PLATFORM APPROACH FOR MODULARISING BATTERY ELECTRIC FAST FERRIES

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ABSTRACT

The transportation sector is responsible for a relevant share of the total emissions and offers great potentials. It is necessary to implement as many zero-emission mobility systems as possible in the shortest time. For fast ferries, which are a relevant transport manner for a large share of the global population, technical issues could be solved and the successful operation was demonstrated. Up to today high-speed ships have been fully individually designed because physical effects demand for an individual optimisation for each use-case. Specifically for battery electric ships the overall efficiency is crucial to ensure not only an ecological but also economical operation.

With today's methods the design and production of such an individual designed ferry does take too long. To cover the rising demand, new approaches for mass production need to be established.

In this paper we describe a method for designing a platform for ships with the example of a battery electric fast ferry. The focus is on the actual modularisation, as other aspects like requirements or results of our example case are published elsewhere and are therefore just included briefly.

The method is validated on the world's first battery powered high-speed ferry.

Keywords: Modularisation, Systems Engineering (SE), platform design, Complexity, Design methods

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1 INTRODUCTION

To prevent global climate from reaching tipping points rapid changes for lower emissions need to happen. The transportation sector is responsible for a relevant share of the total emissions and offers great potentials. It is therefore necessary to implement as many zero-emission mobility systems as possible in the shortest time.
For fast ferries, which are a relevant transport manner for a large share of the global population, the first tests have just been carried out. Technical issues could be solved, and the successful operation was demonstrated. However, up to today high-speed ships have been individually designed because physical effects demand for an individual optimisation for each operation profile. Specifically for battery electric ships the overall efficiency is crucial to ensure not only an ecological but also economical operation.
With today's methods the design and production of such an individual designed ferry does take too long. To cover the rising demand, new approaches for mass production need to be established.
In this paper we describe a method for designing a modular architecture for ships with the example of a platform-based battery electric fast ferry. The focus is on the actual modularisation, as other aspects like requirements or results of our example case are published elsewhere and therefore just included briefly.
We used the design research methodology (Blessing and Chakrabarti, 2009) to conclude this research. Chapter two clarifies the research question. A summary of the first descriptive study is given in chapter three in form of a systematic literature review. Chapter four corresponds to the prescriptive study with explaining the developed method and chapter five describes the second descriptive study with the evaluation.

2 PROBLEM ANALYSIS

Climate protection and the associated reduction of emissions are pursued by various levels of politics. On a global level, the Paris Climate Agreement was adopted and the EU has decided to become climate neutral by 2050 (European Commission, 2018). Several cities have also taken measures to reduce emissions, for example London will introduce a zero-emission zone from 2025, where only zero-emission vehicles will be allowed to drive (Greater London Authority, 2022).
The transport sector is responsible for about 30% of emissions in Europe (European Parliament, 2019) and 15% worldwide, and is the only sector whose emissions have increased since 1990 (Shukla et al., 2022). Studies of public transport show that ferries in particular are responsible for a large proportion of emissions. The Norwegian transport company Kolumbus has identified that ferries cause half of the CO2 emissions, but only cover 10% of the passenger kilometres (Dahle, 2020).
To meet the EU's targets, emission-free alternatives are therefore needed in the ferry sector. However, these alternatives are currently expensive compared to conventional ferries.
The traditional shipbuilding process reinforces these trends because so-called one-off ships are developed that are customised and thus unique. In addition, the focus when buying a ship is primarily on the purchase price, although with ships as capital goods, the majority of the costs are incurred in the actual operation. The customised design and production of ferries also means long development times.
In order to produce many emission-free ferries in a short time, a methodology is needed that drastically reduces the development and production times and offers the possibility to produce many ships in a short time. At the same time, the methodology should allow the exploitation of economies of scale to enable low-cost production and take into account the transition from workshop production to automated production on an industrial scale.
Standardisation of the product is one approach to realise shorter development times because certain components can be reused. In addition, certain components can be further optimised in terms of cost and can be used cost-effectively in later series. For production, standardisation offers the advantage that, on the one hand, economies of scale can be used, but also that production capacities can be expanded. Standardization enables, for example, outsourcing the production of some components to specialized companies that can produce at low cost (Seidenberg et al., 2022). In addition, value creation networks can be formed that can achieve further cost reductions (Disselkamp et al., 2022).
Standardising a ferry is challenging because there are a multitude of interdependencies that are mutually dependent. Adjusting the number of passengers means changing the expected weight. This means that the ship's batteries have to be adjusted and the hull has to be designed for the new weight distribution of the ship (Pfeifer et al., 2020).

