
| 1.1.2.3.1 | Control system (insulation monitor) |
| 1.1.3 | Storing system |
| 1.1.3.1 | batteries |
| 1.1.3.2 | Battery cooling/heat exchange system |
| 1.1.3.3 | Battery control system |
| 1.4 | Generator system |
| 1.4.1 | LNG supply system |
| 1.4.1.1 | Tank |
| 1.4.1.2 | LNG Transfer system |
| 1.4.1.2.1 | Filling system |
| 1.4.1.2.2 | De-earation system |
| 1.4.1.2.3 | Control system |
| 1.4.1.2.4 | Piping system |
| 1.4.1.2.4.1 | Boiled off gas compressor |
| 1.4.1.2.4.2 | Gas Valve Unit |
| 1.4.1.2.4.3 | Gas conditioning system (expansion tank) |
| 1.4.1.3 | Vaporizer |
| 1.4.1.4 | Humidifier |
| 1.4.2 | Fuel oil system |
| 1.4.2.1 | Fuel oil supply system |
| 1.4.2.1.1 | Piping system |
| 1.4.2.1.2 | Tank heating system |
| 1.4.2.2 | Fuel oil storage system |
| 1.4.2.2.1 | Service tank 1 |
| 1.4.2.2.2 | Service tank 2 |
| 1.4.2.2.3 | Overflow tank |
| 1.4.2.2.4 | Bunker tank 1 |
| 1.4.2.2.5 | Bunker tank 2 |
| 1.4.2.3 | Fuel oil transfer system |
| 1.4.2.3.1 | Fuel oil pump system |
| 1.4.2.3.2 | Piping system |
| 1.4.2.3.3 | Filling system |
| 1.4.2.3.4 | De-earation system |
| 1.4.2.3.5 | Alarm system |
| 1.4.2.3.6 | Control system |
| 1.4.2.3.7 | Sounding system |
| 1.4.3 | Lubrication oil system |
| 1.4.3.1 | Piping system |
| 1.4.3.1.1 | Filling system |
| 1.4.3.1.2 | De-earation system |
| 1.4.3.2 | Pumping system |
| 1.4.3.3 | Heat exchange system |
| 1.4.3.4 | Storage system |
| 1.4.3.4.1 | Tank |
| 1.4.3.4.2 | Sludge |
| 1.4.3.4.3 | Oil drum filling |
| 1.4.3.4.4 | Sounding system |
| 1.4.3.5 | Sludge/driptray system |
| 1.4.3.5.1 | Heating system |
| 1.4.3.5.2 | Drip tray |
| 1.4.3.6 | Dirty oil system |
| 1.4.4 | Exhaust system |
| 1.4.4.1 | Piping system |
| 1.4.4.1.1 | Silencer |
| 1.4.4.1.2 | Drip tray |
| 1.4.4.1.3 | SCR unit |
| 1.4.5 | Diesel Generator |
| 1.4.5.1 | Electric engine system |
| 1.4.5.2 | Control system |
| 1.4.5.3 | Heat exchange system |
| 1.4.6 | Air supply system |
| 1.4.6.1 | Piping system air |
| 1.5 | Hydrogen system |
| 1.5.1 | Hydrogen supply system |
| 1.5.1.1 | Vaporizer |
| 1.5.1.2 | Tank |
| 1.5.1.2.1 | Collection system of vaporized H2 |
| 1.5.1.3 | Piping system H2 |
| 1.5.1.3.1 | Boiled off gas compressor |
| 1.5.1.3.2 | Gas Valve Unit |
| 1.5.1.3.3 | Filling system |
| 1.5.2 | Air supply system |
| 1.5.2.1 | Piping system O2 |
| 1.5.2.2 | Separator system |
| 1.5.2.3 | Humidifier |
| 1.5.3 | Fuel cell system |
| 1.5.3.1 | Cooling system |
| 1.5.3.2 | Electrical system |
| 1.5.3.3 | Fuel cell |
| 1.5.3.4 | Control system |

Table C.5: Logical Decomposition version 3 refined for DSM form

| | |
|---|---|
| 1.1.1.1 | Shore connection system DC |
| 1.1.1.2 | Generator connection |
| 1.1.2.1 | Transformer |
| 1.1.2.2 | Switchboard 1 |
| 1.1.2.2.4 | Control system (insulation monitor) |
| 1.1.2.3 | Switchboard 2 |
| 1.1.3.1 | batteries |
| 1.1.3.2 | Battery cooling/heat exchange system |
| 1.1.3.3 | Battery control system |
| 1.4.1.1 | LNG Tank |
| 1.4.1.2.1 | Filling system |
| 1.4.1.2.2 | De-earation system |
| 1.4.1.2.3 | Control system |
| 1.4.1.2.4 | Piping system LNG |
| 1.4.1.2.4.1 | Boiled off gas compressor |
| 1.4.1.2.4.2 | Gas Valve Unit |
| 1.4.1.2.4.3 | Gas conditioning system (expansion tank) |
| 1.4.1.3 | Vaporizer |
| 1.4.1.4 | Humidifier |
| 1.4.2.1.1 | Piping system fuel oil |
| 1.4.2.1.2 | Tank heating system |
| 1.4.2.2.1 | Service tank 1 |
| 1.4.2.2.2 | Service tank 2 |
| 1.4.2.2.3 | Overflow tank |
| 1.4.2.2.4 | Bunker tank 1 |
| 1.4.2.2.5 | Bunker tank 2 |
| 1.4.2.3.1 | Fuel oil pump system |
| 1.4.2.3.2 | Piping system |
| 1.4.2.3.3 | Filling system |
| 1.4.2.3.4 | De-earation system |
| 1.4.2.3.5 | Alarm system |
| 1.4.2.3.6 | Control system |
| 1.4.2.3.7 | Sounding system |
| 1.4.3.1 | Piping system lub oil |
| 1.4.3.1.1 | Filling system lubrication oil |
| 1.4.3.1.2 | De-earation system |
| 1.4.3.2 | Pumping system |
| 1.4.3.3 | Heat exchange system |
| 1.4.3.4.1 | Tank |
| 1.4.3.4.2 | Sludge |
| 1.4.3.4.3 | Oil drum filling |
| 1.4.3.4.4 | Sounding system |
| 1.4.3.5.1 | Heating system |
| 1.4.3.5.2 | Drip tray |
| 1.4.3.6 | Dirty oil system |
| 1.4.4.1 | Piping system exhaust |
| 1.4.4.1.1 | Silencer |
| 1.4.4.1.2 | Drip tray |
| 1.4.4.1.3 | SCR unit |
| 1.4.5 | Diesel Generator |
| 1.4.5.1 | Electric engine system |
| 1.4.5.2 | Control system |
| 1.4.5.3 | Heat exchange system |
| 1.4.6 | Air supply system |
| 1.4.6.1 | Piping system air |
| 1.4.7 | Sludge/driptray system |
| 1.5.1.1 | Vaporizer H2 |
| 1.5.1.2 | Tank |
| 1.5.1.2.1 | Collection system of vaporized H2 |
| 1.5.1.3 | Piping system H2 |
| 1.5.1.3.1 | Boiled off gas compressor |
| 1.5.1.3.2 | Gas Valve Unit |
| 1.5.1.3.3 | Filling system |
| 1.5.2.1 | Piping system O2 |
| 1.5.2.2 | Separator system |
| 1.5.2.3 | Humidifier |
| 1.5.3 | Fuel cell system |
| 1.5.3.1 | Cooling system |
| 1.5.3.2 | Electrical system |
| 1.5.3.3 | Fuel cell |
| 1.5.3.4 | Control system |

# D

# DSM Matrix Logical to Logical mapping

The final Design Structure Matrix which is used for the mapping is shown in this appendix. For this research the clustering used in the DSM method is applied to the logical solution to be able to have system modular results. The results shown in this appendix are analyzed by the clustering algorithm in order to define potential modules.

