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CONCEPTUAL DESIGN FOR MODULAR TOP-MODULE PLATFORM

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TIIVISTELMÄ

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Modulaarisen jäähdytysyksikköalustan konseptisuunnittelu

Diplomityö

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80 sivua, 37 kuvaa, 13 taulukkoa ja 2 liitettä

Tarkastajat: Professori Aki Mikkola
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Hakusanat: tahtigeneraattori, jäähdytys, modulaarinen tuotearkkitehtuuri, hitsauksen korvaaminen

Diplomityön tavoitteena oli suunnitella konsepti modulaarisesta jäähdytysyksikköalustasta suurille tahtigeneraattoreille. Konseptin tarkoitus oli selvittää keinot kokonaiskustannusten alentamiseksi modulaarisen tuotearkkitehtuurin ja hitsauksen korvaavien liitostapojen avulla. Tuotekehitysprosessissa sovellettiin valmistus- ja kokoonpanoystävällisen tuotesuunnittelun huomioivia menetelmiä.

Kirjallisuuskatsaus perehtyy modulaariseen tuotearkkitehtuuriin sekä valmistus- ja kokoonpanoystävälliseen tuotesuunnitteluun. Katsaus johdattaa työn aihealueeseen esittelemällä hitsauksen korvaavat liitosmenetelmät sekä suurten sähkökoneiden jäähdytystavat. Konseptisuunnittelussa kehitettiin kolme konseptia, joista yksi arvioitiin potentiaaliseksi jatkokehitystä varten. Tulokset analysoitiin ja konseptille laadittiin suuntaa antava kustannusarvio. Yhteenvedossa kerrotaan, miten työlle asetetut tavoitteet täyttyivät.

ABSTRACT

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LUT School of Energy Systems
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Conceptual design for modular top-module platform

Master's thesis

2021

80 pages, 37 figures, 13 tables and 2 appendices

Examiners: Professor Aki Mikkola
D. Sc. (Tech.) Kimmo Kerkkänen

Keywords: synchronous generator, cooling, modular product architecture, replacing welding

The purpose of this master's thesis was to develop a modular top-module platform concept for large synchronous generators. The aim of the concept was to find ways to reduce total costs by applying modular product architecture and replacing welding with alternative jointing methods. The product development process considered methods of design for manufacturing and assembly.

The literature review focuses on modular product architecture and design for manufacturing and assembly. The subject area is introduced by defining the alternative jointing methods and cooling technologies for large synchronous electrical machines. Three concepts were developed, and one of them proved to be beneficial for further development. The results were analyzed, and an indicative cost estimate was prepared for the concept. The conclusions describe how the objectives were met.

ACKNOWLEDGEMENTS

This topic of the master's thesis was provided by ABB's product development unit. I thank Janne Kamppuri for advising me in this work, as well as Ari Saarinen, Juha-Pekka Kivioja and others who helped me in this work from the company. I also thank Professor Aki Mikkola and Dr. Kimmo Kerkkänen from LUT University for supervising this work.

Ilkka Hantula
Lappeenranta, 5.6.2021

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LIST OF ABBREVIATIONS

BOM	bill of materials
CAD	computer aided design
D-end	drive-end, describes the side of the machine
DFA	design for assembly
DFM	design for manufacturing
DFMA	design for manufacturing and assembly
IC	international cooling code
IC0A1	designation for open air system with free air circulation
IC0A6	designation for open air system with forced air circulation
IC8A1W7	designation for air-to-water system with free air circulation
IC8A6W7	designation for air-to-water system with forced air circulation
IM	international mounting code
IP	international protection code
MFD	Modular Function Deployment
N-end	non-drive-end, describes the side of the machine
QFD	Quality Function Deployment

1 INTRODUCTION

Electrical machines are devices that converts energy from one form into another form. In this conversion, the electrical energy is usually converted into mechanical work or vice versa. Machines that convert mechanical work into electrical energy are called electrical generators. Usually the mechanical work appears as a rotational movement, which is converted into electricity in an electromechanical conversion. As a side-product, some of the energy is wasted into heat, which must be transferred out of the generator to avoid overheating. In large synchronous generators the heat is transferred to the top-module. Figure 1 illustrates a typical large generator with a top-module mounted on top of the generator frame.

Figure 1. Large synchronous generator with air-to-water top-module (ABB image bank, 2021).

Top-module is a multifunctional subassembly which is mounted on top of the generator frame. The purpose of the top-module is to cool down the heat from the generator. In addition, it protects the generator against atmospheric particles, such as dust and water drops entering inside the generator. The generator’s main connection and instrumentation may be mounted inside the top-module in some machine types.

1.1 Motivation and background of the study

Electrical machine's top-modules are well functioning and reliable entities. The structures and operating principles have remained almost similar for years, although a lot of development work has been done. The field has been studied from many different views and significant improvements have been made. It is obvious that the topic has been investigated thoroughly because the top-modules cover a considerable share of total costs in the electrical machines.

Because the subject area is wide and diverse, some of the possibilities are still unexplored. At the same time, technology is developing and bringing new opportunities. The company invests in this development work from several viewpoints. The results of this study are expected to benefit the company by providing a new modular top-module platform concept, which could be used as a base for further development.

Due to the multiple interfaces and high number of variabilities, top-modules are expensive to manufacture. That results in multiple different top-modules for each machine type and cooling types, which makes the whole manufacturing chain complicated. What comes to manufacturing itself, the process is time consuming because the parts are welded together. Welding is a time-consuming process and leads to additional work phases, such as post processing and surface treatment.

The large number of different top-module options for each machine type provides a possibility to rethink the concept, and to design a conceptual top-module platform which can be used as a basis for different modules. Then the same basis could be used for different cooling technologies just by changing individual modules. Technology industry has also proved cost effective improvements in a field of manufacturing technologies. According to the current trend, the popularity of welding is decreasing as other jointing methods are taking a larger share. Considering that, replacing welding with other jointing methods may provide possibilities to decrease the manufacturing costs of the top-module.

This master's thesis is made for the technology company ABB's purposes to increase the cost efficiency of their electrical machine cooling systems.

1.2 Objectives, research problem and questions

These circumstances raise the question whether these ideas could be utilized to increase the cost effectiveness of top-module manufacturing. It may be beneficial to ease the modularization and configuration by re-using the pre-defined modules and speed up the manufacturing process by replacing welding with other jointing methods. The problem is that there is a lack of knowledge about how these ideas should be implemented. The problem will be approached by finding answers to the following research questions:

1. How the modular platform concept would reduce total costs?
2. How the modular platform concept should be implemented?
3. How the alternative jointing methods should be utilized to replace welding?

The objectives of this study are to find out the main cost drivers of the modular top-module concept which can be exploited when reducing the total costs of the top-module. These findings are expected to be valuable in the concept design phase and therefore to form a baseline for the future implementation. In addition, one goal is to determine the ways how the manufacturing process could be improved to be suitable for alternative jointing methods, that are assumed to speed up the manufacturing process.

The success of the study could be measured by estimating how comprehensive results will be found. Valuable results are justified by numerical values, such as percentual cost savings or amount of reduced parts.

1.3 Content delimitations and research methods

The literature review part will be a brief but incisive summary of findings utilized in the design process. It covers the basics of product architecture and modularity, including a brief overview of DFMA (Design for Manufacturing and Assembly). In addition, the literature review explains the basic features and properties of the generator and introduces the previous research about replacing welding with alternative jointing methods.

The literature review is based on scientific publications, books, and company's documents about the subject. In addition, gaps in knowledge have been filled with tacit knowledge from experts and specialists.

This study is focused on ABB AMG 1600 synchronous generator including five frame length variations. The modular top-module platform concept will be designed to be applied in four different cooling technologies: air cooled, forced air cooled, liquid cooled and forced liquid cooled technology. The concept designed in this study will be a simplified version which can be used to explore the topic and make useful findings for further development. The concept is designed using CAD (Computer-Aided Design) software NX by Siemens.

2 DESIGN METHODS

This chapter is a literature review that deepens on product architecture and modularization. The review chapter continues to DFMA aspects, which are introduced briefly to outline the design product development process. In addition, alternative jointing methods to replace welding are introduced and at the end, basic principles of generator cooling technology are introduced. The most relevant findings that can be utilized in this study are explained in the literature review.

2.1 Product architecture and modularity

The continuous development of global markets makes competition between companies more and more demanding. That challenges companies to respond customer’s needs faster in this ever-changing environment and pushes them to innovate new techniques to succeed. As a result, the last century ticket for success by introducing a low-priced quality product every few years without considering the customer satisfaction has become unsuccessful, and in order to flourish, the business must focus to fulfill the customers’ changing demands rapidly, and surviving of companies is possible only by offering products with greater varieties combined with higher performance and greater overall appeal. (Kamrani & Salhieh, 2002); (Österholm & Tuokko, 2001, p. 6)

When companies started to increase their product assortment complexity in 1980s, the commonality between products reduced, which lead to loss in synergy and coordination among the product assortment. An example from automotive industry showed how the lack of a well-defined interfaces resulted in loss of the synergy between different products. When a car manufacturer wanted to offer an option of a CD player in car’s dashboard, it faced a problem as the CD player designer had not considered the other parts of the car. That led to an annoying situation, where the car manufacturer had to offer different dashboard assemblies between cars with and without the CD player. (Ericsson & Erixon, 1999, p. 4)

In the early 21st century, companies started to concept product platforms, with a main objective to shorten the development lead time and to increase the commonality between products. The aim was to reduce costs in development and production. Developing these product platforms turned out to be challenging, because products may lose their identity and profile, thus harming the building of brand image and decreasing sales volumes. (Ericsson & Erixon, 1999, p. 4)

The key for success is the ability to make products offering distinctive features compared to the competitors. To make this possible, companies must develop their methods and techniques to be capable of reacting rapidly to the changing requirements and to shorten the product development cycle. One significant improvement to product development process is to develop products in parallel from early stages of the product development. (Kamrani & Salhieh, 2002) (Österholm & Tuokko, 2001, p. 6)

2.1.1 Product architecture topology

The product architecture describes the arrangement of how the product is split to physical components. It includes the mapping from functional elements to physical components and the specification of the interfaces between physical components. Product architecture can be distinguished to modular and integral ones. (Ulrich, 1995, pp. 420-422); (Ulrich & Eppinger, 1995, pp. 132-133)

In modular architecture, the product is divided into physical components, each of which supports only a component specific function. Thus, the interaction between components is minimized. In integral architecture, a physical component may support multiple functions which results in higher interaction between physical components. The difference between modular and integral architecture can be demonstrated with an example, where two different trailer architectures were designed using two approaches, modular and integral architecture. **Figure 2** illustrates the trailer designed with a modular architecture approach, and **Figure 3** represents another design with an integral architecture approach. In both approaches, block diagrams describe the mapping between functional elements and physical components. (Ulrich, 1995, pp. 421-422)

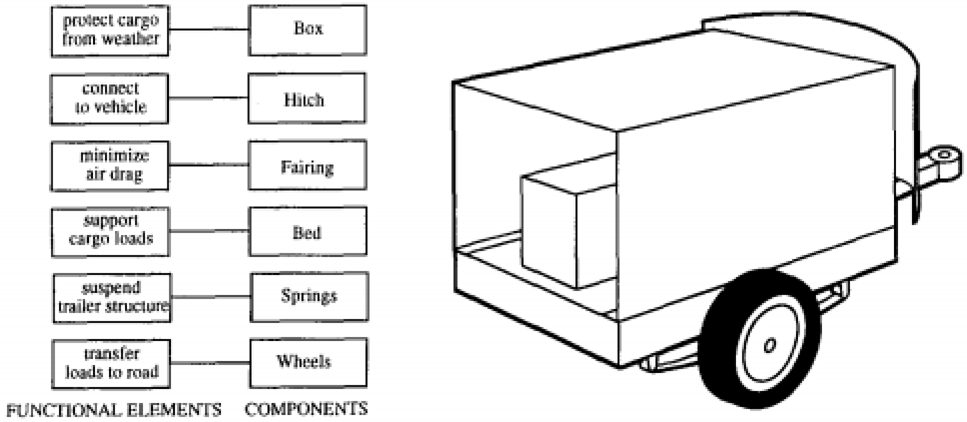

Figure 2. A modular trailer architecture demonstrates a one-to-one mapping (Ulrich, 1995, p. 421).