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In addition to standardisation, customised solutions are also needed. This is partly due to the heterogeneity of the ferry routes. In Norway, there are more than 90 high-speed routes with passenger numbers ranging from 12 to 296 (Ianssen et al., 2017). In addition, the individual ferry operators have their own specific requirements for their fleet, such as a uniform equipment of the bridge with comparable support systems. In addition, the ferry must be customised to the exact route in order to keep operating costs as low as possible (Boulougouris et al., 2021).
In conclusion, a mix of standardisation and customisation is needed to achieve the climate goals quickly and cost-effectively. Modularisation combines the two approaches, which is why different modularisation approaches are presented in the following chapter.

3 STATE OF THE ART

The concept of modularisation can be traced back to Herbert Simon. In the 1960s, he published the system-theoretical principle of the "Architecture of Complexity", which states that all complex systems are almost completely divisible (Simon, 1962). It is precisely this principle that is applied in modularisation. The complexity of systems should be reduced by dividing them into smaller, independent, and less complex structures - the so-called modules (Eitelwein et al., 2012). In this paper, the focus will be on product modularisation and the effects of modularisation on the production of products.
The product structure describes a product by showing the physical and hierarchical relationships between the components and their relationships (Krause and Gebhardt, 2018). The product structure is part of the product architecture.
Modular product structuring is characterized by the fact that it combines the components of the product into modules. These modules are decoupled from the rest of the product. In addition to the structuring of the product, the modular product structure is also closely linked to the variety of the product range, the processes, and resources in all phases of the product life cycle and the subsequent user application. As product structuring is of strategic importance for companies, it is called a product structure strategy (Krause and Gebhardt, 2018).

3.1 RFLP-approach

A well-known and established approach to describing architectural views is the RFLP concept, with R standing for Requirements View, F for Functional View, L for Logical View and P for Physical View. With the RFLP approach, the link between modelling languages and techniques, which in most cases are considered in isolation from each other, is created. The RFLP approach is presented in the following because it provides a basic understanding of the product architecture development process and can be adapted to modular product architecture development. It is based on five principles (Kleiner and Kramer, 2012; Nawzad, 2021):

1. Continuous model-based development
2. Consideration of different levels of abstraction
3. Separation between problem and solution
4. Separation between physical and logical structure
5. Use of overarching quality requirements

In the context of product development, the RFLP approach includes the description of the different system engineering perspectives: Requirements, Functions, the Logical Structure and the Physical Structure. These different perspectives are referred to as viewpoints in the following. Figure 1 shows the viewpoints and their different levels of abstraction. For each individual combination of viewpoint and level of abstraction, there are predefined diagram types and modelling guidelines. The progress of a development project can then be read off the X-axis of the figure - in the direction of the physical viewpoint (Nawzad, 2021).
The requirements viewpoint contains the requirements definition and the requirements engineering including parts of the requirements management. First, all requirements of all stakeholders are collected and bundled into a requirements specification. A separation of functional, logical or technical realisation options is absolutely necessary here. The requirements viewpoint thus describes what the system must achieve and represents the starting point for all other viewpoints (Nawzad, 2021).