| | | |1|2|3|4|5|6|7|8|9|10|11|12|13|14|15|16|17|18|19|20|21|22|23|24|25|26|27|28|29|30|31|32|33|34|35|36|37|38|39|40|41|42|43|44|45|46|47|48|49|50|51|52|53|54|55|56|57|58|59|60|61|62|63|
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.1.1.1 | Shore connection system DC | 1 |■|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.1.1.2 | Generator connection | 2 ||■|||||||||||||||||||||||||||||||||||||||||||X||||||||||||||||||||
| 1.1.2.1 | Transformer | 3 |||■|X|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.1.2.2 | Switchboard 1 | 4 |X|X||■|X||X|||||||||||||||||||||||||||||||||||||||||||||||||||||||X|||
| 1.1.2.2.4 | Control system (insulation monitor) | 5 ||||X|■|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.1.2.3 | Switchboard 2 | 6 |||X|||■||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.1.3.1 | batteries | 7 ||||X|||■||X|||||||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.1.3.2 | Battery cooling/heat exchange system | 8 ||||||||■|X||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.1.3.3 | Battery control system | 9 |||||||||■|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.1.1 | LNG Tank | 10 ||||||||||■|X|||||||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.1.2.1 | Filling system | 11 |||||||||||■||||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.1.2.2 | De-earation system | 12 ||||||||||X||■|||||||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.1.2.3 | Control system | 13 ||||||||||X|X|X|■||X|X|||||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.1.2.4 | Piping system LNG | 14 ||||||||||X||||■|||X|X|||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.1.2.4.1 | Boiled off gas compressor | 15 ||||||||||||||X|■|||||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.1.2.4.2 | Gas Valve Unit | 16 ||||||||||||||X|X|■||X|||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.1.2.4.3 | Gas conditioning system (expansion tank) | 17 ||||||||||||||X|||■|||||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.1.3 | Vaporizer | 18 ||||||||||||||X||||■||||||||||||||||||||||||||||||||||||||||||||||||
| 1.4.2.1.1 | Piping system fuel oil | 19 ||||||||||||||||||||■|X|X|||||||||||||||||||||||X|||||||||||||||||||||||
| 1.4.2.1.2 | Tank heating system | 20 |||||||||||||||||||X|■|||||||||X|||||||||||||||||||||||||||||||||||||
| 1.4.2.2.1 | Service tank 1 | 21 ||||||||||||||||||||X|■||||X|X|||||||||||||||||||||||||||||||||||||||
| 1.4.2.2.3 | Overflow tank | 22 |||||||||||||||||||||■|||X||||||||||||||||||||||||||||||||||||||||
| 1.4.2.2.4 | Bunker tank 1 | 23 ||||||||||||||||||||X||■||X|X|||||||||||||||||||||||||||||||||||||||
| 1.4.2.3.1 | Fuel oil pump system | 24 ||||||||||||||||||||X||X|■|X|||||||||||||||||||||||||||||||||||||||
| 1.4.2.3.2 | Piping system | 25 ||||||||||||||||||||X|X|X|X|■|||||||||||||||||||||||||||||||||||||||
| 1.4.2.3.3 | Filling system | 26 ||||||||||||||||||||X||X|||■|||||||||||||||||||||||||||||||||||||||
| 1.4.2.3.4 | De-earation system | 27 ||||||||||||||||||||X|X|X||||■|||||||||||||||||||||||||||||||||||||||
| 1.4.2.3.5 | Alarm system | 28 ||||||||||||||||||||X|X|X||X|||■|||||||||||||||||||||||||||||||||||||||
| 1.4.2.3.6 | Control system | 29 |||||||||||||||||||||||||||X|■|X|||||||||||||||||||||||||||||||||||
| 1.4.2.3.7 | Sounding system | 30 ||||||||||||||||||||X|X|X|||||||■|||||||||||||||||||||||||||||||||||
| 1.4.3.1 | Piping system lub oil | 31 ||||||||||||||||||||||||||||||■|X||X|X||X|||||||X||||||||||||||||||||||||||||||
| 1.4.3.1.1 | Filling system lubrication oil | 32 |||||||||||||||||||||||||||||||■|||X||||||||||||||||||||||||||||||||
| 1.4.3.1.2 | De-earation system | 33 ||||||||||||||||||||||||||||||||■||X||||||||||||||||||||||||||||||||
| 1.4.3.2 | Pumping system | 34 ||||||||||||||||||||||||||||||X|||■|X||X||||||||||||||||||||||||||||||||
| 1.4.3.4.1 | Tank | 35 ||||||||||||||||||||||||||||||X||X||■||X||||||||||||||||||||||||||||||||
| 1.4.3.4.2 | Sludge | 36 ||||||||||||||||||||||||||||||X|||X|X|■|||||||||||||||||||||||||||||||||
| 1.4.3.4.3 | Oil drum filling | 37 ||||||||||||||||||||||||||||||X||||||■||||||||||||||||||||||||||||||||
| 1.4.3.4.4 | Sounding system | 38 ||||||||||||||||||||||||||||||||||X|||■||||||||||||||||||||||||||||||||
| 1.4.3.6 | Dirty oil system | 39 ||||||||||||||||||||||||||||||X||||||||■||||||||||||||||||||||||||||||
| 1.4.4.1 | Piping system exhaust | 40 |||||||||||||||||||||||||||||||||||||||■|X|||X|||||||||||||||||||||||||
| 1.4.4.1.1 | Silencer | 41 |||||||||||||||||||||||||||||||||||||||X|■||X||||||||||||||||||||||||||
| 1.4.4.1.2 | Drip tray | 42 |||||||||||||||||||||||||||||||||||||||X||■||||||||||||||||||||||||
| 1.4.4.1.3 | SCR unit | 43 |||||||||||||||||||||||||||||||||||||||X|||■|X||||||||||||||||||||||||
| 1.4.5 | Diesel Generator | 44 |||||||||||||X||X|||X||||||X||||||X||||X|||||||||■|X|X||X||||||||||||||||||||
| 1.4.5.1 | Electric engine system | 45 ||||X||||||||||||||||||||||||||||||||||||||||X|■||||||||||||||||||||
| 1.4.5.2 | Control system | 46 |||||||||||||||||||||||||||||||||||||||||||||■||||||||||||||||||||
| 1.4.5.3 | Heat exchange system | 47 |||||||||||||||||||||||||||||||||||||||||||X|||■||||||||||||||||||||
| 1.4.6.1 | Piping system air | 48 |||||||||||||||||||||||||||||||||||||||||||||||■||||||||||||||||||
| 1.4.7 | Sludge/driptray system | 49 ||||||||||||||||||X|X|X||X|||X|X|||||||||X||||||||||||||||||■||||||||||||||
| 1.5.1.1 | Vaporizer H2 | 50 |||||||||||||||||||||||||||||||||||||||||||||||||■|X|||||||||||||||
| 1.5.1.2 | Tank | 51 ||||||||||||||||||||||||||||||||||||||||||||||||||■|||||X|||||||||
| 1.5.1.2.1 | Collection system of vaporized H2 | 52 ||||||||||||||||||||||||||||||||||||||||||||||||||X|■|||||||||||||
| 1.5.1.3 | Piping system H2 | 53 |||||||||||||||||||||||||||||||||||||||||||||||||X|X|X|■|X||||||||||
| 1.5.1.3.1 | Boiled off gas compressor | 54 ||||||||||||||||||||||||||||||||||||||||||||||||||X|||■|||||||||||
| 1.5.1.3.2 | Gas Valve Unit | 55 |||||||||||||||||||||||||||||||||||||||||||||||||X||||X|■|||||||||||
| 1.5.1.3.3 | Filling system | 56 |||||||||||||||||||||||||||||||||||||||||||||||||||||||■||||||||
| 1.5.2.1 | Piping system O2 | 57 ||||||||||||||||||||||||||||||||||||||||||||||||||||||||■|||||||
| 1.5.2.2 | Separator system | 58 |||||||||||||||||||||||||||||||||||||||||||||||||||||||X||■||||||
| 1.5.2.3 | Humidifier | 59 ||||||||||||||||||||||||||||||||||||||||||||||||||||X||||X|X|■|||||
| 1.5.3.1 | Cooling system | 60 |||||||||||||||||||||||||||||||||||||||||||||||||||||||||||X|■||||
| 1.5.3.2 | Electrical system | 61 ||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||■|X|X|
| 1.5.3.3 | Fuel cell | 62 ||||||||||||||||||||||||||||||||||||||||||||||||||||||X||X|||X||■||
| 1.5.3.4 | Control system | 63 ||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||X|■|