The modular architecture example presents a one-to-one mapping, where each function has own physical component. For example, function of the box is to protect cargo from weather and it thus fulfills only one function in the entire system. It shares interfaces with a bed and fairing, which has their own functions to perform. The specification of the interfaces includes the properties of the mounting, for example the dimensions between contact area, the positions and sizes of the fixtures, and the maximum force the interface should tolerate. (Ulrich, 1995, p. 422)

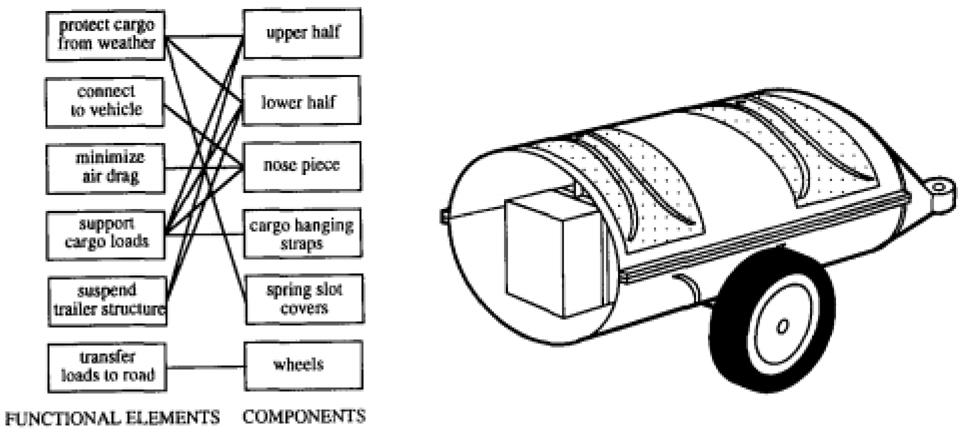

Figure 3. An integral trailer architecture demonstrates a complex mapping between functional elements and physical components (Ulrich, 1995, p. 422).

In the integral architecture, the mapping between functional elements and physical components is more complex. Each component may have multiple functional elements to fulfill, which is called function sharing. (Ulrich, 1995, pp. 422-423) The interaction between components are inaccurate and may be peripheral to the primary functions of the products.

Boundaries between components may be challenging to identify. Integral product architecture often focuses to achieve the highest possible performance at the expense of modification. Modifications in integral architecture component may affect many functional elements, and require changes to several related components. (Ulrich & Eppinger, 1995, p. 133)

Decisions about how to split the product into components and which kind of product architecture should be implemented are strongly associated to several important issues: product performance, product change, product variety, component standardization, manufacturability, and project management. (Ulrich & Eppinger, 1995, p. 133)

Product performance can be defined as how well a product fulfills its intended functions. Usually these performance characteristics are related to speed, efficiency, and accuracy. Typically, these characteristics depend on size, shape, or mass of a product. Generally integral architecture is a more likely approach to achieve higher performance; hence it provides better optimization by function sharing. In addition, integral architecture enables parts to be designed for a low cost production, and the component integration results in at reduced number of parts, which affects also to the manufacturability. (Ulrich & Eppinger, 1995, pp. 135-137)

On the other hand, modularity decreases the physical changes to the entire product in a case of a product change, which motive may be for example a technical upgrade or a change of a worn component. This ease of change provides benefits also in product variety, which refers to the choice of product models that a company can introduce in a particular extent of time in response to the changing market demand. Multiple variants from different component combinations can be generated easily. Modularity provide benefits also in component standardization, which refers to the use of the same component in multiple products. The standardization enables higher volumes in manufacturing, which lowers the costs and increases quality. (Ulrich & Eppinger, 1995, pp. 133-135)

Modular and integral architectures require different project management styles. Modular architecture demands very careful planning during the system-level design phase, unlike the integral architecture. In modular approach, the detail design phase is mainly concerning that the components are fulfilling the requirements in performance, cost, and schedule. Integral architecture requires more integration conflict resolution and coordination in the detail design phase. (Ulrich & Eppinger, 1995, pp. 137-138)

2.1.2 Modular system

A product family is a term to a group of related products, that are derived from a product platform to fulfill a variety of market niches. (Simpson, et al., 2007, p. 3) It describes a set of products that share common technologies. These technologies may be functions and components, or they may share interfaces at technological, functional, or physical level. (Windheim, 2020, p. 6)

Modular product families are often designed to enable many product variants to be created effectively, based on core technology that is called product platform. Developing product platforms instead of individual product variants provides an ability to offer more precise products for customers. Product platform is a term for modules that can be combined with variation modules to form a product variant. (Österholm & Tuokko, 2001, p. 12). According to Robertson and Ulrich (1998) Product platform can be defined as a "collection of assets that are shared by a set of products". Those assets can be divided into different elements, such as components, processes, knowledge, people and relationships. Coupling these assets together forms the product platform (Robertson & Ulrich, 1998, p. 20). **Figure 4** illustrates the relation between modular system, product platform and product family.

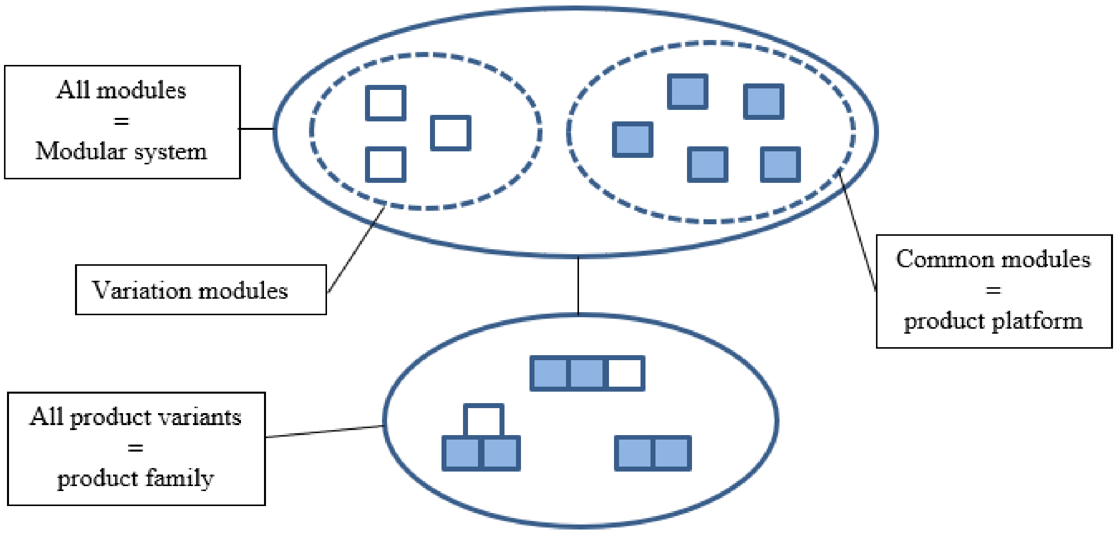

Figure 4. Modular system, product platform and product family (Mod. Österholm & Toukko, 2001, p. 12).

Platform-based product development has proved its benefits in multiple ways. It reduces development time and system complexity. In addition, platform-based product development reduces development and production costs and offers an improved ability to upgrade products. Furthermore, the approach enhances better learning across products and it may be beneficial by reducing testing and certification of complex products. (Simpson, 2004, p. 4)

2.1.3 Objectives in modularity

Modular design technique aims to divide the complex product into independent modules. These modules are units that support one or more functions. When these modules are coupled together, they form a product, which supports a larger function. (Kamrani & Salhieh, 2002, p. 45); (Ericsson & Erixon, 1999, p. 5)

The idea behind is that the parts that should vary to meet the customer needs are well pre-defined and separated from the parts which should form the basis for the product. This enables a situation where a company can increase the number of product variants but keep its internal complexity under control at the same time, and the company can retrieve control of the product and product-related activities. An example about successful modularization of the truck cab by a truck manufacturer Scania shown in **Figure 5**. (Ericsson & Erixon, 1999, p. 5)

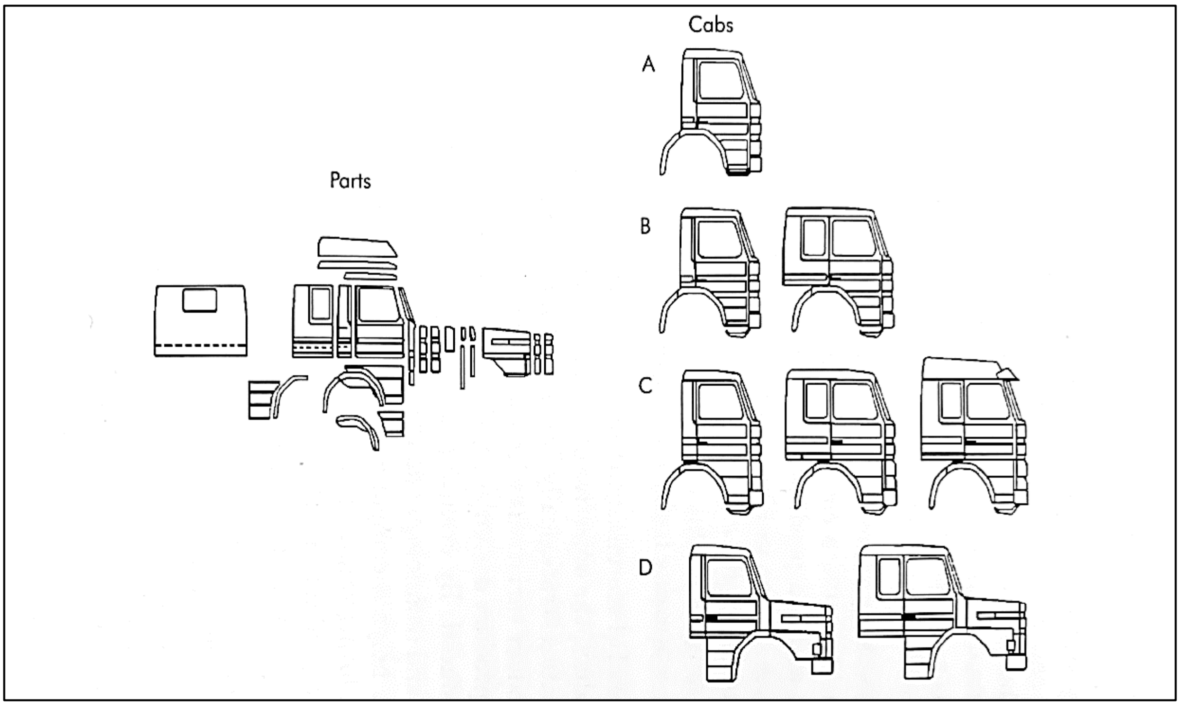

Figure 5. Modularization of a Scania truck cab (Ericsson & Erixon, 1999, p. 6).

The example presented in figure above shows how Scania handled their product assortment complexity. Complex product structures of different cab variations were dismantled into smaller units that are easier to handle. As a result, the ability to provide customers a wider range of products improved. In addition, the platform required fewer parts and manufacturing tools. Furthermore, the assembly time was shortened significantly. (Ericsson & Erixon, 1999, p. 5)

The objective of a modular platform is to design strategically flexible products, instead of trying to find the optimal design for an optimal product. Products should allow variation without requiring modifications to surrounding product design, so the whole product does not require changes every time when a new variant is created. A well planned modular product architecture will provide easier management of changes and also limits their impact. (Ericsson & Erixon, 1999, p. 5)

2.1.4 Modularity types and module categories

Generally, modularity can be applied in different areas. These modularity types are product design, design problems and production systems. (Kamrani & Salhieh, 2002, p. 45)

Product modularity is defined as products which are combinations of distinct modules that fulfill various overall functions. These overall functions can be divided into sub-functions that can be implemented by different modules of components. The product is formed around a basic core, which is a platform where different modules can be attached. The variety appears in the modules itself, so different versions of the product can be produced easily combining different module variations together. (Kamrani & Salhieh, 2002, pp. 45-46)

Modularity in design problems is a technique used to solve complex problems by decomposing the problem into a set of simpler sub-problems that are easier to manage. The overall problem should be divided into functionally independent sub-problems, minimizing the interaction between sub-problems. The purpose is to avoid situations where a small change in one sub-problem affects to other sub-problems. (Kamrani & Salhieh, 2002, p. 46)

In modular system, the modules can be divided into two major categories, function modules and production modules. Function modules can be identified as modules that perform various technical functions independently or combined with other function modules. Production modules can be identified as modules that are designed to meet production considerations and are independent of their function. Function modules can be classified by defining the various types of function that recur in modular system. Those can be combined as sub-functions to fulfill the different overall function. (Pahl, et al., 2007, p. 496) (Kamrani & Salhieh, 2002, p. 47). Function modules and module types illustrated in **Figure 6**.