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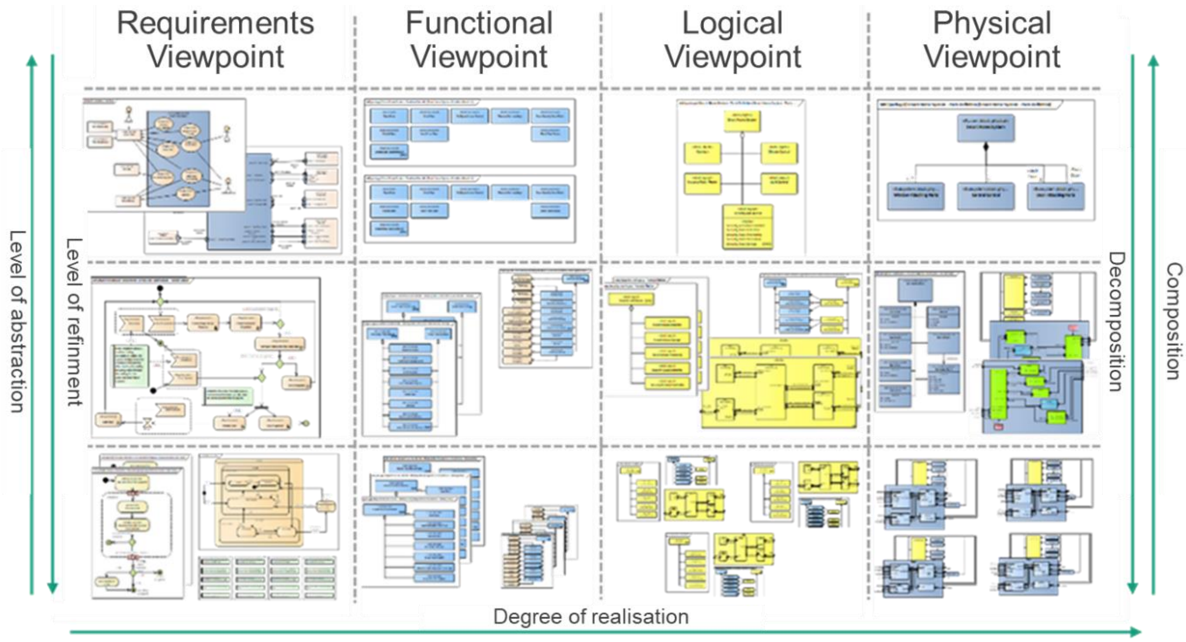

Figure 1. Viewpoints of the RFLP approach according to (Nawzad, 2021).

Within the functional viewpoint, the functional requirements/use cases are supplemented by details of the functional realisation. In addition, depending on the level of abstraction to be considered, a consolidation of functional requirements is carried out. In accordance with the principles of the RFLP approach, it must be ensured that the focus is solely on the description of the function and not on logical structures or physical function carriers (Nawzad, 2021).

The logical viewpoint decouples the technical requirements for the physical elements from the requirements placed on the logical system, in which the logical architectural elements of the system are represented separately. This reduces development efforts with high technical variance, as physical elements can be changed without affecting logical elements. The logical viewpoint therefore provides information about the effective concepts, whereas the subsequent physical viewpoint provides information about the actual technology used (Nawzad, 2021).

In the physical viewpoint, the technical realisation of the system is considered over different levels of abstraction. This viewpoint describes the physical architecture elements and their interrelationships and interfaces. Information that is necessary for the production of the system, such as surface requirements, size or weight, is defined within the physical viewpoint. The physical viewpoint then represents the starting point for all further development disciplines (Nawzad, 2021).

3.2 Modular product development according to Göpfert

The modularisation method according to Göpfert focuses less on the formation and combination of modules than on a common design of technical components and organisational units. The goal of the method is therefore to develop the product architecture together with the product development organisation. The reason for this approach is that each technical interface between two components that are responsible for different organisational units leads to an organisational coordination effort. To be able to carry out the development process as efficiently as possible, product architecture and project organisation must be coordinated with each other (Göpfert, 1998).

The core idea of the procedure according to Göpfert is the transparent presentation of the technical as well as organisational structures for the development of a product. The basis for this is the diamond-shaped representation of the functional structure and the building structure (product structure). With the help of this representation, both the technical design and the organisational design can now be represented together. As shown in Figure 2, the organisational units are assigned to the diamond-shaped representation according to their tasks.

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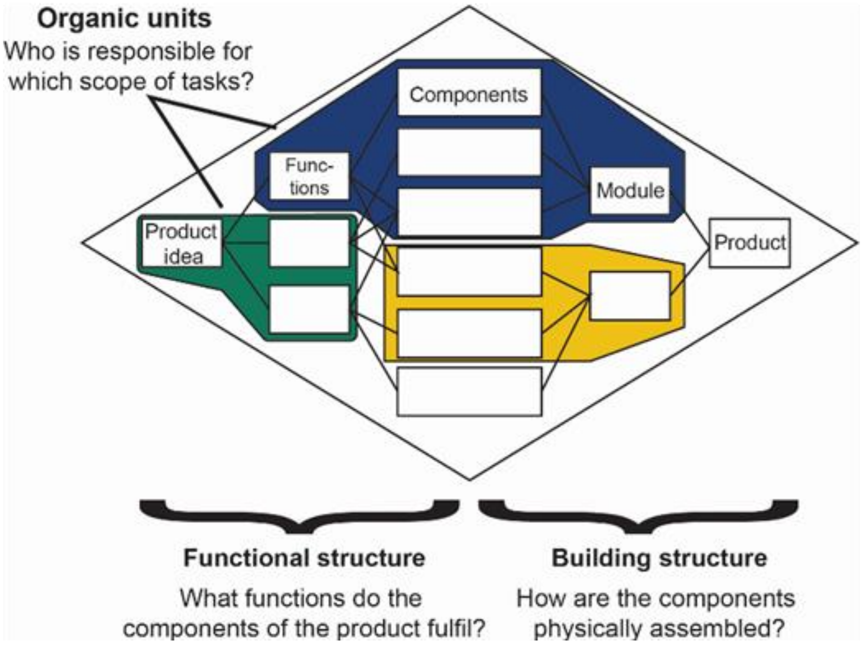

Figure 2. Outline of the modular product development (Göpfert, 1998).