Figure D.1: DSM matrix setup for logical to logical interaction mapping

# E

# Matlab input code

This appendix shows the input data for the clustering algorithm. Specifically it is the translation of the matrix shown in Appendix D into data which can be used by the Matlab algorithm. Four columns are used instead of one to crop the data for the report. In this data the size of the matrix is defined as well as all the interactions between sub-systems. The interactions are defined by a value of 1 where the absence of an interaction is defined by a 0.

Table E.1: DSM algorithm input part A; element connections

```
% ***********************\\
% DSM TEMPLATE\\
% ***********************\\

DSM_size = 63;
DSM = zeros(DSM_size);

% ***** DSM ENTRIES *****

DSM(1,1)     = 1;

DSM(2,2)     = 1;
DSM(46,2)    = 1;

DSM(3,3)     = 1;
DSM(4,3)     = 1;

DSM(1,4)     = 1;
DSM(2,4)     = 1;
DSM(4,4)     = 1;
DSM(5,4)     = 1;
DSM(7,4)     = 1;

DSM(4,5)     = 1;
DSM(5,5)     = 1;

DSM(3,6)     = 1;
DSM(6,6)     = 1;

DSM(4,7)     = 1;
DSM(7,7)     = 1;
DSM(9,7)     = 1;

DSM(8,8)     = 1;
DSM(9,8)     = 1;

DSM(9,9)     = 1;

DSM(10,10)   = 1;
DSM(11,10)   = 1;

DSM(11,11)   = 1;

DSM(10,12)   = 1;
DSM(12,12)   = 1;

DSM(10,13)   = 1;
DSM(11,13)   = 1;
DSM(12,13)   = 1;
DSM(13,13)   = 1;
DSM(15,13)   = 1;
DSM(16,13)   = 1;

DSM(10,14)   = 1;
DSM(14,14)   = 1;
DSM(17,14)   = 1;
DSM(18,14)   = 1;

DSM(14,15)   = 1;
DSM(15,15)   = 1;

DSM(14,16)   = 1;
DSM(10,16)   = 1;
DSM(15,16)   = 1;
DSM(18,16)   = 1;

DSM(14,17)   = 1;
DSM(17,17)   = 1;

DSM(14,18)   = 1;
DSM(18,18)   = 1;

DSM(19,19)   = 1;
DSM(20,19)   = 1;
DSM(21,19)   = 1;
DSM(45,19)   = 1;

DSM(19,20)   = 1;
DSM(20,20)   = 1;
DSM(29,20)   = 1;

DSM(20,21)   = 1;
DSM(21,21)   = 1;
DSM(25,21)   = 1;
DSM(26,21)   = 1;

DSM(22,22)   = 1;
DSM(25,22)   = 1;

DSM(21,23)   = 1;
DSM(23,23)   = 1;
DSM(25,23)   = 1;
DSM(26,23)   = 1;

DSM(21,24)   = 1;
DSM(23,24)   = 1;
DSM(24,24)   = 1;
DSM(25,24)   = 1;

DSM(21,25)   = 1;
DSM(22,25)   = 1;
DSM(23,25)   = 1;
DSM(24,25)   = 1;
DSM(25,25)   = 1;

DSM(21,26)   = 1;
DSM(23,26)   = 1;
DSM(26,26)   = 1;

DSM(21,27)   = 1;
DSM(22,27)   = 1;
DSM(23,27)   = 1;
DSM(27,27)   = 1;

DSM(21,28)   = 1;
DSM(22,28)   = 1;
DSM(23,28)   = 1;
DSM(25,28)   = 1;
DSM(28,28)   = 1;

DSM(28,29)   = 1;
DSM(29,29)   = 1;
DSM(30,29)   = 1;

DSM(21,30)   = 1;
DSM(22,30)   = 1;
DSM(23,30)   = 1;
DSM(30,30)   = 1;

DSM(31,31)   = 1;
DSM(32,31)   = 1;
DSM(34,31)   = 1;
DSM(35,31)   = 1;
DSM(37,31)   = 1;
DSM(45,31)   = 1;

DSM(32,32)   = 1;
DSM(35,32)   = 1;

DSM(33,33)   = 1;
DSM(35,33)   = 1;

DSM(31,34)   = 1;
DSM(34,34)   = 1;
DSM(35,34)   = 1;
DSM(37,34)   = 1;

DSM(31,35)   = 1;
DSM(33,35)   = 1;
DSM(35,35)   = 1;
DSM(37,35)   = 1;

DSM(31,36)   = 1;
DSM(33,36)   = 1;
DSM(35,36)   = 1;
DSM(36,36)   = 1;

DSM(31,37)   = 1;
DSM(37,37)   = 1;

DSM(35,38)   = 1;
DSM(38,38)   = 1;

DSM(31,39)   = 1;
DSM(34,39)   = 1;
DSM(35,39)   = 1;
DSM(39,39)   = 1;

DSM(31,40)   = 1;
DSM(40,40)   = 1;
DSM(39,40)   = 1;

DSM(41,41)   = 1;
DSM(42,41)   = 1;
DSM(45,41)   = 1;

DSM(41,42)   = 1;
DSM(42,42)   = 1;
DSM(44,42)   = 1;

DSM(41,43)   = 1;
DSM(43,43)   = 1;

DSM(41,44)   = 1;
DSM(44,44)   = 1;
DSM(45,44)   = 1;

DSM(14,45)   = 1;
DSM(16,45)   = 1;
DSM(19,45)   = 1;
DSM(25,45)   = 1;
DSM(31,45)   = 1;
DSM(45,45)   = 1;
DSM(46,45)   = 1;
DSM(47,45)   = 1;
DSM(49,45)   = 1;

DSM(4,46)    = 1;
DSM(45,46)   = 1;
DSM(46,46)   = 1;

DSM(47,47)   = 1;

DSM(45,48)   = 1;
DSM(48,48)   = 1;

DSM(49,49)   = 1;

DSM(50,50)   = 1;
DSM(51,50)   = 1;

DSM(51,51)   = 1;
DSM(56,51)   = 1;

DSM(51,52)   = 1;
DSM(52,52)   = 1;

DSM(50,53)   = 1;
DSM(51,53)   = 1;
DSM(52,53)   = 1;
DSM(53,53)   = 1;
DSM(54,53)   = 1;
DSM(51,54)   = 1;
DSM(54,54)   = 1;

DSM(50,55)   = 1;
DSM(54,55)   = 1;
DSM(55,55)   = 1;

DSM(56,56)   = 1;

DSM(57,57)   = 1;

DSM(56,58)   = 1;
DSM(58,58)   = 1;

DSM(53,59)   = 1;
DSM(57,59)   = 1;
DSM(58,59)   = 1;
DSM(59,59)   = 1;

DSM(59,60)   = 1;
DSM(60,60)   = 1;

DSM(61,61)   = 1;
DSM(61,62)   = 1;
DSM(61,63)   = 1;

DSM(55,62)   = 1;
DSM(57,62)   = 1;
DSM(60,62)   = 1;
DSM(62,62)   = 1;

DSM(62,63)   = 1;
DSM(63,63)   = 1;
```