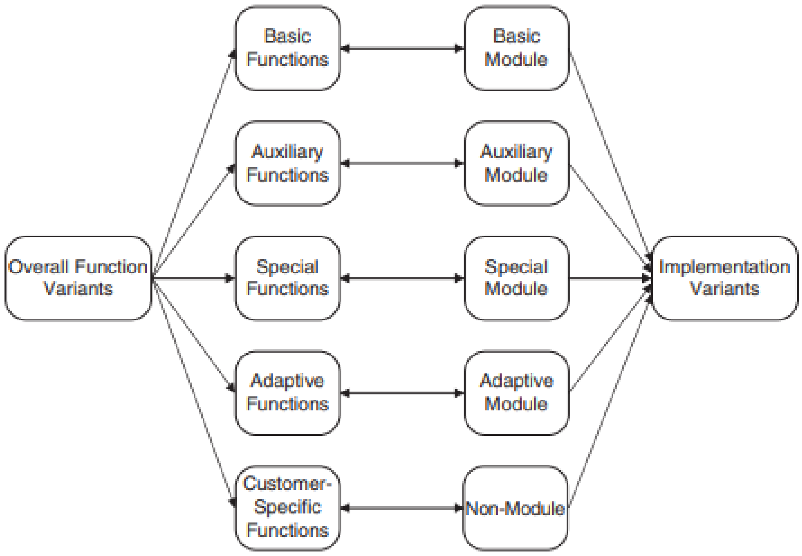

Figure 6. Function modules and module types (Kamrani & Salhieh, 2002, p. 47).

Basic functions can fulfill the overall function independently or in combination with other functions. They are fundamental to a system and they are not variable in principle. Basic modules are "essential modules". (Pahl, et al., 2007, p. 496)

Auxiliary or secondary functions are implemented by locating or joining auxiliary modules in harmony with basic modules. Auxiliary modules are usually "essential modules". (Pahl, et al., 2007, p. 496)

Special functions are complementary and task-specific sub-functions that may not appear in all overall function variants and are implemented by special modules that are used as add-ons to or accessories for the basic modules. Special modules are "possible modules". (Pahl, et al., 2007, p. 496)

Adaptive functions are implemented for adaptation to other products or systems. They are implemented by adaptive modules that allow for unpredictable circumstances. Adaptive modules are either "essential modules" or "possible modules". (Pahl, et al., 2007, p. 496)

Customer-specific functions are functions that are not provided by the modular system. They are implemented by non-modules which must be designed independently for specific purposes. If they are used, the result is “mixed system” that is a mixture of modules and non-modules. (Pahl, et al., 2007, p. 496)

2.1.5 Typologies of modularity

Product modularity can be divided into different categories. Literature shows several different classification criterion approaches. The criterion may be based on how the final product configuration is built or on the nature of the interface between components. (Salvador, et al., 2002). Kamrani & Salhieh (2002) represented the following classification.

Product modularity can be divided in four different categories, depending on the types of combinations between the modules. The focus in this approach is on the interactions between different modules. These four categories are component-swapping modularity, component-sharing modularity, fabricate-to-fit modularity, and bus modularity. (Kamrani & Salhieh, 2002, p. 48). In addition to these four types of combinations mentioned, sectional modularity is relevant to be introduced.

Component-swapping modularity is based on the same product family components (larger rectangular blocks in **Figure 7**), that are combined with two or more alternative types of components (small triangular and rectangular) to create different variants of the same product. (Kamrani & Salhieh, 2002, p. 48). The component-swapping modularity enables changes in the module’s function by interchanging two or more components of it. (Gershenson, et al., 2003, p. 302). A concrete example from computer industry is represented by matching various types of devices, such as monitors and keyboards to the same motherboard. (Kamrani & Salhieh, 2002, p. 49)

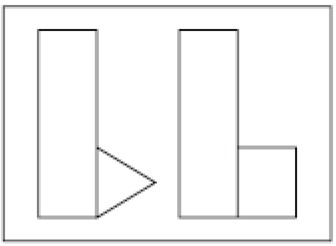

Figure 7. Component-swapping modularity (Kamrani & Nasr, 2010, p. 62).

The component-sharing modularity means that the module is created around the same core (larger blocks in **Figure 8**) using different basic components (small circles). (Gershenson, et al., 2003, p. 302). The component-sharing modularity is almost identical as the component-swapping modularity, except the roles are counter to each other. Swapping involves the same basic product using different components and sharing involves different basic products using the same component. An concrete example from computer industry is the use of the same microprocessor in different product families.(Kamrani & Salhieh, 2002, p. 49) An example from automotive industry. An auto manufacturer company could offer 100 car models that each would have a distinct steering wheel design, one design for each car model. A more reasonable approach may be to have a smaller amount of steering wheel designs that can be used on all car models. (Fisher, et al., 1999, p. 297)

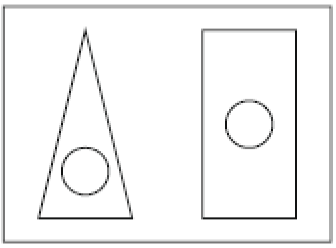

Figure 8. Component-sharing modularity (Kamrani & Nasr, 2010, p. 62).

Fabricate-to-fit modularity is based on the use of standard components (triangles in **Figure 9**) with one or more infinitely variable additional components (rectangular blocks), which physical dimensions can be modified. An example from industry is cable assemblies where standard connectors are combined with a cable with an arbitrary length. (Kamrani & Salhieh, 2002, p. 50)

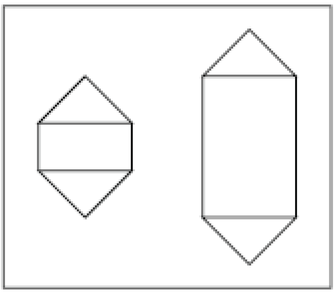

Figure 9. Fabricate-to-fit modularity (Kamrani & Nasr, 2010, p. 63).

Bus modularity means that module's interfaces can be matched with any number of basic components. (Gershenson, et al., 2003, p. 302). The number and location of basic components (small triangles and rectangular in **Figure 10**) can vary in a product (large rectangles). An example from computer industry is the different input and output units which can typically be used for number of devices. Different types of mice, hard drives and other devices can exist varying their port location and number. (Kamrani & Salhieh, 2002, p. 50)

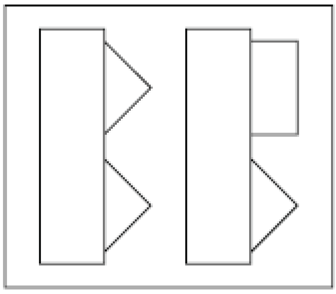

Figure 10. Bus modularity (Kamrani & Nasr, 2010, p. 63).

Sectional modularity aims to create products by mixing and matching a set of components in an arbitrary way. Elements are mounted to each other by their identical interfaces, so there is not a single element used to collect all the other components together. Sectional modularity is applied for example in sectional sofas. (Ulrich & Eppinger, 1995, p. 424); (Salvador, et al., 2002, p. 552). Sectional modularity illustrated in **Figure 11**.

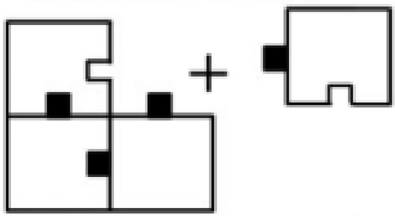

Figure 11. Sectional modularity (Choi & Erikstad, 2017, p. 3).

2.2 Modular function deployment

Modular Function Deployment™ (MFD™) is a method applied to find the optimal product design. It is a structured and company supportive method that considers the company's specific needs and is used to support the entire product development process from product idea to manufacturing drawings. The method can be applied for the entire product range and it can be implemented by a cross-functional project team. (Ericsson & Erixon, 1999, p. 29). The method includes five major steps, that are presented shortly in **Figure 12** and following sections.

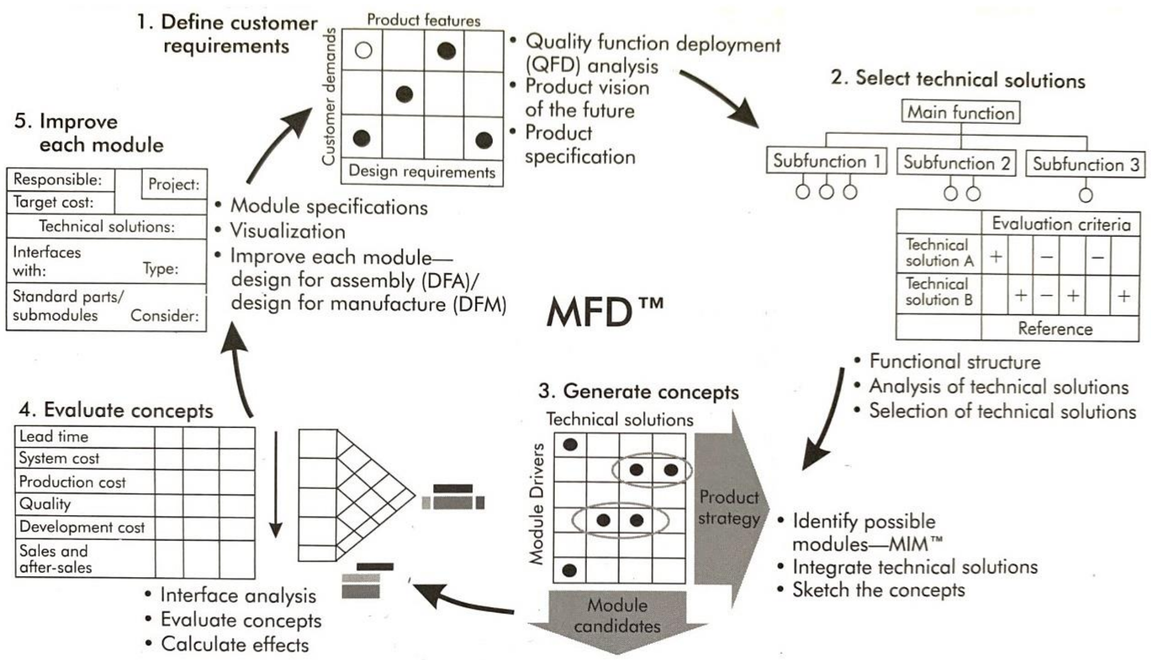

Figure 12. Steps of Modular Function Deployment (Ericsson & Erixon, 1999, p. 30).

The first step determines the right design requirements which are derived from the customer demands. The properties must fulfill the present and future market demands. Those are identified by analyzing competition and customer requirements. (Ericsson & Erixon, 1999, pp. 29-32)

The second step identifies the functions and their technical solutions that fulfills the demands. There may be various specific solutions to fulfill the requirements, but the most appropriate solutions are selected regarding customer needs and other company-relevant criteria. (Ericsson & Erixon, 1999, pp. 29-34)

The third step analyzes the technical solutions considering their potential for being modules. The concepts are generated regarding the aspects which covers the entire product life cycle, such as product development and design, variance, production, quality, purchase and after sales. (Ericsson & Erixon, 1999, pp. 34-38)

In the fourth step, the module concepts are generated and the relations between their interfaces are derived and evaluated. Furthermore, the expected effects of modularization are qualified. (Ericsson & Erixon, 1999, pp. 38-40)

The final step optimizes the modules. A specification is established for each module, including technical information, cost targets, planned development, description of variants, etc. Depending on the module's properties DFMA tools may be applied. (Ericsson & Erixon, 1999, pp. 40-41)

2.3 Design for Manufacturing and Assembly DFMA

Time and cost reduction are important drivers in product development. They are needed to meet the competitiveness in market. DFMA aims to reduce time and costs in manufacturing and assembly phases. (Selvaraj, et al., 2009)

The methodology is a combination of two systematic procedures: Design for Manufacture (DFM) and Design for Assembly (DFA) which are used in engineering and product development. DFM aims to maximize the use of manufacturing processes in the design of components while DFA aims to maximize the use of each component in the design of a product. This combination may be a beneficial tool for analyzing proposed product designs. (Edwards, 2002, p. 651)

Typically, the basic principle behind DFMA is part count reduction by integrating parts. It results in simplified product structure that is easier to manufacture. Furthermore, it simplifies the assembly phase by reducing the number of assembly steps. (Selvaraj, et al., 2009, pp. 13-15); (Bralla, 1998, p. 1019). According to Bralla (1998), the most significant benefits for manufacturability derive from design for assembly, because the largest single item of cost in entire product manufacturing may come from final assembly labor and overhead together. This typical principle of DFMA that aims to achieve more integral product architecture conflicts against platform-based product design, which aspires to more modular product architecture. Integral product architecture aims to reduce the amount of parts, while modular product architecture tries to increase the variety. On the other hand, modularity aims to increase commonality, which results in reduced overall part count within a product family (Simpson, 2004). In other words, DFM aims to save time in design by standardization and modular product architecture. The situation is challenging but not impossible, integrating these methodologies may be beneficial by optimizing manufacturing costs and product development time. (Emmatty & Sarmah, 2012, p. 697) (Simpson, 2004, p. 14).