3.3 Integration analysis methodology according to Pimmler/Eppinger

The Integration Analysis Methodology according to Pimmler/Eppinger (Pimmler and Eppinger, 1994) is divided into a three-stage procedure:

In the **first step** functional elements are used for decomposition, especially for new developments since the physical elements have usually not yet been identified. The decomposition is followed by the identification and documentation of the interactions between the elements determined from the decomposition. The elements are compared in a Design Structure Matrix (DSM) and evaluated at their interfaces. In the **next step** the elements are clustered using algorithms. Clustering can either be based on the interactions alone, or it can consider other architectural and resource-related criteria such as business strategies, expected technological changes, manufacturability as well as team ability, core competencies, etc. In this work, clustering is only carried out based on the interaction evaluations, since it can significantly influence the coordination complexity of the design process, which results from this analysis. **Finally**, the clustering algorithms must rearrange the rows and columns in the matrix so that the positively evaluated interactions are clustered closer to the diagonal. The result is a block structure in the third step, with the individual blocks representing possible modules. In general, computer-aided algorithms are used for this, such as a heuristic exchange algorithm.

4 DEVELOPED METHOD

The suggested procedure consists of three phases with several steps each. It follows the general principle of developing different aspects of the architecture based on the viewpoints of the RFLP (Requirements, Functional, Logical, Physical) framework in a specific order. We interpret these viewpoints with respect to our context and the target to not develop one product but a modular architecture. The understanding of each viewpoint will be described in the following chapters.

During the development it became obvious that a complete modular construction kit can hardly be achieved for a battery powered fast ferry based on physical limitations and multiple interdependencies of systems. However, this was not unexpected as the ideal modular construction kit is hardly achieved for complex mechatronic products. Similar to other industries like aviation and car manufacturing the goal is therefore to define as many standard modules as possible but to allow the implementation of more individual solutions where needed. Where a standard module is not possible at least a universal interface needs to be defined which covers all applications to allow parallel development based on design and construction rules. The combination of defined interfaces, design rules and standard modules is referred to as a platform approach where the platform is acting as connecting element to provide standardised interfaces for standard and individual modules. Parts of the platform can already

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be developed to a level of maturity corresponding to physical parts while others are staying purely conceptual based on design rules for interfaces.
The first phase of the suggested method helps gathering the needed top-level requirements not on a single product but the complete product class by considering multiple sources of information (Seidenberg et al., 2023). In the second phase the platform gets designed which includes all shared elements of the system and is meant to standardise as much as possible. In the third phase systems get designed inside of the platform elements to allow for individual solutions in some parts of the overall ferry. Each of the three phases consists of several steps. An overview of the method is given in figure 3.