Table E.2: DSM algorithm input part B; Label allocation

```
% ******************************
%DSM Elements Labels
% *******************************

DSMLABEL = cell(DSM_size,1);

DSMLABEL{1,1} = ’1.1.1.1’;
DSMLABEL{2,1} = ’1.1.1.2’;
DSMLABEL{3,1} = ’1.1.2.1’;
DSMLABEL{4,1} = ’1.1.2.2’;
DSMLABEL{5,1} = ’1.1.2.2.4’;
DSMLABEL{6,1} = ’1.1.2.3’;
DSMLABEL{7,1} = ’1.1.3.1’;
DSMLABEL{8,1} = ’1.1.3.2’;
DSMLABEL{9,1} = ’1.1.3.3’;

DSMLABEL{10,1} = ’1.4.1.1’;
DSMLABEL{11,1} = ’1.4.1.2.1’;
DSMLABEL{12,1} = ’1.4.1.2.2’;
DSMLABEL{13,1} = ’1.4.1.2.3’;
DSMLABEL{14,1} = ’1.4.1.2.4’;
DSMLABEL{15,1} = ’1.4.1.2.4.1’;
DSMLABEL{16,1} = ’1.4.1.2.4.2’;
DSMLABEL{17,1} = ’1.4.1.2.4.3’;
DSMLABEL{18,1} = ’1.4.1.3’;
DSMLABEL{19,1} = ’1.4.2.1.1’;

DSMLABEL{20,1} = ’1.4.2.1.2’;
DSMLABEL{21,1} = ’1.4.2.2.1’;
DSMLABEL{22,1} = ’1.4.2.2.3’;
DSMLABEL{23,1} = ’1.4.2.2.4’;
DSMLABEL{24,1} = ’1.4.2.3.1’;
DSMLABEL{25,1} = ’1.4.2.3.2’;
DSMLABEL{26,1} = ’1.4.2.3.3’;
DSMLABEL{27,1} = ’1.4.2.3.4’;
DSMLABEL{28,1} = ’1.4.2.3.5’;
DSMLABEL{29,1} = ’1.4.2.3.6’;

DSMLABEL{30,1} = ’1.4.2.3.7’;
DSMLABEL{31,1} = ’1.4.3.1’;
DSMLABEL{32,1} = ’1.4.3.1.1’;
DSMLABEL{33,1} = ’1.4.3.1.2’;
DSMLABEL{34,1} = ’1.4.3.2’;
DSMLABEL{35,1} = ’1.4.3.4.1’;
DSMLABEL{36,1} = ’1.4.3.4.2’;
DSMLABEL{37,1} = ’1.4.3.4.3’;
DSMLABEL{38,1} = ’1.4.3.4.4’;
DSMLABEL{39,1} = ’1.4.3.5’;

DSMLABEL{40,1} = ’1.4.3.6’;
DSMLABEL{41,1} = ’1.4.4.1’;
DSMLABEL{42,1} = ’1.4.4.1.1’;
DSMLABEL{43,1} = ’1.4.4.1.2’;
DSMLABEL{44,1} = ’1.4.4.1.3’;
DSMLABEL{45,1} = ’1.4.5’;
DSMLABEL{46,1} = ’1.4.5.1’;
DSMLABEL{47,1} = ’1.4.5.2’;
DSMLABEL{48,1} = ’1.4.5.3’;
DSMLABEL{49,1} = ’1.4.6.1’;

DSMLABEL{50,1} = ’1.5.1.1’;
DSMLABEL{51,1} = ’1.5.1.2’;
DSMLABEL{52,1} = ’1.5.1.2.1’;
DSMLABEL{53,1} = ’1.5.1.3’;
DSMLABEL{54,1} = ’1.5.1.3.1’;
DSMLABEL{55,1} = ’1.5.1.3.2’;
DSMLABEL{56,1} = ’1.5.1.3.3’;
DSMLABEL{57,1} = ’1.5.2.1’;
DSMLABEL{58,1} = ’1.5.2.2’;
DSMLABEL{59,1} = ’1.5.2.3’;

DSMLABEL{60,1} = ’1.5.3.1’;
DSMLABEL{61,1} = ’1.5.3.2’;
DSMLABEL{62,1} = ’1.5.3.3’;
DSMLABEL{63,1} = ’1.5.3.4’;

% ****************************************
%Functional Mapping to Physical Elements
% ****************************************

% Each of the functional labels represents the functional
% requirement for which the physcial DSM element represents
% Used to cross-reference the physical elemnts and
% functional requiremnts
```

# F

# Algorithm parameter and working elaboration

In this appendix an elaboration is given on the different parameters used and the functions which are used for the clustering algorithm. This way it is better understandable how the algorithm works and why the parameter values are chosen.

The first file is the Run_cluster_Ship which is the script file to lead the DSM for analysis and to run the clustering algorithm and to graph the results. In this file first 8 important parameters set for the algorithm. These are:

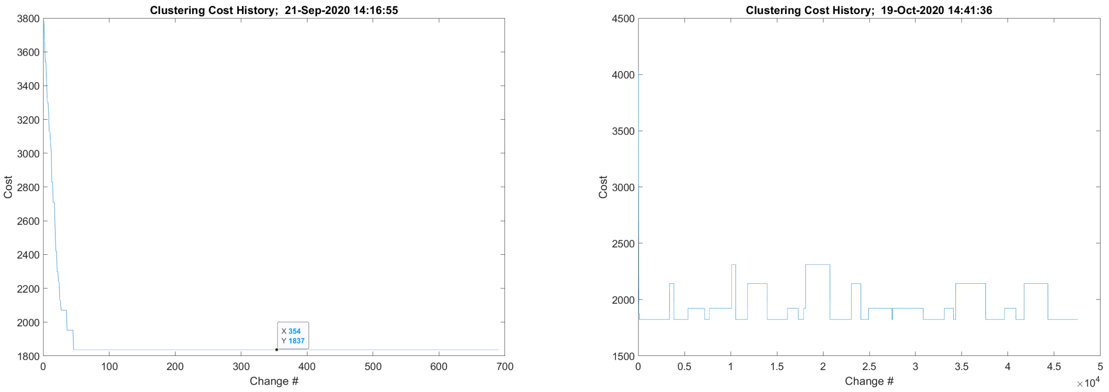
**Cluster_param.pow_cc = 1**
Meaning a penalty assigning to cluster size in order to reduce the size of clusters. When omitting this parameter it is possible that the total system can become one as the amount of interactions outside this total cluster then become 0. However, this would not lead to a feasible solution thus using the cluster size penalty. The pow_cc parameter increase above 1 had no or minimal effect on reducing the maximum cluster size which means that the value of 1 was used for this parameter[92].

**Cluster_param.pow_bid = 2**
As well as the previous parameter now there is a higher penalty for large clusters. This means that the goal is to have multiple smaller clusters instead of a few large ones. This is used in the algorithm and also supported in the research as the goal is to avoid defining inclusive modules which become more complicated. The pow_bid in the original problem was set to 1 as the result otherwise was the generation of multiple small clusters[92]. However, this was not really the case in this research as is also shown in the results. The value therefore was set to 2 as in the first solution the problem was that even with the value of 2 the clusters were relatively large.

**Cluster_param.pow_dep = 4**
The focus of this parameter is to have a focus on high interactions between elements. High interaction elements are values highly which makes them more critical in the clustering. As the interactions are important and should be minimized. Lower numbers than 4 resulted in many small clusters and a value higher than 4 did not give a significant change to the results than the value of 4[92].