DFMA enables parallel engineering for cost-effective product design. It helps to avoid issues in the downstream stages of product development process by considering manufacturing and assembly aspects during the design phase. (Emmatty & Sarmah, 2012, p. 699). DFMA procedure should be applied as early as possible in the design process to maximize the benefits form the procedure. (Boothroyd, et al., 2002, p. 34) (Edwards, 2002, p. 651).

There are various methods how the DFMA procedure may be performed. It may be based on the guidelines that are statements of good design practice used to help managing and reducing the large amount of information comprehended. These statements are empirically derived from designers' experience. Another commonly used method is introduced by Boothroyd and Dewhurst. That procedure-based method includes various analysis stages to examine the product designs. Typical steps taken in the procedure-based method are illustrated in **Figure 13**. (Edwards, 2002, pp. 651-652)

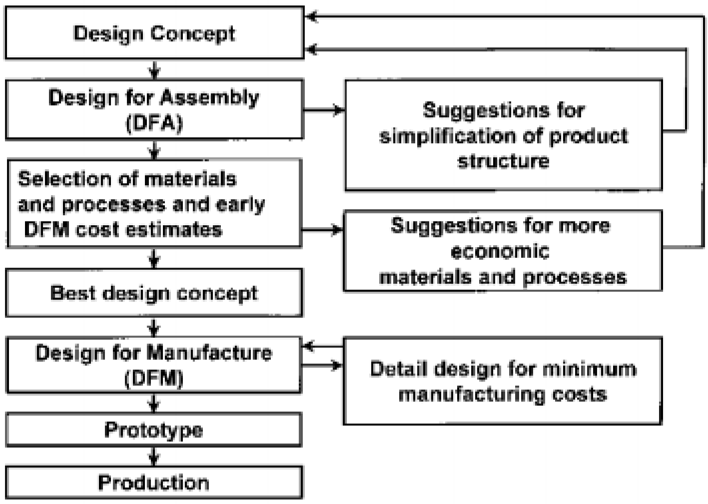

Figure 13. Typical steps in a DFMA procedure (Boothroyd, et al., 2002, p. 30).

The figure above summarizes the steps of the DFMA procedure. The procedure starts from DFA analysis, which leads to a simplification of the product structure. The next step is to formulate early cost estimates using DFM for the parts used in both designs: the original and the new, so the trade-off decisions can be made. During that, the suggestion for more economic materials and processes to be used are considered. When the selection has been made, a more comprehensive analysis for DFM can be performed for the detailed design. (Boothroyd, et al., 2002, p. 30)

Emmatty & Sarmah (2012) developed a modular product development framework that considers DFMA aspects. The method eases the development of platform-based product derivatives concerning DFMA aspects. It integrates customer requirements and modularity by considering the voice of customers in the product design. The method optimizes cost and time by refining the design alternatives. In addition, the method integrates the concept design and detail design without harming the functionality of the products. (Emmatty & Sarmah, 2012, p. 700). The integrated framework for modular product development is introduced in **Figure 14**, including its eight steps.

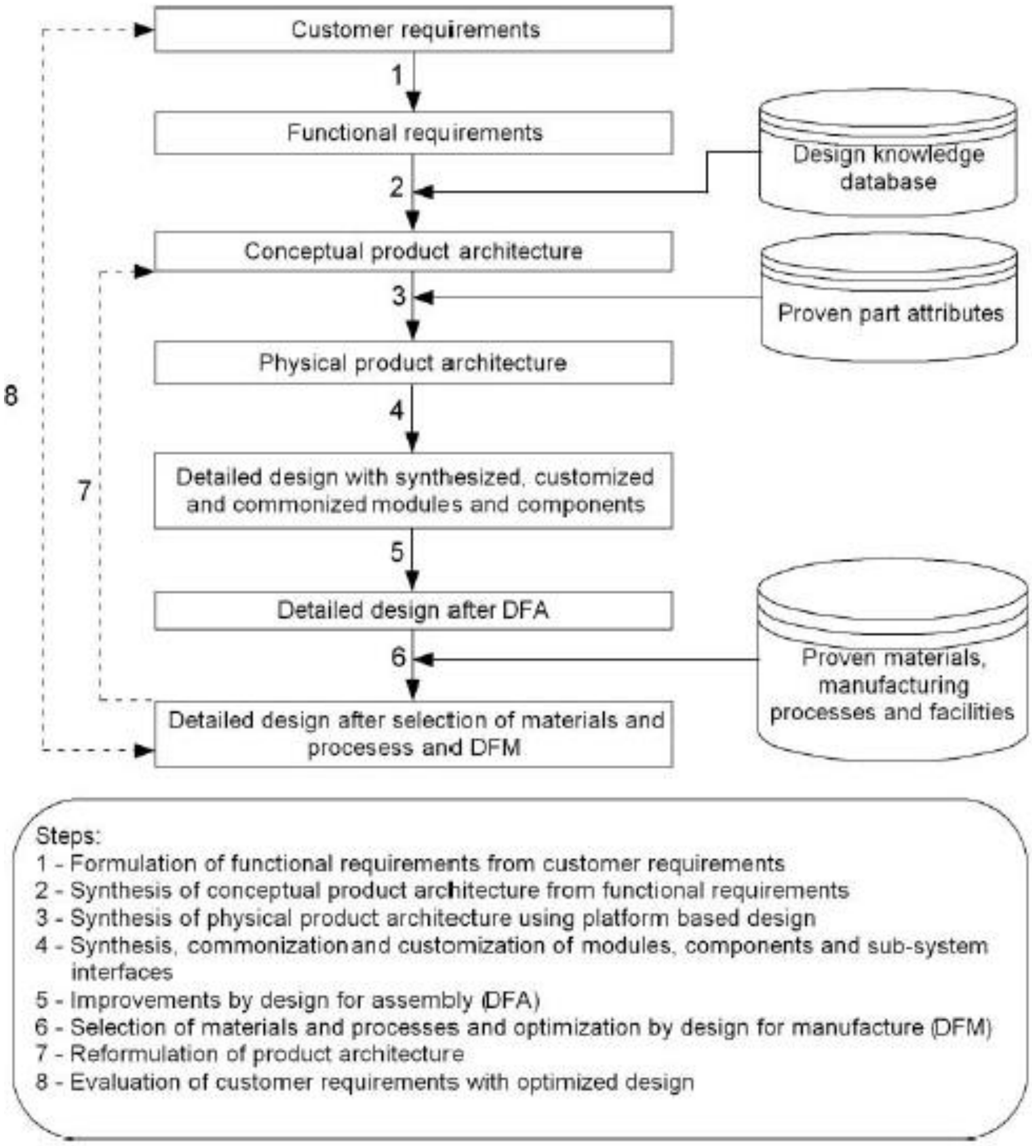

Figure 14. Integrated framework for modular product development (Emmatty & Sarmah, 2012, p. 701).

According to Emmatty & Sarmah (2012) the integrated framework is a functional approach of how the product is created by modular product architecture. The method captures and refines the thought process of the designer. In addition, the architecture eases the reuse of platform components and modules. The platform-based design methodology optimizes the use of common modules for different products, while the parts used in a specific product are optimized by applying DFA principles. DFM is applied to optimize the use of the manufacturing processes required in part manufacturing. DFMA should be used to optimize the costs of individual products, instead of a whole range of products. The optimization results in increased integrality of the product, which affects by diminishing the cost and time savings achieved from modularity and platform-based design. On the other hand, the methodology provides cost savings by increasing the commonality and modularity among products. The methodology has proved to be a trade-off between platform-based design and DFMA. (Emmatty & Sarmah, 2012, pp. 712-713)

2.4 Benefits of modularity

Modular product design and modularity has a significant effect on entire product life cycle. It may influence on the efficiency of the product design economically, ecologically, and socially, and therefore, be an important influencer for product design. Bonvoisin et al. (2016) made a systematic literature review about modular product design, where they summarized published literature from 163 publications. The study offers a structured compilation of drivers, design principles, and metrics for modularization. The results show the most cited and strongly interlinked aspects of product modularity, in both positive and negative influence. These aspects are presented below.

Modularity allows parallel development, which reduces the product development time and therefore, provides a shorter time-to-market and reduced development costs. In addition, decreasing the complexity between part interfaces provides faster design changes in product design by allowing the distribution of design tasks and reducing the required intensity of communication between teams. Modularity benefits also in product maintenance by allowing separated diagnoses of product components and isolation of wear parts. Therefore, modularity can be seen to improve the environmental friendliness of the product design. The properties of modular product architecture provide possibilities to upgrade, adapt, and modify the product and thus, extend the service life of a product and therefore reduce the environmental load of products. In addition, the modular product architecture facilitates the disassembly of a product at its end-of-life stage. Therefore, it eases the part sorting to their post-life treatment for repair, reuse, remanufacturing, recycling, or disposal for example, which also reduces the environmental load of the product. (Bonvoisin, et al., 2016, p. 505)

Modular product architecture may limit the product optimization by disabling the part integration. Modularity supports product variety, but on the other hand, it may lead to a structural similarity in product families. Similarly, it may influence negatively to the flexibility of the product family. In addition, the lack of product optimization on modular products may limit the product aesthetics. Also, the modular product architecture may ease the reverse engineering and therefore increase the competition per imitation. (Bonvoisin, et al., 2016, p. 505)

2.5 Costs

It is commonly known that product modularity reduces product costs and the literature shows a variety of reasons for supporting this relationship. Generally, one of these reasons is the increased economics of scale. Modular design requires fewer unique components or subassemblies, which is explained by reduced amount of unique part numbers narrowing production volume distribution. It increases production volumes per part, which shows up in accelerated productivity and lower product costs. The increased economics of scale benefits in inventory, which is a significant component of unit cost. Reduced inventory levels result in a reduction of transportation costs and consequently the total cost. (Jacobs, et al., 2007, pp. 1048-1049)

What comes to product development and lead time, modularization enables work in parallel, which decreases lead time in development. Different parts of the product can be developed simultaneously. According Ericsson & Erixon (1999) case studies, the change between a part-by-part built product and a modular product decreased lead time 30…60% with a median of 45%.

When thinking about product development and new product generations, one significant influencer on development costs is the number of carryover modules. These carryovers are parts or subsystems of a product that can be carried over to the next generation of the product, without any design changes. The share of carryover modules affects directly to the development costs. (Ericsson & Erixon, 1999, pp. 109-110)

A physical product requires material and labor, which takes significant share of production costs. According to Ericsson and Erixon (1999), the detailed product design of each module has a remarkable influence on the product cost. Thus, DFMA principles are recommended to be applied in the design of each module. Modularity requires extra interfaces, which might lead to expectation that direct material costs would increase. On the other hand, case studies have proved that companies have succeed to avoid that by applying proper risk control of increased material costs. According to Ericsson and Erixon (1999), the effect was measured and the results on the material costs were between an increase of 3% and a decrease of 10%, with a median of 6% decrease. (Ericsson & Erixon, 1999, p. 112)

The product costs include module-specific capital costs as well as other expenses due to e.g. the use for tools, fixtures, etc. These costs are affected by the number of articles and components, as well as by the complexity of the module assortment. The goal should be to minimize the complexity of the product assortment by reducing the amount of variation modules and interfaces without losing the ability to fulfill the customer requirements. (Ericsson & Erixon, 1999, p. 113)

System costs are the total costs from items that support the assembly system. These items arise from purchase, production planning, quality control, production engineering, logistics, etc. The share of system costs depends on the proportion of manufacturing the product modules by the company itself or out-sourcing them outside the company. The highest system costs will occur if all product modules are manufactured in-house. As well, the lowest system costs will occur if all product modules are purchased from vendors. The relation between the system costs and the share of purchased modules is inversely dependent. (Ericsson & Erixon, 1999, p. 116)

Modular product design provides also other cost savings, such as savings from shortened lead time in assembly due to the DFA consideration, faults avoided in the assembly system due to the improved quality by module testing on earlier stages of assembly, and the ease of service and upgrading operations due to easier interchangeability of modules. (Ericsson & Erixon, 1999, pp. 118-128)

2.6 Jointing methods

The current top-module design is manufactured by welding bended sheet metal components together. Welded structure is strong, but the process is time consuming, which increases the manufacturing costs. Avoiding this time-consuming welding process might accelerate the manufacturing process and thus, reduce the manufacturing costs of the top-module. The modular product platform concept provides an opportunity to replace welding with other jointing methods, that are less time consuming, and perhaps, may offer other advantages for the whole product cycle.