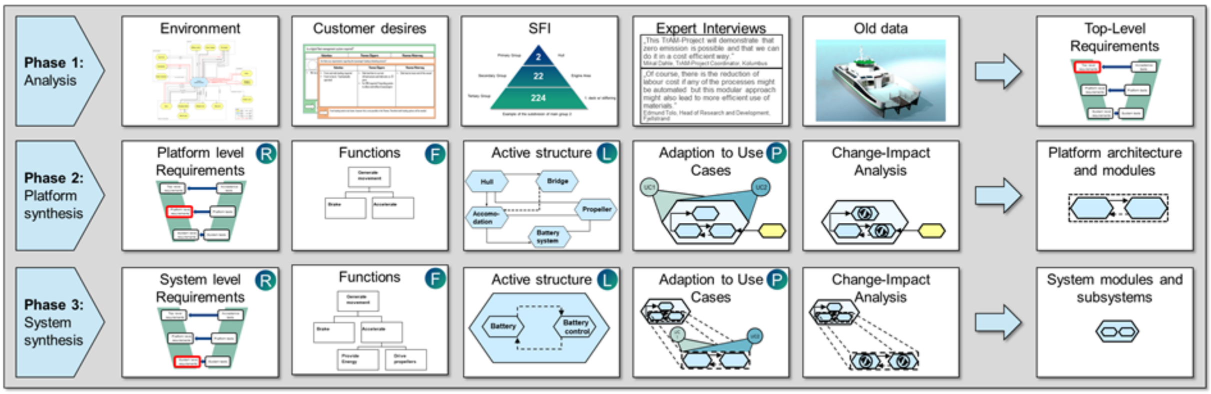

Figure 3. Modularisation method

4.1 Phase 1 - analysis

The first phase is made up of six steps. First, the problem is refined and expanded with the help of a stakeholder analysis, use case descriptions and an environment model. In the further steps, requirements of four stakeholder groups (regulator, buyer, staff, customers) are examined in more detail. These four steps can be carried out in parallel. Finally, in the sixth step, all the elicited requirements are combined into a requirements specification.
Step 1 - Problem refinement and extension: The aim of this step is to analyse the problem and create a common understanding among all people involved in the project. For this purpose, an outline of the overall problem is created with the help of use case descriptions. A stakeholder analysis and the creation of an environment model according to CONSENS are also carried out. CONSENS is a multidisciplinary specification technique that provides a modelling language and a method for the creation of the system model in the concept phase.
Step 2 to 5 - Requirement elicitation: In the steps two to five, the requirements of the individual stakeholders are recorded. Each of these steps considers one of the following requirement views: Regulative conditions (laws, etc.), buyers, staff and customers. Each of the four steps is divided into three sub-steps. In the first sub-step, the knowledge of the stakeholders under consideration is determined using appropriate investigation techniques. In the second sub-step, requirements are derived and documented from the identified knowledge at the level of the use cases. Finally, in the third sub-step, the requirements are combined into a requirements specification and consolidated with the help of the coordination rules of the International Requirements Engineering Board (IREB) (Glinz, 2017). The IREB rules have the advantage of specifically identifying different categories of requirements and suggesting when group and individual techniques should be used.
Step 6 - Creation of the requirements specification: In the third phase of the method, the four requirement specifications are merged into one requirements specification. Industry specifications techniques are then used to structure the requirements specification and identify gaps. Requirements from existing developments are then used to supplement and resolve the gaps. Subsequently, the requirements are analysed for contradictions and corrected by the respective persons involved with the help of the coordination rules of the IREB. Finally, the requirements are reviewed together with the developers and clients.

4.2 Phase 2 - platform synthesis

In this phase, the architecture of the platform is defined. The general idea is to follow the RFLP procedure, starting with requirements and define which functions are needed to satisfy these

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requirements. Then logical elements are collected to fulfil the corresponding functions. Each logical element then is converted to a physical element which is use-case related. The changes made for each use-case are analysed and consolidated in the platform architecture.

Step 1 - Requirements at platform level: The first step is the systematic identification of platform level requirements based on the top level requirements of phase one. They are the link between top level requirements and the system level. The challenge is to be precise and include all relevant information for all use-cases that need to be covered by the platform while being as solution-neutral as possible. All requirements need to be updated based on the findings of the platform and system structure to have consistent architecture at the end. As all requirements from all use-cases need to be included, potential conflicts are possible that are solved with the modular architecture.

Step 2 - Platform-level functions: In the second step, functions are derived from the previously identified requirements. This involves the development of a hierarchy of functions representing a higher-level function (e.g. transporting passengers) and main functions (e.g. providing energy). The number of levels that need to be defined and fulfilled by the platform can vary and depends on the complexity and diversity of the product. As a general orientation there are as many levels and details needed in this step as are required to describe all functions which are identical for all use-cases. However, the fulfilment of the functions or the working principle can be different and is not part of the comparison.

Step 3 - Active structure on platform level: In the third step, a platform-level active structure is created that represents the inner workings of the system and the interfaces of the individual platform elements that must fulfil the main functions (e.g. supply model - provide energy). Therefore, each platform element is fulfilling at least one function, however the aim is to prevent several elements being necessary for one function to generate independent modules. The active structure is the logical viewpoint in the RFLP framework. Between the platform elements there are connections representing energy, material, information flows and interfering influences. It is important to consider the environmental model and the relationships to the active structure, as all relations and influences of the environment need to be considered on platform level.

This step and the next two are worked on iterative until the final structure on platform level is designed.