**Cluster_param.max_cluster_size = DSM_size**
This parameter defines the maximum cluster size. Even though the goal is to find multiple smaller clusters for potential modules, the maximum allowable size is the total DSM. This allows for all the options to be possible.

**Cluster_param.rand_accept = 2*DSM_size**
The algorithm uses simulated annealing for an optimal result. For this the parameters rand_bid and rand_accept are defined. These specify how often the algorithm makes a less optimal change than the best solution. The algorithm is a random algorithm and has no idea when the optimal solution is found in this version of the code. This means that this parameter is set to proceed with the clustering options up to 2 times the size of



(a) Clustering result using times parameter of 5 and stable limit parameter of 5

(b) Clustering result using times parameter of 25 and stable limit parameter of 5

Figure F.1: Influence of increasing the times and stable limit parameters on the clustering costs

the DSM. This means for instance when using 60 elements in a DSM that the algorithm continues to accept random options up to 120 times.

**Cluster_param.rand_bid = 2*DSM_size**

To ensure that the solution is not stuck on a local optimum there is also the parameter to accept other solutions than the optimum solution. This parameter is defined to accept 1 out of 2 times the DSM size the second highest bid/option. Using the previous example it would mean that 1 in 120 times the second highest bid is used to check if there is a better option. The original algorithm worked better when the simulated annealing occurred less often. For this reason it only occurs once every 2 times of the size of the DSM[92].

**Cluster_param.times = 2**

This parameter is focused on the duration of the clustering. It is the attempted “times” the size of the DSM before a system stability check is run. This means that with a higher value, there are more attempts before the stability is checked.

**Cluster_param.stable_limit = 2**

The final parameter is to loop the stable limits times the size before a solution is given. This means that the process is done in this case 2 times before the final result is shown. In the original code and example the value was set to 2 as a higher value did not seem to result in better results[92]. This however was different for this research where the results did change when increasing this value.

Even though the advise is to use the value 2 for both the times and stable limit parameters a change was made in the use of the algorithm. In the case of this research there was an increase in optimization using a higher value. Also the certainty for a better result becomes higher which means fewer simulations have to be done to get reliable results. This is visualized in the example of Figures F.1a and F.1b. Where the optimal result for multiple runs was 1837 for Figure F.1a using a value of 5 for the times parameter and a value of 5 for the stable limit parameter. when increasing the Time parameter a cost value of 1823 was the worst solution when using a value of 25 for the times parameter and the same value of 5 for the stable limit parameter. The bests solution for this parameter setting resulted in 1583 as shown in Figure F.1b. This shows that there is a decrease in costs which means that an increase in parameters gives better results for this research than the defined parameters in Thebeau [92]. When increasing the values higher the results did not increase much more which was tested for run 24 and 25 for the battery and hydrogen configuration.

**Likeness calculation**

The final function is to find the average value or likeness of the results to be able to determine how consistent the results are. This means that the clustering is run multiple times and the likeness of the result is shown to have a say about the results. For this the Likeness_calc is used.

The like elements between two clusters are obtained by taking the dot product of the cluster matrices.

The likeness of the two clusters twice the sum of the elements is divided by the sum of the total elements in the two clusters. As the elements are found in both clusters the measurement uses two times the number of elements. The formula used for the likeness is shown below in Equation F.1:

$$Likeness(X,Y) = \frac{XinY + YinX}{TotalXY} \text{where}\, 0 \leq \text{likeness} \leq 1 \tag{F.1}$$

Where:

X = Cluster X of run 1
Y = Cluster Y of Run 2
XinY = Number of element in cluster X that can be found in cluster Y
YinX = Number of elements in cluster Y that can be found in cluster X
XinY = YinX
TotalXY = Total number of elements in cluster X and Y for all X and Y in both runs

# G

# Clustering results

## G.1. Clustering results all data input

RUN 1 OUT: 4,6,9,28,29,46,63

| | |
|---|---|
| Cluster_param.times | 5 |
| Cluster_param.stable_limit | 25 |
| Cost | 2544 |

| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 | Cluster 7 | Cluster 8 | Cluster 9 | Cluster 10 | Cluster 11 |
|---|---|---|---|---|---|---|---|---|---|---|
| 21 | 50 | 10 | 57 | 31 | 44 | 40 | 33 | 10 | 19 | 56 |
| 22 | 51 | 14 | 59 | 32 | 45 | 41 | 35 | 11 | 20 | 58 |
| 23 | 52 | 15 | 60 | 34 | 47 | 42 | 36 | 12 | 49 | |
| 24 | 53 | 16 | 61 | 37 | 48 | 43 | 38 | 13 | | |
| 25 | 54 | 17 | 62 | 39 | | | | | | |
| 27 | 55 | 18 | | | | | | | | |
| 30 | | | | | | | | | | |

RUN 2 OUT: 4,6,9,28,29,46,63

| | |
|---|---|
| Cluster_param.times | 5 |
| Cluster_param.stable_limit | 25 |
| Cost | 2960 |

| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 | Cluster 7 | Cluster 8 | Cluster 9 | Cluster 10 | Cluster 11 |
|---|---|---|---|---|---|---|---|---|---|---|
| 19 | 50 | 31 | 10 | 57 | 32 | 44 | 40 | 10 | 22 | 56 |
| 20 | 51 | 32 | 14 | 59 | 33 | 45 | 41 | 11 | 24 | 58 |
| 21 | 52 | 34 | 15 | 60 | 35 | 47 | 42 | 12 | 25 | |
| 22 | 53 | 35 | 16 | 61 | 36 | 48 | 43 | 13 | | |
| 23 | 54 | 37 | 17 | 62 | 38 | | | | | |
| 26 | 55 | 39 | 18 | | | | | | | |
| 27 | | | | | | | | | | |
| 30 | | | | | | | | | | |
| 49 | | | | | | | | | | |

RUN 3 OUT: 4,6,9,28,29,46,63

| | |
|---|---|
| Cluster_param.times | 5 |
| Cluster_param.stable_limit | 25 |
| Cost | 2689 |

| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 | Cluster 7 | Cluster 8 | Cluster 9 | Cluster 10 | Cluster 11 |
|---|---|---|---|---|---|---|---|---|---|---|
| 21 | 50 | 57 | 32 | 31 | 14 | 44 | 40 | 10 | 19 | 56 |
| 22 | 51 | 59 | 33 | 32 | 15 | 45 | 41 | 11 | 20 | 58 |
| 23 | 52 | 60 | 35 | 34 | 16 | 47 | 42 | 12 | 49 | |
| 25 | 53 | 61 | 36 | 37 | 17 | 48 | 43 | 13 | | |
| 26 | 54 | 62 | 38 | 39 | 18 | | | | | |
| 27 | 55 | | | | | | | | | |
| 30 | | | | | | | | | | |
| 49 | | | | | | | | | | |

RUN 4 OUT: 4,6,9,28,29,46,63

Cluster_param.times 25

Cluster_param.stable_limit 5

Cost 3102

| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 | Cluster 7 | Cluster 8 | Cluster 9 | Cluster 10 | Cluster 11 |
|---|---|---|---|---|---|---|---|---|---|---|
| 50 | 21 | 13 | 57 | 32 | 44 | 40 | 31 | 10 | 19 | 36 |
| 51 | 22 | 14 | 59 | 33 | 45 | 41 | 34 | 11 | 20 | 49 |
| 52 | 23 | 15 | 60 | 35 | 47 | 42 | 37 | 12 | 45 | |
| 53 | 25 | 16 | 61 | 36 | 48 | 43 | 39 | 13 | | |
| 54 | 26 | 17 | 62 | 38 | | | | | | |
| 55 | 27 | 18 | | | | | | | | |
| 56 | 30 | | | | | | | | | |
| 58 | | | | | | | | | | |