Previous research has been made around the subject. Hantula (2019) introduced a study on replacing weld joints with other jointing methods in top-module manufacturing. Purpose of the study was to reduce the total costs, weight, and production time by developing a new top-module concept that avoids welding by applying the perspectives of DFMA and modular product architecture. Different alternatives for welding were compared considering the use and circumstances, and the findings were applied in the new concept design. The strategy was to reduce the overall number of joints by integration and the structure was designed to support these alternative jointing methods.

The alternative jointing methods were imported from two main categories: mechanical and chemical jointing methods. Their combination, hybrid jointing, was also considered. The group of mechanical jointing methods included screw joints, rivet joints and clinch joints. Chemical jointing methods included gluing with various types of adhesives. (Hantula, 2019)

The comparison between jointing methods were performed by analyzing their suitability for different arrangements. The requirements and circumstances of the attachment should be pre-defined to ensure reliable results. Therefore, the comparison was performed for various situations. Joints of the top-module were divided into different groups, based on their similarity. (Hantula, 2019, p. 42). *Table 1* combines the tables used in the comparison of jointing methods applied for each group. The jointing methods were applied in top-module structure presented in **Figure 15**.

Table 1. Comparison of jointing methods.

Criterion	Screw joint	Rivet joint	Clinch joint	Gluing
Overall strength	good	good	good	needs further research
Long-term sustainability	good	good	good	needs further research
Overall difficulty	easy	easy	easy	challenging
Duration of implementation	fast	fast	fast	relatively slow
Part positioning	easy	easy	challenging	challenging
Space requirements	access to both sides	one-sided	access to both sides	-
Fastener head size	major	minor	minor	-
Suitability for multiple sheets	good	good	requires special equipment	good
Water resistance	needs sealant	needs sealant	needs sealant	good

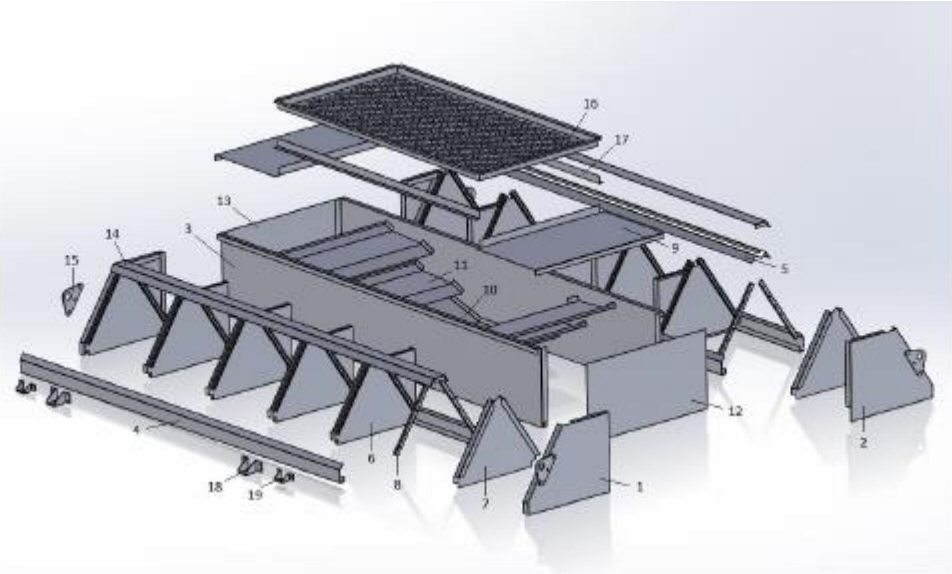

Figure 15. Exploded view of top-module concept developed in previous study (Hantula, 2019, p. 43).

The first group included large and simple sheet metal components (part numbers 1…7,9…14 and 17 in **Figure 15**). The commonality between them was large contact surfaces with relatively low forces affecting to them. All mechanical jointing methods turned out to be suitable for this group due to their durability and fast implementation. The rivet joint was chosen to be the best solution, because it does not require access to both sides of the joint. (Hantula, 2019, pp. 44-46)

The second group included the air filter holders (part number 8), the secondary function of whose were to reinforce the structure. A specialty that set this apart from other groups was the arrangement, where three layers of sheet were jointed together, so the overall thickness of joint excluded the option for clinch joint. Also, the space for fastener heads was limited in both, axial and radial dimensions, which made the situation more challenging. (Hantula, 2019, pp. 46-49)

The third group included small parts, such as lifting lugs (15) and various types of brackets (numbers 18 and 19), which were affected by extremely high loads. The group required more strength properties than other groups, so welding was chosen to be suitable jointing method, because of its high strength properties. Parts of this group were small sized, and the number of parts were small, so the disadvantages from welding remained marginal. (Hantula, 2019, p. 49)

The final group dialed with the mounting of the modules together. The circumstances related to the contact interfaces were almost like the parts in the first group, except the operating space which may be limited. Therefore, screw joint recommended to be the most suitable solution for that, because of its relatively little space requirements. (Hantula, 2019, p. 51)

Generally, the results showed that the welds can often be replaced with other jointing methods, because the mechanical jointing methods were strong and reliable enough. Overall, the most optimal jointing methods turned out to be rivet joint and screw joint. In some cases, welding was not replaced, because it was the most optimal solution for situations where the amount and size of parts were small, and the mounting required extremely high strength properties. Hybrid jointing method turned out to be suitable especially in situations, where water resistance was required. (Hantula, 2019)

The alternative jointing methods turned out to provide more cost-efficient structure. The methods were less time consuming than welding, because of the easier part positioning and overall labor demanded. In addition, replacing welding provided opportunity to implement modular product architecture, which provides advantages in logistics and haulage. (Hantula, 2019, p. 58)

2.7 Generator and cooling technologies

Generators are electrical machines which convert mechanical work to electrical energy. This electromechanical energy conversion is based on an interaction between the magnetic coupling field and current carrying conductors. (Vukosavić, 2013, p. 3)

Rotating electrical machines have a rotating part, that is called a rotor. It rotates around the generator axis, colinearly with a nonmoving stator. Usually in large synchronous generators the current circuits called windings are mounted on the stator core and the magnets called poles are mounted on the rotor shaft. Due to the hollow cylindrical shape of the stator, the rotor can be positioned inside the stator. (Vukosavić, 2013, pp. 4-5). In large synchronous generators, the stator is attached to the stator frame and the rotor shaft lays on bearings, which are mounted on both ends of the generator. (Vukosavić, 2013, p. 148)

In addition to the parts mentioned above, the generator consists of various other parts which have their own functions. The main components of large synchronous generator are presented in **Figure 16**.

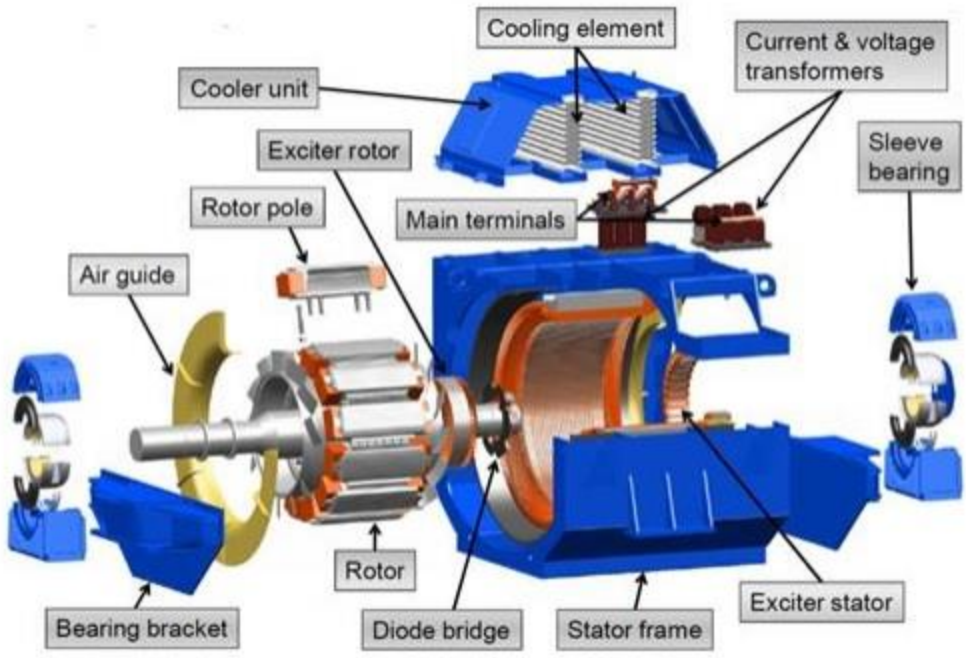

Figure 16. Exploded view of large synchronous generator (ABB, 2018).

As can be seen from the figure above, the structure consists of several subassemblies which are mounted around the stator frame. Some of the parts may vary depending on the machine type, for example the cooling technology may be different, which shows up in different cooler unit.

The components related to the cooling can be seen in the figure above. In open cooled systems the cooling fan is mounted on the rotor shaft next to the rotor poles. When the shaft rotates, the fan produces air stream which is guided inside the stator core by the air guide. The air flows through the stator cooling down the heat from the stator. Finally, the air stream flows into the cooler unit, which transfers the heat outside the generator.

There are multiple different technologies to transfer the heat away from the machine. Usually the technology depends on the use of the generator and the properties of surrounding environment. ABB uses two different cooling arrangements in conventional AMG 1600 generators: open-air and air-to-water cooling. (Tervaskanto, 2012). Both technologies are illustrated in **Figure 17** below.

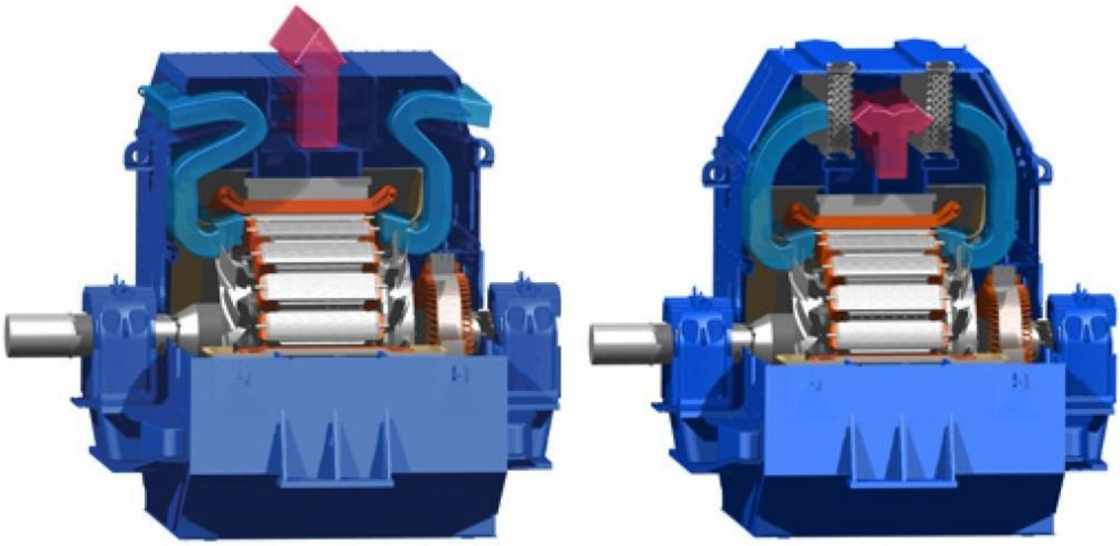

Figure 17. Air circulation in open-air (left) and air-to-water (right) cooled systems (Tervaskanto, 2012).

Open-air cooling is used in environments where the air is relatively clean, and the air circulation is at an adequate level. The air stream is drawn through air filters inside the machine, cooling down the active parts of the generator until the warm air is exhausted back to the environment. (Tervaskanto, 2012)

Air-to-water cooling is used in situations where the surrounding environment circumstances do not allow direct cooling due to the poor air quality or limited ventilation. Air-to-water cooling system emits hardly any heat to surrounding environment (5%) and is therefore an ideal solution when closed cooling is required, for example use in limited ventilated engine rooms. In air-to-water cooling the air circulates in a closed circuit through the active parts of the generator and then through an air-to-water heat exchanger which absorbs the heat away from the machine and transfers it to cooling pipeline (Tervaskanto, 2012)

Usually most of the generators are self-circulated, which means that the air stream is generated with a shaft-mounted fan. Depending on the machine properties, self-circulated system may not be optimal solution to generate the air stream. The rotation speed of the rotor must be in certain range to ensure proper cooling and high operating efficiency. If the rotation speed is too low, the fan does not generate enough air stream to ensure proper cooling. As well, if the rotation speed is too high, the air resistance of the rotor increases which decreases the operating efficiency, due to the braking torque of the fan (Vukosavić, 2013, p. 385).