Step 4 - Adaptation to use cases at platform level: In the fourth step, the logical elements are adapted to the physical system of the use cases. On the platform level this still might be based on e.g. specific interfaces, main dimensions and weight and not on a detailed visual model. When designing the application-specific physical platform structure, care should be taken to ensure that all common components and working principles are placed in the platform and that all deviating elements are placed at the system level. The platform shall in the end be the unifying level that is the same for all use-cases. Based on how different the solutions look the physical structure of the platform will be more abstract or detailed.

Step 5 - Analysing the impact of changes at the platform level: In the fifth step the differences between the platform elements for the physical viewpoint are analysed. It is investigated, if these differences and commonalities indicate a different logical structure would be more appropriate for the goal to have the platform as detailed as possible with standard solutions while still covering all use-cases. Furthermore, as a result the platform elements are categorised on one of the following groups: standard, variable, optional and individual. Standard elements are always present in the exact same way. Variable elements are adaptable in a specific way, e.g. can be scaled by adding multiple sections. Optional elements are only used for some use-case and offer a range of finished designed elements to choose from. Individual elements are characterised if there is no ecological sensible solution to standardise the elements as changes are always necessary, e.g. if required by certain physical effect. However, for all elements, also the individual ones, the interfaces are described and regulated.

Step 6 - Consolidating the platform architecture: The sixth step is to consolidate the findings of all individual steps into the final architecture, described by all mentioned RFLP viewpoints. It is necessary to perform a consistency check to ensure no linkages between the viewpoints are conflicting and all requirements are covered. While previous steps can be done paper-based in workshops, the final documentation of the architecture with all details should take place in a sufficient software.

4.3 Phase 3 - system synthesis

In this phase, the system level is described with the help of further subordinate functions. The necessary sub-functions to fulfil the main functions are identified and the components that are expected within the modules are determined.

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Step 1 - System level requirements: In the first step, the requirements are adapted to the system level considering all use-cases. Similar to phase two conflicts are possible and will lead to alternative solutions later. However, the more contradictory the requirements are, the less beneficial can the effect of standardisation be.

Step 2 - System level functions: The second step is to define the individual sub-functions that must be performed at the system level to fulfil the main functions. This process is based on decomposing main functions and shall not add completely new aspects.

Step 3 - Active structure on system level: In the third step, the active structures for the individual modules are defined. These structures are based on the logical platform viewpoint by having a much more detailed structure inside of each platform element. Those components located in a platform element should have most connections to other elements inside of the same platform part. If there are connections to components located in other platform elements, these are not directly connected but through the platform elements to solve interdependencies. It is expected to find connections on platform level which are not included yet and need to be updated in the progress.

Step 4 - Adaptation to use cases at system level: Similar to the procedure on platform level, the logical elements are adapted to physical elements for each use-case. The level of concretisation is very advanced already and could even include specific systems with type and manufacturer. Therefore, this step needs a lot of time in the development process. It is however very usual work for designers and engineers and follows the standard domain specific procedures for generating drafts. This step provides the designer with the specific active structure of a ferry for one use-case and prepares for the later following final design process.

Step 5 - Analysis of the impact of changes on the system level: In the fifth step the differences between the system elements for the physical viewpoint are analysed like step five in the previous phase. It is investigated, if these differences and commonalities indicate a different logical structure would be more appropriate on system level as well as on platform level. The resulting system elements are also categorised in one of the following groups: standard, variable, optional and individual. Based on the results, adaptions in previous steps or even on the platform level might occur.

Step 6 - Consolidation on system level: Finally, the architecture is documented by generating consistent viewpoints on all levels of abstraction.

5 APPLICATION OF THE METHOD

The modularisation method was applied in the TrAM (**Tr**ansport: **A**dvanced and **M**odular) project. The TrAM project consortium developed a modular battery electric fast ferry that allows the vessel to be quickly adapted to different use cases in order to meet the growing demand for zero-emission transport.

5.1 Phase 1 - analysis

In the **first step** an environment model was created, including environment elements such as a payment system, charging infrastructure, water and weather. Furthermore, the description of use-cases was done and a stakeholder analysis was carried out.

The **steps two to five** are repetitive, but with different groups that have been in focus for each step. Based on interviews, questionnaires and workshops the knowledge and opinion of each group was systematically gathered and consolidated, following the rules of the International Requirements Engineering Board.

In the **last step** ship-specific techniques like the SFI Code (The SFI Code is the world's most widely used classification system for the maritime and offshore industry) were used to structure the requirements and identify gaps. These were filled by considering experiences of past projects.