RUN 5 OUT: 4,6,9,28,29,46,63

Cluster_param.times 25

Cluster_param.stable_limit 5

Cost 3042

| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 | Cluster 7 | Cluster 8 | Cluster 9 | Cluster 10 | Cluster 11 | Cluster 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 21 | 13 | 50 | 31 | 57 | 53 | 44 | 40 | 33 | 10 | 19 | 56 |
| 22 | 14 | 51 | 32 | 60 | 57 | 45 | 41 | 35 | 11 | 20 | 58 |
| 23 | 15 | 52 | 34 | 61 | 59 | 47 | 42 | 36 | 12 | 49 | |
| 25 | 16 | 53 | 37 | 62 | 60 | 48 | 43 | 38 | 13 | | |
| 26 | 17 | 54 | 39 | | | | | | | | |
| 27 | 18 | 55 | | | | | | | | | |
| 30 | | | | | | | | | | | |

RUN 26 OUT: 4,6,9,28,29,46,63

Cluster_param.times 25

Cluster_param.stable_limit 5

Cost 2487

| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 | Cluster 7 | Cluster 8 | Cluster 9 | Cluster 10 | Cluster 11 |
|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 50 | 21 | 57 | 44 | 40 | 33 | 31 | 22 | 56 | 19 |
| 14 | 51 | 23 | 59 | 45 | 41 | 35 | 34 | 24 | 58 | 20 |
| 15 | 52 | 26 | 60 | 47 | 42 | 36 | 37 | 25 | | |
| 16 | 53 | 27 | 61 | 48 | 43 | 38 | 39 | | | |
| 17 | 54 | 30 | 62 | | | | | | | |
| 18 | 55 | 49 | | | | | | | | |

RUN 27 OUT: 4,6,9,28,29,46,63

Cluster_param.times 25

Cluster_param.stable_limit 5

Cost 2487

| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 | Cluster 7 | Cluster 8 | Cluster 9 | Cluster 10 | Cluster 11 |
|---|---|---|---|---|---|---|---|---|---|---|
| 31 | 50 | 21 | 57 | 14 | 44 | 40 | 10 | 22 | 19 | 56 |
| 32 | 51 | 23 | 59 | 15 | 45 | 41 | 11 | 24 | 20 | 58 |
| 33 | 52 | 26 | 60 | 16 | 47 | 42 | 12 | 25 | 49 | |
| 34 | 53 | 27 | 61 | 17 | 48 | 43 | 13 | | | |
| 35 | 54 | 30 | 62 | 18 | | | | | | |
| 36 | 55 | 49 | | | | | | | | |
| 37 | | | | | | | | | | |
| 38 | | | | | | | | | | |
| 39 | | | | | | | | | | |

## G.2. Clustering results Diesel and Battery configuration

| | | | | | |
|---|---|---|---|---|---|
| RUN 6 | OUT: 4,6,9-18,28,29,46,49-63 | | | | |
| Cluster_param.times | | | 25 | | |
| Cluster_param.stable_limit | | | 5 | | |
| Cost | | | | | |
| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 |
| 19 | 32 | 31 | 44 | 40 | 22 |
| 20 | 33 | 32 | 45 | 41 | 24 |
| 21 | 35 | 34 | 47 | 42 | 25 |
| 23 | 36 | 37 | 48 | 43 | 27 |
| 26 | 38 | 39 | | | |
| 27 | | | | | |
| 30 | | | | | |
| 49 | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| RUN 7 | OUT: 4,6,9-18,28,29,46,49-63 | | | | |
| Cluster_param.times | | | 25 | | |
| Cluster_param.stable_limit | | | 5 | | |
| Cost | | | 1583 | | |
| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 |
| 21 | 44 | 40 | 33 | 31 | 19 |
| 22 | 45 | 41 | 35 | 34 | 20 |
| 23 | 47 | 42 | 36 | 37 | 49 |
| 24 | 48 | 43 | 38 | 39 | |
| 25 | | | | | |
| 26 | | | | | |
| 27 | | | | | |
| 30 | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| RUN 8 | OUT: 4,6,9-18,28,29,46,49-63 | | | | |
| Cluster_param.times | | | 25 | | |
| Cluster_param.stable_limit | | | 5 | | |
| Cost | | | 1583 | | |
| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 |
| 21 | 44 | 40 | 33 | 31 | 19 |
| 22 | 45 | 41 | 35 | 34 | 20 |
| 23 | 47 | 42 | 36 | 37 | 49 |
| 24 | 48 | 43 | 38 | 39 | |
| 25 | | | | | |
| 26 | | | | | |
| 27 | | | | | |
| 30 | | | | | |

RUN 9 OUT: 4,6,9-18,28,29,46,49-63

| | |
|---|---|
| Cluster_param.times | 25 |
| Cluster_param.stable_limit | 5 |
| Cost | 1844 |

| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 |
|---|---|---|---|---|---|
| 21 | 31 | 44 | 40 | 33 | 19 |
| 22 | 32 | 45 | 41 | 35 | 20 |
| 23 | 34 | 47 | 42 | 36 | 49 |
| 24 | 35 | 48 | 43 | 38 | |
| 25 | 37 | | | | |
| 26 | 39 | | | | |
| 27 | | | | | |
| 30 | | | | | |

RUN 12 OUT: 4,6,9-18,28,29,46,49-63

| | |
|---|---|
| Cluster_param.times | 25 |
| Cluster_param.stable_limit | 5 |
| Cost | 1823 |

| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 | Cluster 7 |
|---|---|---|---|---|---|---|
| 21 | 31 | 44 | 40 | 33 | 22 | 19 |
| 23 | 32 | 45 | 41 | 35 | 24 | 20 |
| 26 | 34 | 47 | 42 | 36 | 25 | |
| 27 | 37 | 48 | 43 | 38 | | |
| 30 | 39 | | | | | |
| 49 | | | | | | |

## G.3. Clustering results Dual fuel and Battery configuration

RUN 10 OUT: 4,6,9,28,29,46,49-63

| | |
|---|---|
| Cluster_param.times | 25 |
| Cluster_param.stable_limit | 5 |
| Cost | 2252 |

| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 | Cluster 7 | Cluster 8 | Cluster 9 |
|---|---|---|---|---|---|---|---|---|
| 31 | 10 | 21 | 44 | 40 | 14 | 22 | 33 | 19 |
| 32 | 11 | 23 | 45 | 41 | 16 | 24 | 36 | 20 |
| 34 | 12 | 26 | 47 | 42 | 17 | 25 | | |
| 37 | 13 | 27 | 48 | 43 | 18 | | | |
| 38 | 15 | 30 | | | | | | |
| 39 | 16 | | | | | | | |

RUN 11 OUT: 4,6,9,28,29,46,49-63

| | |
|---|---|
| Cluster_param.times | 25 |
| Cluster_param.stable_limit | 5 |
| Cost | 2491 |

| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 | Cluster 7 | Cluster 8 | Cluster 9 |
|---|---|---|---|---|---|---|---|---|
| 21 | 44 | 40 | 33 | 31 | 14 | 10 | 22 | 19 |
| 23 | 45 | 41 | 35 | 34 | 16 | 11 | 24 | 20 |
| 26 | 47 | 42 | 36 | 37 | 17 | 12 | 25 | |
| 27 | 48 | 43 | 38 | 39 | 18 | 13 | | |
| 30 | | | | | | | | |

RUN 13 OUT: 4,6,9,28,29,46,49-63

| | |
|---|---|
| Cluster_param.times | 25 |
| Cluster_param.stable_limit | 5 |
| Cost | 1487 |

| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 | Cluster 7 |
|---|---|---|---|---|---|---|
| 10 | 21 | 31 | 44 | 40 | 33 | 19 |
| 11 | 22 | 32 | 45 | 41 | 35 | 20 |
| 12 | 23 | 34 | 47 | 42 | 36 | |
| 13 | 24 | 37 | 48 | 43 | 38 | |
| 15 | 25 | 39 | | | | |
| 16 | 26 | | | | | |
| 17 | 27 | | | | | |
| 18 | 30 | | | | | |