In some machine types the air steam can be generated with external fan units, which are mounted into the top-module. External fan motor is used to generate the air stream that is independent of the rotation of the generator. Top-modules can be equipped with multiple fan units to enable redundancy, so one or more fan motors can be shut down if extra cooling is not needed. It also provides reliability in case of a malfunction. External fan motors are mounted on both sides of the exhaust channel to generate symmetric air stream when both fan motors are operating. (Halme, 2013)

3 CONCEPT DEVELOPMENT AND RESULTS

This chapter starts by introducing the basics about generators and cooling systems that are needed to understand the subject area. After that the concept development process and its results are presented.

3.1 Generator top-module types

Currently there are three top-module types available for conventional AMG 1600 generators, two of them are for open-air systems and one is for closed air-to-water cooled systems. There are two different air circulation technologies for open cooled top-module, self-circulation option for shaft mounted fan and forced option for external fan units. For closed air-to-water cooled system there is only self-circulation technology available. Two of these top-module types are presented in **Figure 18**.

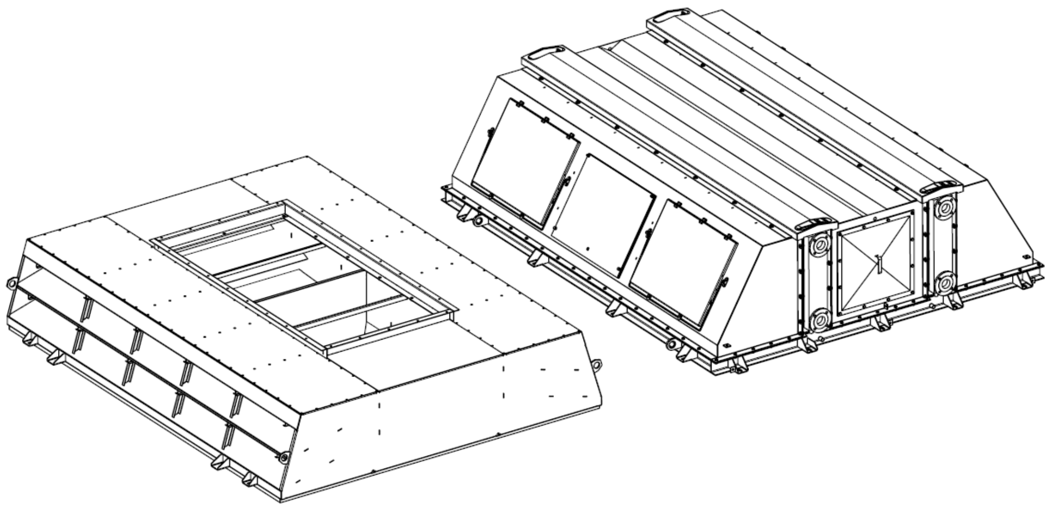

Figure 18. Two top-module types for conventional AMG 1600 generator. Open-air (left) and closed air-to-water (right).

All top-module versions are designed for different stator frame structures, but the operational interfaces are similar. The cool air interfaces are located on both sides of the structure and the warm air interface locates in the middle.

In open-air circulation cooling top-modules, the air filters are attached to the inlet channels. The filters are mounted on two separate levels to achieve a large surface area while keeping the structure compact. The placement of the air filters are visualized by red color in **Figure 19**. The outlet channel is equipped with drip guard, which enables air stream to go upwards but protects the machine from water entering the machine. Drip guard is presented in **Figure 20**.

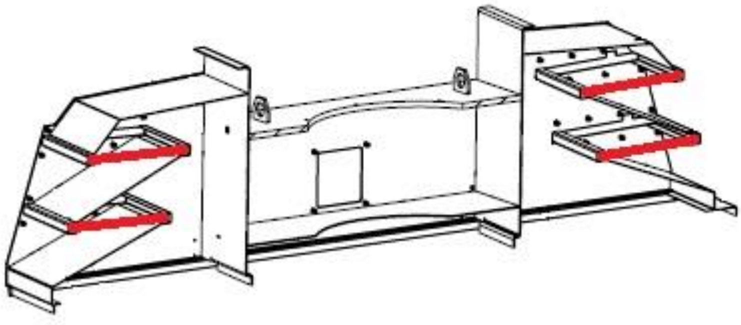

Figure 19. Visualization of air filter placement.

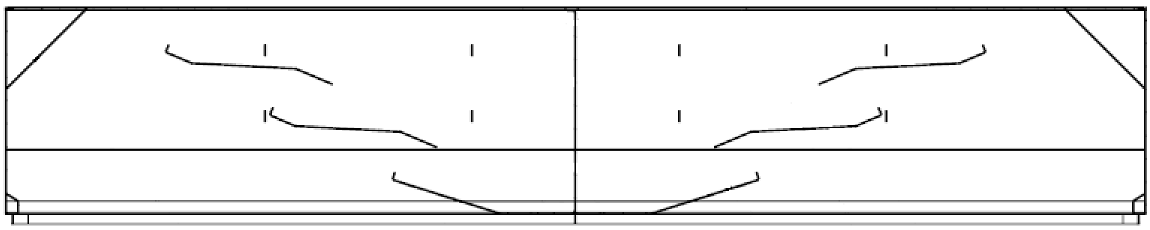

Figure 20. A cross section of the outlet channel.

Closed circulation air-to-water top-modules are equipped with water heat exchangers. They are located on both sides of the middle section of the top-module, separating the cold air channels from the hot air channel.

3.2 Design boundaries

The subject of this study was relatively wide. To ensure appropriate results, the design process followed certain pre-defined guidelines and boundaries. At the beginning of this study, the boundaries for design were defined. These boundaries included general requirements about the machine type, use, frame lengths, air circulation, standards and classifications, material properties and surface treatment. Also, the machine specific requirements were considered, such as dimensional requirements and component specific requirements.

Machine type, use, frame lengths and air circulation set up the concrete basis for the platform. These requirements defined the machines that the platform was made for, and were in a key role in defining the structure and functionality of the system by determining the exact dimensional requirements for the platform interfaces. The most important requirements for platform development are presented in *Table 2*.

Table 2. List of general requirements for platform development.

Machine type	AMG 1600
Use	Land, Marine
Frame length indicator	L, Q, S, U, W
Cooling	Cooling must follow the IC code Open-air: IC0A1, IC0A6 Air-to-water: IC8A1W7, IC8A6W7* (IEC 60034-6)
Protection	The concepts must fit to certain IP classes Open-air: IP23, IP44* Air-to-water: IP44, IP54*, IP55* (IEC 60034-5, IEC 60529)
Air circulation	Symmetric

**Nice-to-have -option*

Standards and classifications were needed to ensure the proper functionality of the system. Top-modules were designed according to IEC standards to fulfill the requirements for protection, cooling and mounting. IP code (International protection code) classify the protection level against water and solid objects (IEC 60034-5, 2020). IC code (International cooling code) define the cooling technology (IEC 60034-6, 1991). IM code (International mounting code) define the construction, mounting arrangements and terminal box positions for electrical machines (IEC 60034-7, 2020). These requirements were essential to follow to ensure the reliability and safety.

Material properties and surface treatment were important factors to consider but they did not have visible influence on result. These requirements influence costs by offering alternative opportunities in manufacturing phases.

Machine specific requirements set boundaries to design by limiting the allowed size and dimensions for the system. Size and dimensions were important to consider in order to ensure that the platform will be suitable for client's purposes and overall functionality. Following the component specific requirements was important to avoid this study spreading out of scope. Additionally, these components and their properties were pre-known, which facilitated the design process and analyzing functionality. The component specific requirements covered air filters, fan motors and heat exchangers.

3.3 Design process

Both the Modular Function Deployment and the integrated framework for modular product development were considered in this design process. These tools formed the guidelines to follow and were mixed with some improvements and freedoms to make them suitable for the application.

Both approaches started from defining the customer requirements. In this case, list of these requirements was short, because the application was not a typical customer product. Conversely, the product was a technical detail in a larger overall picture, power plant. The most important requirements were costs, performance, and reliability. The balance between maximal performance and reliability had to be offered with a minimal price. The circumstances sounded like a description of modularization which does not target to the highest performance. Instead of that, it aims to save costs while keeping the performance in an adequate level. Thus, modular product architecture seemed to be reasonable approach to apply in the present problem.

The integrated framework for modular product development recommends to formulate the functional requirements from customer requirements. Customer requirements were listed and connections between functionalities were found. These connections are presented in **Figure 21**.

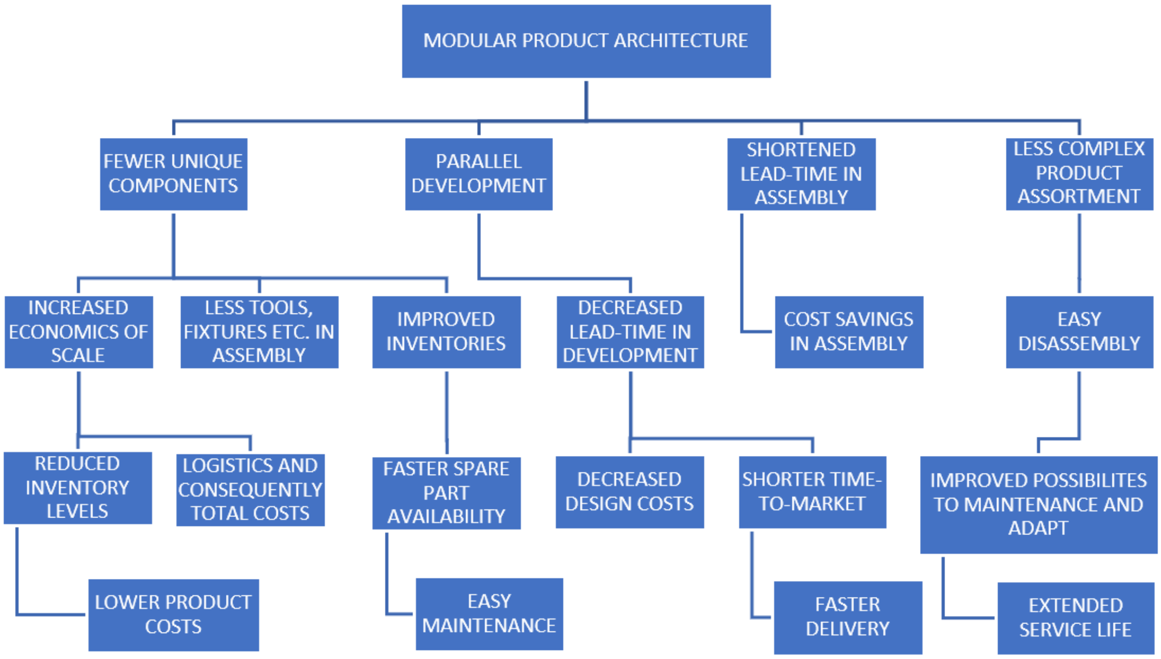

Figure 21. Formulating functional requirements from customer requirements.

The diagram is a summary based on aspects presented in the literature review, and correlates to customer requirements. The clear path from customer requirements to functional requirements can be seen. Some of the aspects are in a major role based on their multiple connections. The area is so wide that only the main aspects are presented in following *Table 3*, which concludes the formulation.

Table 3. Conclusions from requirement formulation.

Customer requirement	**Functional requirement**
Lower costs	Fewer unique components → less complex product assortment
Faster delivery	Parallel development → clear interfaces
Easy maintenance	Fewer unique components → less complex product assortment
Long service life	Less complex product assortment

These were combined with general requirements introduced in the previous chapter and the basis for the platform was formed. The platform had to be suitable for pre-defined machine type and its properties, and it had to meet the functional requirements derived from customer requirements.

The physical mounting interface worked as the base for platform. The mounting interface is the interface between stator frame and top-module. Because of the multiple frame length options, the interface dimensions change. The base for the platform is presented in **Figure 22**.

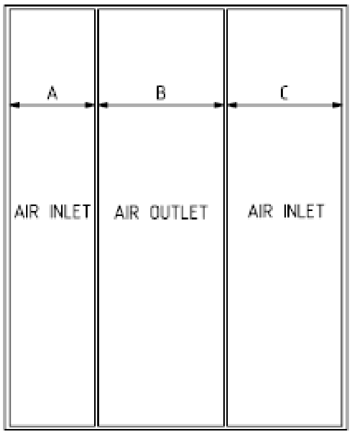

Figure 22. The mounting interface.