5.2 Phase 2 - platform synthesis

In the **first step** of this phase the top level requirements from the first phase were tailored for the platform level. Difficulties were observed with distinguishing between requirements and specifications and how to stay solution neutral.

The main function was identified in the **second step** as “transport passengers”. The subfunctions on the second function-level are "accommodate passengers", "hull floating", "ship manoeuvring", "vessel operating" and "provide energy". Although not uniform to each other this was the best compromise that could be found in terms of clarity and meaningfulness.

In the **third step** the logical structure on platform level was generated. It consists of four elements where each is fulfilling one or two main functions: 1. Supply module – provide energy; 2. Hull – hull floating, ship manoeuvring, 3. Superstructure – accommodate passengers, 4. Bridge – vessel operating Based on how individual different ships are built even for similar use-cases this was the most level of standardisation that could be achieved.

As **fourth step** the adaption to individual use-cases took place based on the customer requirements and individual limitations like water depth or docking conditions. This leads to different shapes and systems as for example in London, the ships need a low air clearance because there are many bridges where in Stavanger the only bridge would allow for more than 10 meters of height.

In the **fifth step** it became obvious that individual hulls would be needed for each use-case. Not only in relation to the hydrodynamics and therefore the shape, but also with respect to propulsion concepts. Finally, the results have been consolidated in the **last step** to generate a consistent architecture. Several iterations were necessary to end up with the final definition of a standardised bridge, variable supply module, variable superstructure and individual hull. Definitions of interfaces between all elements have been made and a common understanding was established.

5.3 Phase 3 - system synthesis

A list of the detailed results would exceed the limits of this paper. Therefore, this paragraph will be briefly illustrated with a single example of the main function "accommodate passengers".

In the **first step** the requirements were checked and adapted accordingly to the system level, including specifications and solution specific aspects. In the **second step** the sub-functions were derived: "control passenger condition", "passenger communication", "provide secure travel area", "count passenger" and "provide comfort". In the **third step** the corresponding platform element "superstructure" was filled by systems as for example seats and the ticketing system. The connection between the superstructure and the supply module was defined because a power supply is required. In **step four** different regulations of e.g. the counting of passengers were considered by selecting individual systems. With **step number five** the similarities were analysed and changes to the architecture were made for refinement. In the **final step** the architecture was checked for consistency and the software-based model was completed.

6 DISCUSSION

In this paper, a modularisation method was presented that makes it possible to structure complex mechatronic systems to a platform architecture and therefore utilise the effects of standardisation.

The method consists of three phases. In the first phase, the requirements are elaborated. In the second step the unifying platform elements are generated. Finally, these platform elements are further refined into system elements. System elements are categorised in standard, variable, optional and individual. In addition to flexible adaptation to the use cases, this offers the possibility of considerably reducing the time to market because a large proportion of the components can be reused, thus eliminating costly development times. However, successful modularisation not only offers opportunities for development, but production also benefits, because individual products can be manufactured using standard components and therefore use economies of scale. In addition, it is possible to outsource certain components to specialised companies, reducing costs for production and development further.

The method was designed and applied to the specific problem of the TrAM project where a modular battery electric high-speed ferry was successfully developed and built. Therefore, the method works for the intended use-case as expected. With the developed structure the adaption of the built demonstrator is possible as investigated in validation use-cases.

Although the design of a modular, battery electric ship presented an excellent stress test for the method as physical effects and strong interdependencies were present, there is a need for further research in applying the method to other industrial sectors. In addition, industry-specific standards that are used for clustering in the first phase should be adopted to further lower the entry barriers for modularising products.

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REFERENCES

Blessing, L.T. and Chakrabarti, A. (2009), DRM, a Design Research Methodology, Springer London, London.

Boulougouris, E., Papanikolaou, A., Dahle, M., Tolo, E., Xing-Kaeding, Y., Jürgenhake, C., Seidenberg, T., Sachs, C., Brown, C. and Jenset, F. (2021), "Implementation of Zero Emission Fast Shortsea Shipping", in Day 2 Thu, October 28, 2021, 27.10.2021 - 29.10.2021, Providence, Rhode Island, USA, SNAME.

Dahle, M. (2020), "Ensuring efficiency and safety in electric vessels", available at: https://tramproject.eu/2020/08/06/recording-from-webinar-now-available/ (accessed 3 December 2020).