RUN 14 OUT: 4,6,9,28,29,46,49-63

| | |
|---|---|
| Cluster_param.times | 25 |
| Cluster_param.stable_limit | 5 |
| Cost | 1903 |

| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 | Cluster 7 | Cluster 8 |
|---|---|---|---|---|---|---|---|
| 21 | 32 | 31 | 14 | 10 | 44 | 40 | 19 |
| 22 | 33 | 32 | 15 | 11 | 45 | 41 | 20 |
| 23 | 35 | 34 | 16 | 12 | 47 | 42 | |
| 24 | 36 | 37 | 17 | 13 | 48 | 43 | |
| 25 | 38 | 39 | 18 | 15 | | | |
| 26 | | | | | | | |
| 27 | | | | | | | |
| 30 | | | | | | | |

RUN 15 OUT: 4,6,9,28,29,46,49-63

| | |
|---|---|
| Cluster_param.times | 25 |
| Cluster_param.stable_limit | 5 |
| Cost | 1960 |

| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 | Cluster 7 | Cluster 8 |
|---|---|---|---|---|---|---|---|
| 21 | 31 | 14 | 44 | 40 | 33 | 10 | 19 |
| 22 | 32 | 15 | 45 | 41 | 35 | 11 | 20 |
| 23 | 34 | 16 | 47 | 42 | 36 | 12 | |
| 24 | 35 | 17 | 48 | 43 | 38 | 13 | |
| 25 | 37 | 18 | | | | | |
| 26 | 39 | | | | | | |
| 27 | | | | | | | |
| 30 | | | | | | | |

RUN 16 OUT: 4,6,9,28,29,46,49-63

| | |
|---|---|
| Cluster_param.times | 25 |
| Cluster_param.stable_limit | 5 |
| Cost | 1651 |

| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 | Cluster 7 | Cluster 8 |
|---|---|---|---|---|---|---|---|
| 21 | 10 | 32 | 44 | 40 | 31 | 14 | 19 |
| 22 | 11 | 33 | 45 | 41 | 34 | 17 | 20 |
| 23 | 12 | 35 | 47 | 42 | 37 | 18 | |
| 24 | 13 | 36 | 48 | 43 | 39 | | |
| 25 | 15 | 38 | | | | | |
| 26 | 16 | | | | | | |
| 27 | | | | | | | |
| 30 | | | | | | | |

RUN 17 OUT: 4,6,9,28,29,46,49-63

| | |
|---|---|
| Cluster_param.times | 25 |
| Cluster_param.stable_limit | 10 |
| Cost | 2387 |

| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 | Cluster 7 | Cluster 8 | Cluster 9 |
|---|---|---|---|---|---|---|---|---|
| 10 | 32 | 31 | 21 | 44 | 40 | 10 | 22 | 19 |
| 14 | 33 | 32 | 23 | 45 | 41 | 11 | 24 | 20 |
| 15 | 35 | 34 | 26 | 47 | 42 | 12 | 25 | |
| 16 | 36 | 37 | 27 | 48 | 43 | 13 | | |
| 17 | 38 | 39 | 30 | | | | | |
| 18 | | | | | | | | |

RUN 18 OUT: 4,6,9,28,29,46,49-63

| | |
|---|---|
| Cluster_param.times | 25 |
| Cluster_param.stable_limit | 25 |
| Cost | 1216 |

| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 |
|---|---|---|---|---|---|
| 31 | 10 | 21 | 44 | 40 | 19 |
| 32 | 11 | 22 | 45 | 41 | 20 |
| 33 | 12 | 23 | 47 | 42 | |
| 34 | 13 | 24 | 48 | 43 | |
| 35 | 14 | 25 | | | |
| 36 | 15 | 26 | | | |
| 37 | 16 | 27 | | | |
| 38 | 17 | 30 | | | |
| 39 | 18 | | | | |

RUN 19 OUT: 4,6,9,28,29,46,49-63

| | |
|---|---|
| Cluster_param.times | 25 |
| Cluster_param.stable_limit | 25 |
| Cost | 1958 |

| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 | Cluster 7 |
|---|---|---|---|---|---|---|
| 10 | 21 | 31 | 32 | 44 | 40 | 19 |
| 11 | 22 | 32 | 33 | 45 | 41 | 20 |
| 12 | 23 | 34 | 35 | 47 | 42 | |
| 13 | 24 | 35 | 36 | 48 | 43 | |
| 14 | 25 | 37 | 38 | | | |
| 15 | 26 | 39 | | | | |
| 16 | 27 | | | | | |
| 17 | 30 | | | | | |
| 18 | | | | | | |

## G.4. Clustering results Batteries and Hydrogen configuration

| | | | |
|---|---|---|---|
| RUN 20 | OUT: 4,6,9-49,63 | | |
| Cluster_param.times | | | 25 |
| Cluster_param.stable_limit | | | 5 |
| Cost | | | 333 |
| Cluster 1 | cluster 2 | Cluster 3 | |
| 50 | 57 | 56 | |
| 51 | 59 | 58 | |
| 52 | 60 | | |
| 53 | 61 | | |
| 54 | 62 | | |
| 55 | | | |

| | | | |
|---|---|---|---|
| RUN 21 | OUT: 4,6,9-49,63 | | |
| Cluster_param.times | | | 25 |
| Cluster_param.stable_limit | | | 5 |
| Cost | | | 387 |
| Cluster 1 | cluster 2 | Cluster 3 | |
| 50 | 56 | 57 | |
| 51 | 58 | 61 | |
| 52 | 59 | 62 | |
| 53 | 60 | | |
| 54 | | | |
| 55 | | | |

| | | | |
|---|---|---|---|
| RUN 22 | OUT: 4,6,9-49,63 | | |
| Cluster_param.times | | | 25 |
| Cluster_param.stable_limit | | | 5 |
| Cost | | | 333 |
| Cluster 1 | cluster 2 | Cluster 3 | |
| 50 | 57 | 56 | |
| 51 | 59 | 58 | |
| 52 | 60 | | |
| 53 | 61 | | |
| 54 | 62 | | |
| 55 | | | |

| | | | |
|---|---|---|---|
| RUN 23 | OUT: 4,6,9-49,63 | | |
| Cluster_param.times | | | 25 |
| Cluster_param.stable_limit | | | 5 |
| Cost | | | 516 |
| Cluster 1 | cluster 2 | Cluster 3 | Cluster 4 |
| 50 | 60 | 57 | 56 |
| 51 | 61 | 59 | 58 |
| 52 | 62 | 60 | |
| 53 | | | |
| 54 | | | |
| 55 | | | |

| | | | |
|---|---|---|---|
| RUN 24 | OUT: 4,6,9-49,63 | | |
| Cluster_param.times | | | 25 |
| Cluster_param.stable_limit | | | 25 |
| Cost | | | 755 |
| Cluster 1 | cluster 2 | Cluster 3 | |
| 52 | 50 | 56 | |
| 53 | 51 | 58 | |
| 57 | 52 | | |
| 59 | 53 | | |
| 60 | 54 | | |
| 61 | 55 | | |
| 62 | | | |

| | | | |
|---|---|---|---|
| RUN 25 | OUT: 4,6,9-49,63 | | |
| Cluster_param.times | | | 25 |
| Cluster_param.stable_limit | | | 25 |
| Cost | | | 333 |
| Cluster 1 | cluster 2 | Cluster 3 | |
| 50 | 57 | 56 | |
| 51 | 59 | 58 | |
| 52 | 60 | | |
| 53 | 61 | | |
| 54 | 62 | | |
| 55 | | | |