As the figure presents, the interface is three sectional, cold air inlet channels are in both sides and the warm air outlet channel is in the middle. Dimensions A and C are equal on all frame sizes, but dimension B is changing along the frame length, because of the variable length of active parts.

This cooling system interface worked as a base for different functions. The construction had to be suitable for all the functions performed by the different top-module variations. These functions variate between different cooling technologies, but some similarities were found. **Figure 23** shows the functions of open-air and air-to-water cooling systems.

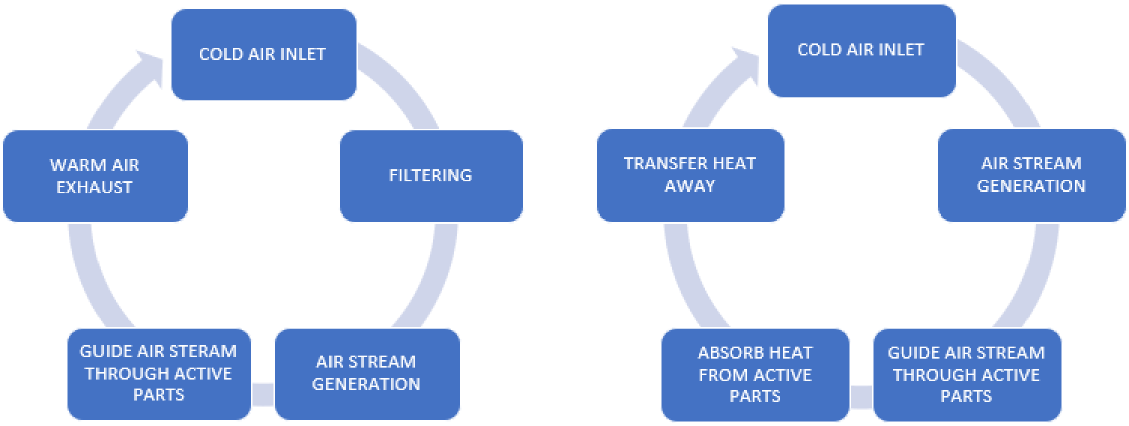

Figure 23. Functions in open-air cooling technology (left) and air-to-water cooling technology (right).

The biggest difference between open-air and air-to-water cooling technologies is the air circulation. In both technologies, it is symmetric, but in open-air cooling technology the system is open, so that the warm air stream is exhausted out of the system. In air-to-water cooling technology the system is closed. Warm air is guided to the heat exchangers, that transfer the heat away from the system and the cooled air stream is guided back to the cold air inlet. These differences between open and closed systems show up in functions that different cooling systems should perform. Due to the open system, the cool air stream should be filtered before it is guided into the machine. On the other hand, in a closed system the heat from outlet air should be cooled before it is guided into the machine. The differences between cooling technologies are presented in more detail in *Table 4.*

Table 4. Differences in components between cooling technologies.

Properties	**Open-air**		**Air-to-water**	
IC code	**IC0A1**	**IC0A6**	**IC8A1W7**	**IC8A6W7**
Integrated fan	x		x	
External fan unit		x		x
IP23	x	x		
IP44			x	x
Air filters	x	x		
Drip guard	x	x		
Heat exchanger			x	x
Emergency cooling			x	x
Symmetric air channels		x	x	x

As can be seen from table above, cooling technologies split into four categories by their IC code. Both open-air and air-to-water technologies have options for free air circulation with integrated fan and for forced air circulation with external fan unit. While open-air variations have air filters and drip guards, air-to-water variations are equipped with heat exchangers and emergency cooling.

Maximum performance, when generating air stream, can be achieved with radial fans. The most optimal location for them is on the cold side of the air circulation. For maximum cooling properties the heat exchangers should be tall and thin in order to minimize pressure losses.

3.4 Sketching

The aim of this work was was to find a solution that would combine all functions and features into a concept that can be mounted to the interface. Moreover, the focus was in finding the optimal balance between maximal performance and a less complex product assortment.

Different approaches were applied when trying to find the most optimal solution. First approach was to investigate the current top-module and to try to divide it into modules in some reasonable way. Another approach was to divide the functionalities into different modules, that performs their special feature. Alternatively, the solution might be found outside the box. One approach was to replace a wide range of top-module variations with a standardized one, so that only a single top-module for each cooling technology would be left. These top-modules could be mounted to different size machines with external adapters, that rules out problems with unmatching interfaces. It was also considered that maybe the most optimal solution for the problem would be a combination of these different approaches. The original top-module variations are proven to be successful solutions, so the process was started by investigating their properties and the reasons why they are so special.

The original top-module variations are designed by applying an integral product architecture. Mapping between functional elements and physical components is complex. It resembles a trailer example from previous chapter, where most of the components have multiple functional elements to fulfill. **Figure 24** shows an example of mapping between functional elements and physical components in an open-air (IC0A1) top-module.

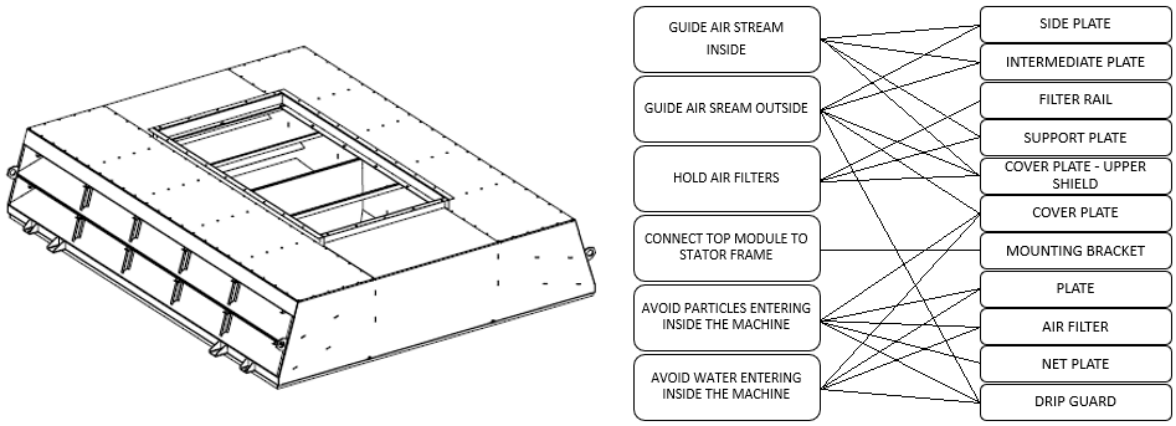

Figure 24. Mapping between functional elements and physical components in IC0A1 top-module.

Applying integral architecture in design has been a successful choice to achieve highest possible performance in compact size. Moreover, considerable effort in product development has been made to achieve the current result. Physical positions of each functionality are thoroughly considered and calculated to achieve the optimal solution. These facts were considered in concept design, to ensure proper functioning.

First approach was to visualize the possible location for each function. A universal scheme for different options was outlined and it is presented in **Figure 25**.

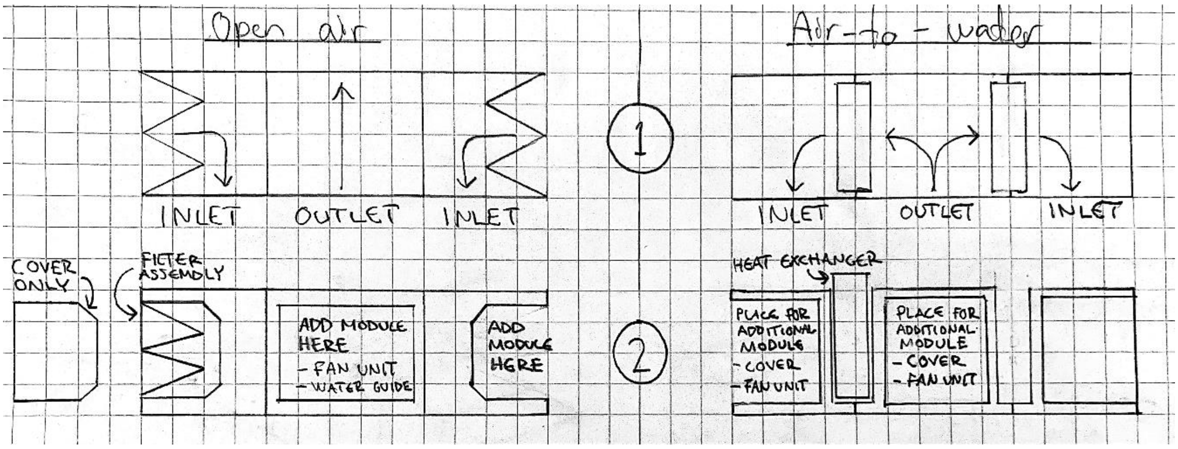

Figure 25. The universal scheme for concept design.

The scheme presents optional positions for each function for different cooling technologies. The platform interface defined the locations for inlets and the outlet, which limited the freedom in design. Especially in air-to-water machines, closed cooling system combined with the platform interface limited the air circulation as presented in the figure above. In open-air system, the interface defined the inlets and the outlet. Suction of fresh air and exhaust of warm air stream were not defined by the interface. However, there were other factors that affect them.

The environmental circumstances and IP classifications set challenges. Air should be sucked inside the top-module while the possibility of dust and water drops entering inside the machine should be avoided. Dust and other particles are filtered by air filters, that were pre-defined for the design. To fulfill the IP requirements, those air filters must be at least on 45-degree angle from horizontal axis, so that the water drops flow away along the filter surface, instead of penetrating the filter. However, the direction of air suction does not have a significant effect on performance, so theoretically the air stream could be sucked into the top-module from side or top.

In open cooled system, the exhaust stream should be directed straight upwards, or more precise, slightly towards D-end of the machine. This is because the air ventilation of the powerplant is often located above the diesel engines that run the generators.

In component level, the physical size of the components limited the possibilities of their locations. Sometimes the locations were influenced by their properties to function in certain environment. For example, radial fans work more effectively on cold air side. Sometimes compromises are obligatory: for example, in an open cooled system with external fan unit (IC0A6) the fans are located on the warm side because of the lack of space in cold side. In those situations, the fan motors must be covered and protected from warm air stream.

Another important factor was the shape, size, and position of heat exchangers. Thin heat exchangers are excellent options due to low pressure loss and inexpensive price compared to thicker alternatives with smaller width and height dimensions. The heat exchangers tend to be positioned vertically, because of the easier control of drip water in case of malfunction. Without that challenge, solution with horizontally positioned single heat exchanger would be the more cost-effective solution due to decreased height of top-module and the fact that a single double width heat exchanger is cheaper than two normal size heat exchangers. On the other hand, vertically positioned heat exchangers require space between them to ensure proper airflow through the heat exchangers. This aspect was considered to set more crucial restrictions in practice than decreased performance on warm air side fan motor.

The universal scheme for concept design was outlined to visualize the idea behind it. The visualization itself reminds about component-sharing. The scheme could have been visualized by other ways as well. Typologies of modularity turned out to be a helpful methodology to approach the topic. Ideas derived from typologies of modularity explained in *Table 5.*

Table 5. Examples based on typologies of modularity.

Typology	**Example**
Component-swapping modularity	Single specific frame with specific places for different kind of modules
Component-sharing modularity	Different frame options, standardized modules
Fabricate-to-fit modularity	Standardized top-modules, different adapters
Bus modularity	Universal interface so that the modules can be matched varying the location and amount
Sectional modularity	Simple interfaces all over the modules. Modules can be mounted to each other in various ways

The example of component-sharing approach did not match perfectly on the typology due to two different frame options, one for each cooling technology. The idea was taken further by developing a frame that suits for both purposes. **Figure 26** shows an early stage outlining of how component-sharing typology could be implemented in both cooling technologies.