Disselkamp, J.-P., Seidenberg, T., Anacker, H. and Dumitrescu, R. (2022), "Design of an optimised value creation network for zero emission ferries", in 2022 IEEE 28th International Conference on Engineering, Technology and Innovation (ICE/ITMC) & 31st International Association For Management of Technology (IAMOT) Joint Conference, 19.06.2022 - 23.06.2022, Nancy, France, IEEE, pp. 1–9.

Eitelwein, O., Malz, S. and Weber, J. (2012), "Erfolg durch Modularisierung", ZfCM (Controlling & Management), Vol. 56 No. S2, pp. 79–84.

European Commission (2018), "A clean planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy", available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0773 (accessed 3 December 2020).

European Parliament (2019), "CO2 emissions from cars: facts and figures - Society", available at: https://www.europarl.europa.eu/news/en/headlines/society/20190313STO31218/co2-emissions-from-cars-facts-and-figures-infographics (accessed 12 February 2021).

Glinz, M. (2017), "A Glossary of Requirements Engineering Terminology. International Requirements Engineering Board, version 1.7", available at: http://www.compliance-technologies.com/DS/ireb_cpre_glossary_17.pdf (accessed 30 November 2022).

Göpfert, J. (1998), Modulare Produktentwicklung: Zur gemeinsamen Gestaltung von Technik und Organisation, Zugl.: München, Univ., Diss., 1998, Gabler-Edition Wissenschaft Markt- und Unternehmensentwicklung, Dt. Univ.-Verl; Gabler, Wiesbaden.

Greater London Authority (2022), "Green Transport", available at: https://www.london.gov.uk/what-we-do/transport/green-transport (accessed 17 October 2022).

Ianssen, C., Ianssen, E. and Sandblost, T. (2017), "Battery/fuel cell fast ferry", available at: https://www.nho.no/siteassets/nox-fondet/rapporter/2018/nox-report---rev-8.doc-002.pdf (accessed 11 March 2021).

Kleiner, S. and Kramer, C. (2012), "Entwerfen und Entwickeln mit Systems Engineering auf Basis des RFLP-Ansatzes in V6", in Stelzer, R., Grote, K.-H., Brökel, K., Rieg, F. and Feldhusen, J. (Eds.), Entwerfen, entwickeln, erleben: Methoden und Werkzeuge in der Produktentwicklung, TUDpress, Dresden, pp. 459–474.

Krause, D. and Gebhardt, N. (2018), Methodische Entwicklung Modularer Produktfamilien: Hohe Produktvielfalt Beherrschbar Entwickeln, Springer Vieweg, Berlin, Heidelberg.

Nawzad, D. (2021), "Architektur im SE: Anforderungs- und Architekturmodelle strukturiert aufbauen", available at: https://blog.sophist.de/2021/11/22/architektur-im-se-anforderungs-und-architekturmodelle-strukturiert-aufbauen/ (accessed 30 November 2022).

Pakkanen, J., Juuti, T. and Lehtonen, T. (2016), "Brownfield Process: A method for modular product family development aiming for product configuration", Design Studies, Vol. 45, pp. 210–241.

Pfeifer, S., Seidenberg, T., Jürgenhake, C., Anacker, H. and Dumitrescu, R. (2020), "Towards a modular product architecture for electric ferries using Model-Based Systems Engineering", Procedia Manufacturing, Vol. 52, pp. 228–233.

Pimmler, T.U. and Eppinger, S.D. (1994), "Integration analysis of product decom-positions".

Seidenberg, T., Disselkamp, J.-P., Schräder, E. and Anacker, H. (2022), "Towards an Optimised Value Creation Network for Modular Investment Goods", Proceedings of the Design Society, Vol. 2, pp. 2513–2522.

Seidenberg, T., Disselkamp, J.-P., Jürgenhake, C., Grobbel, D., Dumitrescu, R. and Papanikolaou, A. (2023), "Development of a modular architecture for complex mechatronic systems", Proceedings of 33rd CIRP Design Conference, in Press.

Shukla, P.R., Skea, J., Reisinger, A., Slade, R., Fradera, R., Pathak, M., Khourdajie, A.A., Belkacemi, M., van Diemen, R., Hasija, A., Lisboa, G., Luz, S., Malley, J., McCollum, D., Some, S. and Vyas, P. (2022), "Climate Change 2022 - Mitigation of Climate Change. Summary for Policymakers", available at: https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_SummaryForPolicymakers.pdf (accessed 17 October 2022).

Simon, H.A. (1962), "The Architecture of Complexity", Proceedings of the American Philosophical Society, Vol. 106 No. 6, pp. 467–482.

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