## G.5. Reduced clustering results

Table G.1: Reduced potential clusters based on all configurations

| Cluster 1 | cluster 2 | Cluster 3a | Cluster 3b | Cluster 4a | Cluster 4b | Cluster 4c | Cluster 4d | Cluster 5 | Cluster 6 | Cluster 7 | Cluster 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 50 | 57 | 32 | 31 | 21 | 21 | 22 | 21 | 44 | 40 | 10 | 10 |
| 51 | 59 | 33 | 32 | 22 | 22 | 23 | 23 | 45 | 41 | 14 | 11 |
| 52 | 60 | 35 | 33 | 23 | 23 | 24 | 26 | 47 | 42 | 15 | 12 |
| 53 | 61 | 36 | 34 | 24 | 25 | 25 | 27 | 48 | 43 | 16 | 13 |
| 54 | 62 | 38 | 35 | 25 | 26 | 30 | 30 |  |  | 17 |  |
| 55 |  |  | 36 | 27 | 27 |  | 49 |  |  | 18 |  |
|  |  | 31 | 37 | 30 | 30 | 21 |  |  |  |  |  |
|  |  | 32 | 38 |  | 19 | 23 | 22 |  |  |  |  |
|  |  | 34 | 39 | 19 | 20 | 26 | 24 |  |  |  |  |
|  |  | 37 |  | 20 | 49 | 27 | 25 |  |  |  |  |
|  |  | 39 |  | 49 |  | 49 |  |  |  |  |  |

Table G.2: Reduced potential clusters based on diesel and battery configuration

| Cluster 1a | Cluster 1b | cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 |
|---|---|---|---|---|---|
| 21 | 21 | 44 | 40 | 33 | 31 |
| 23 | 22 | 45 | 41 | 35 | 34 |
| 26 | 23 | 47 | 42 | 36 | 37 |
| 27 | 24 | 48 | 43 | 38 | 39 |
| 30 | 25 |  |  | 32 | 32 |
| 49 | 26 |  |  |  |  |
|  | 27 |  |  |  |  |
| 22 | 30 |  |  |  |  |
| 24 |  |  |  |  |  |
| 25 | 19 |  |  |  |  |
|  | 20 |  |  |  |  |
| 19 | 49 |  |  |  |  |
| 20 |  |  |  |  |  |

Table G.3: Reduced potential clusters based on dual fuel and battery configuration

| Cluster 1a | Cluster 1b | Cluster 1c | Cluster 1d | Cluster 2a | Cluster 2b | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 |
|---|---|---|---|---|---|---|---|---|---|
| 31 | 31 | 31 | 32 | 10 | 10 | 21 | 44 | 40 | 19 |
| 32 | 32 | 32 | 33 | 11 | 11 | 23 | 45 | 41 | 20 |
| 33 | 34 | 34 | 35 | 12 | 12 | 26 | 47 | 42 |  |
| 34 | 37 | 37 | 36 | 13 | 13 | 27 | 48 | 43 |  |
| 35 | 38 | 39 | 38 | 14 |  | 30 |  |  |  |
| 36 | 39 |  |  | 15 | 14 | 22 |  |  |  |
| 37 |  | 33 | 31 | 16 | 15 | 24 |  |  |  |
| 38 | 33 | 35 | 34 | 17 | 16 | 25 |  |  |  |
| 39 | 36 | 36 | 37 | 18 | 17 |  |  |  |  |
|  |  | 38 | 39 |  | 18 |  |  |  |  |

Table G.4: Reduced potential clusters based hydrogen and battery configuration

| Cluster 1 | cluster 2 | Cluster 3 | Alternative |
|---|---|---|---|
| 50 | 57 | 56 | 56 |
| 51 | 59 | 58 | 58 |
| 52 | 60 |  | 59 |
| 53 | 61 |  | 60 |
| 54 | 62 |  |  |
| 55 |  |  | 57 |
|  |  |  | 61 |
|  |  |  | 62 |

## G.6. Interaction analysis between and outside clusters

Table G.5: Interaction analysis between and outside clusters defining the amount of interactions part A

| Cluster | Element | Input from | Element | Output to | Interactions excluding numbers 9,28,29,46,63 | Interactions combining overlapping connections |
|---|---|---|---|---|---|---|
| 1a | 14 | 44 | | | 2 | 1 |
| | 16 | 44 | | | | |
| 1b | 10 | 14,16 | 13 | 15,16 | 10 | 7 |
| | 14 | 44 | 14 | 10 | | |
| | 15 | 13 | 16 | 10 | | |
| | 16 | 44,13 | | | | |
| 2a | 21 | 19, 49, 28 | 21 | 20 | 10 | 6 |
| | 22 | 28 | 49 | 36,19,20 | | |
| | 23 | 49, 28 | | | | |
| | 25 | 44, 28 | | | | |
| | 26 | 49 | | | | |
| | 30 | 29 | | | | |
| 2b | 21 | 23,24,25,30,19,28 | 21 | 20 | 21 | 16 |
| | 23 | 24,25,30,28 | 49 | 36,23,19,20 | | |
| | 26 | 23 | | | | |
| | 22 | 27,28 | | | | |
| | 23 | 26,27,49,28 | | | | |
| | 25 | 21,23,44,28 | | | | |
| | 30 | 29 | | | | |
| 2c | 21 | 24,25,19,49,28 | 21 | 25,2 | 22 | 13 |
| | 23 | 24,25,49,28 | 23 | 25 | | |
| | 26 | 49 | 27 | 22 | | |
| | 27 | 49 | 30 | 22 | | |
| | 30 | 29 | | | | |
| | 22 | 27,3 | 24 | 21,23 | | |
| | 25 | 22,23 | 25 | 21,23 | | |
| 2d | 19 | 49,44 | 19 | 21,45 | 6 | 5 |
| | 20 | 21,49 | 20 | 29 | | |

Table G.6: Interaction analysis between and outside clusters defining the amount of interactions part B

| **Cluster** | **Element** | **Input from** | **Element** | **Output to** | **Interactions excluding numbers 9,28,29,46,63** | **Interactions combining overlapping connections** |
|---|---|---|---|---|---|---|
| 3a | 31 | 44 | 31 | 45 | 3 | 3 |
| | 36 | 49 | | | | |
| 3b | 32 | 31 | 35 | 31,37 | 17 | 12 |
| | 35 | 31,32,34 | 36 | 31 | | |
| | 36 | 49 | | | | |
| | 31 | 35,36,44 | 31 | 32,35,45 | | |
| | 37 | 35 | 32 | 35 | | |
| | | | 34 | 35 | | |
| 3c | 31 | 44,36 | 31 | 45 | 11 | 10 |
| | 35 | 33,36 | 35 | 33 | | |
| | 33 | 35 | 33 | 35 | | |
| | 36 | 49 | 36 | 31,35 | | |
| 4 | 44 | 40,43 | 44 | 25,31,14,<br>16,19,46 | 11 | 11 |
| | 45 | 31,19 | 45 | 4 | | |
| 5 | | | 40 | 44 | 2 | 1 |
| | | | 43 | 44 | | |
| 6a | 53 | 59 | 51 | 56 | 3 | 3 |
| | 55 | 62 | | | | |
| 7a | 62 | 63 | 59 | 53,58 | 3 | 3 |
| | | | 61 | 63 | | |
| | | | 62 | 55 | | |
| 8a | 56 | 51 | | | 2 | 2 |
| | 58 | 59 | | | | |
| 6/7/8 b | 56 | 51 | 59 | 53,57 | 7 | 7 |
| | 60 | 62 | | | | |
| | 57 | 59 | 61 | 63 | | |
| | 62 | 63 | 62 | 55,60 | | |