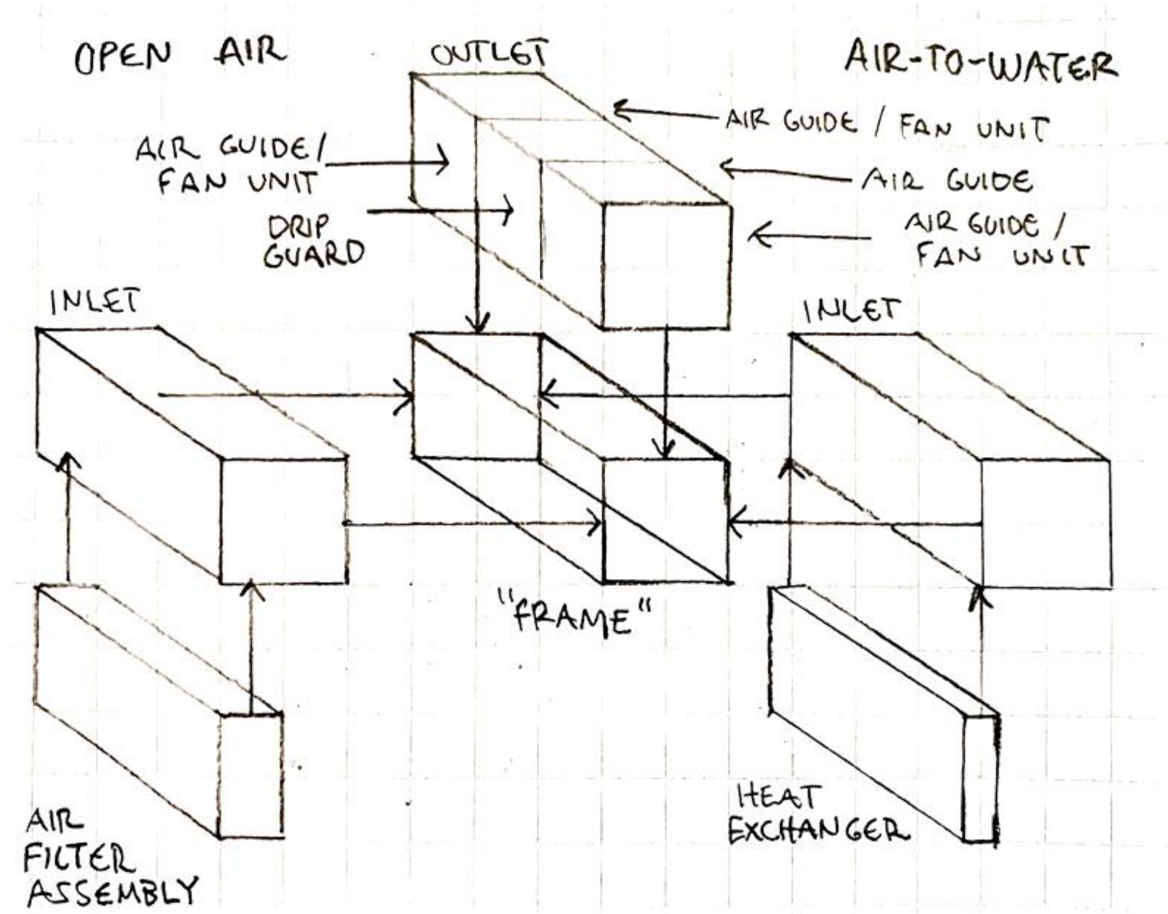

Figure 26. Component-sharing sketch.

The idea behind component-sharing typology concept was to create a top-module around a frame that works as an interface for both, open-air and air-to-water modules. Different stator frame sizes could be handled with different frame options, one for each frame size. The modules themselves used with different frame sizes could be same, which reduces the number of components without decreasing the variety.

Component-swapping modularity is almost identical to component-sharing modularity, but instead of swapping the base component, frame in this case, it remains same. In component-swapping concept, the frame should be flexible to be able to fit for different stator frame sizes. The idea about this flexible frame was visualized with extravagant mechanisms, to make the example easier to understand. Examples presented in **Figure 27**.

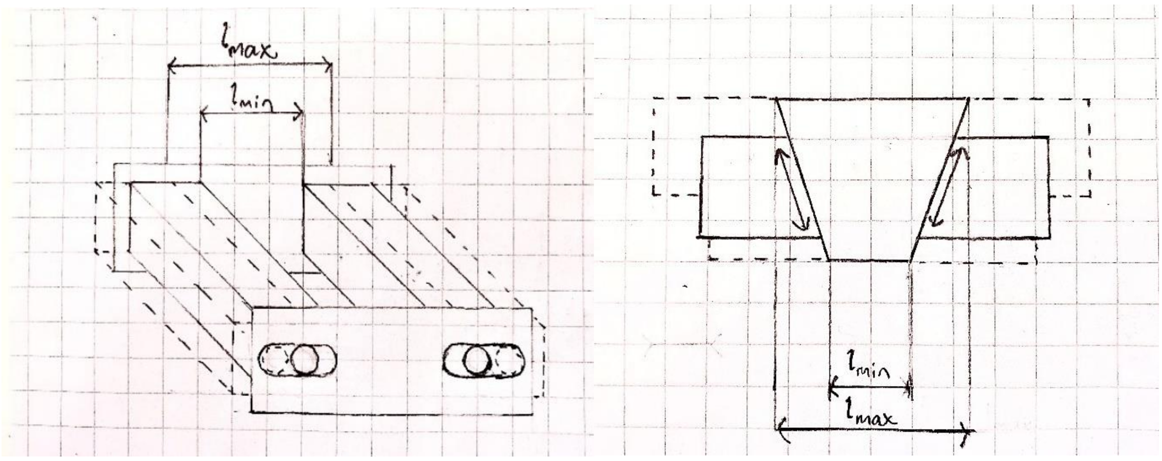

Figure 27. Component-swapping modularity sketch.

Instead of applying probably expensive slot mechanisms, the concept could be implemented in a more conventional way by adding extra screw holes for different positions. The middle section, outlet channel, could be adjusted for different stator frame sizes. **Figure 27** shows two different examples, one for each cooling technology. In open-air technology, the middle section should be separated from end sections to avoid cold and warm air streams mixing. In air-to-water technology, the air stream should enter from middle to both ends, so the interface between sections must be open. The example has also nuance of bus modularity as the universal frame can be equipped with any number of modules, whose number and location may vary, provided that the interfaces are similar.

The topic can be approached with other typologies of modularity as well. Another early stage outlining presented sectional modularity. Typical to sectional modularity is - instead of creating everything around to a specific frame - to build the product from modules, that form the structure together. Those modules have universal interfaces, so that they can be matched in various ways. **Figure 28** represents the idea how the sectional modularity could be implemented in modular top-module platform concept.

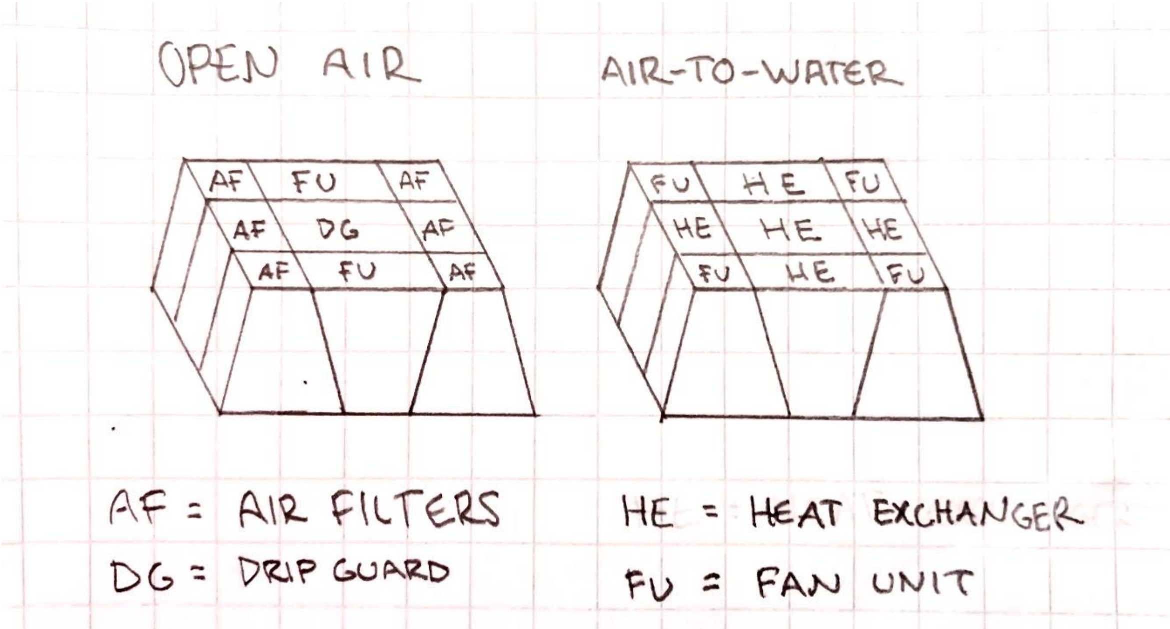

Figure 28. Sectional modularity sketch.

As can be seen, the top-modules could be divided into modules that have similar interfaces. That enables creation of the top-modules by mixing and matching modules in arbitrary way. The example does not perfectly follow the sectional modularity topology but has still potential to provide benefits.

Fabricate-to-fit modularity turned out to be challenging to apply in this type of product, that does not have infinitely variable additional components, whose physical dimensions can be modified. However, the typology was applied, and the derived idea was quite different from the other concepts. Instead of splitting the structure based on different functions, the top-modules could be split in half. The upper part could be a standardized top-module for each of the cooling technologies while the lower part works as a variable additional component. The upper and lower parts could be mixed and matched as in **Figure 29**.

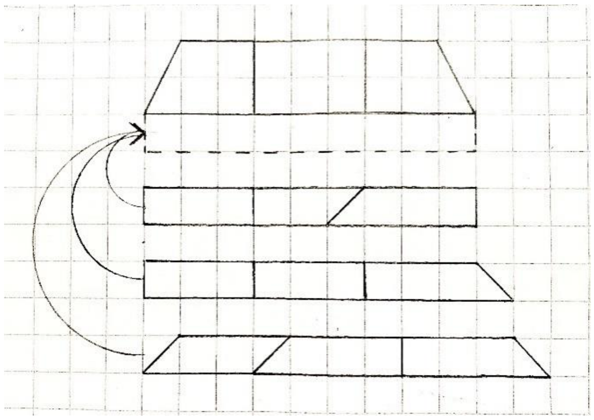

Figure 29. Adapter fit sketch.

Instead of trying to solve the fitment problem by creating various number of different size modules or multi-functional frame, the problem could be solved by adding an adapter. Theoretically, all five frame lengths for four different cooling technologies could be carried out with four independent top-modules and five adapter modules.

None of these early phase sketches were suitable for implementation as such, but the sketches outlined different viewpoints, that may have potential to be developed further. Those ideas could be also be combined in some level.

The level of modularity was important aspect to consider. How many main modules are needed, and how those main modules could be split into submodules? **Figure 30** presents an idea about three main modules, whose inlet modules are divided into submodules.

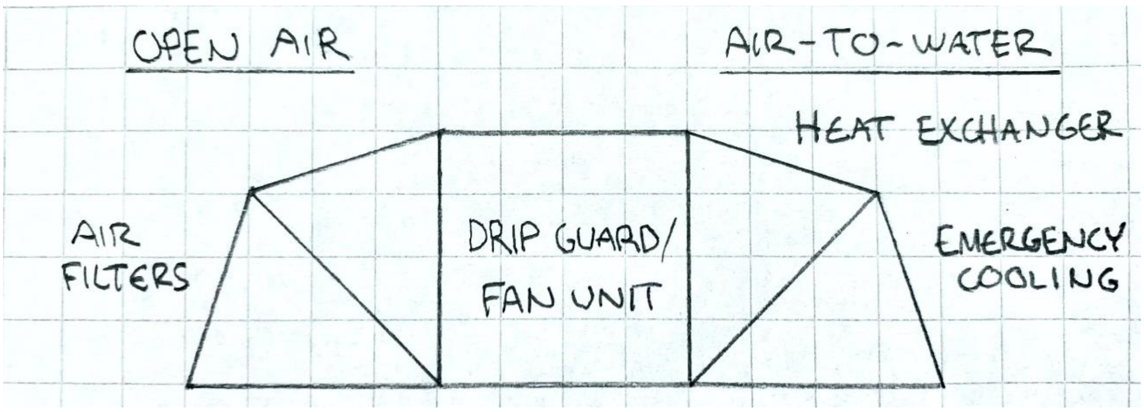

Figure 30. Alternative approach for module deployment. Three main modules could be divided into submodules.

Figure above shows a bit different solution for module deployment: it consists of three different modules, of which two are divided into submodules. Or alternatively, it consists of a total of five different modules.

Another option was to investigate how much similarity is shared by the different modules. Would it be beneficial, or even possible to split main modules into submodules? Further research resulted into a concept focusing more into module deployment instead of trying to find a solution that would be able to manage different frame size options. The concept was sketched for both cooling technologies.

The concept for open-air cooling technology is presented in **Figure 31**. As can be seen, the top-module is divided into three main modules based on air stream direction, two identical inlet modules and one outlet module. Inlet module works as an air filtering module, which is a single module without sub modules. The outlet module includes three variation modules for different functions: drip guard, fan unit, and air guide.

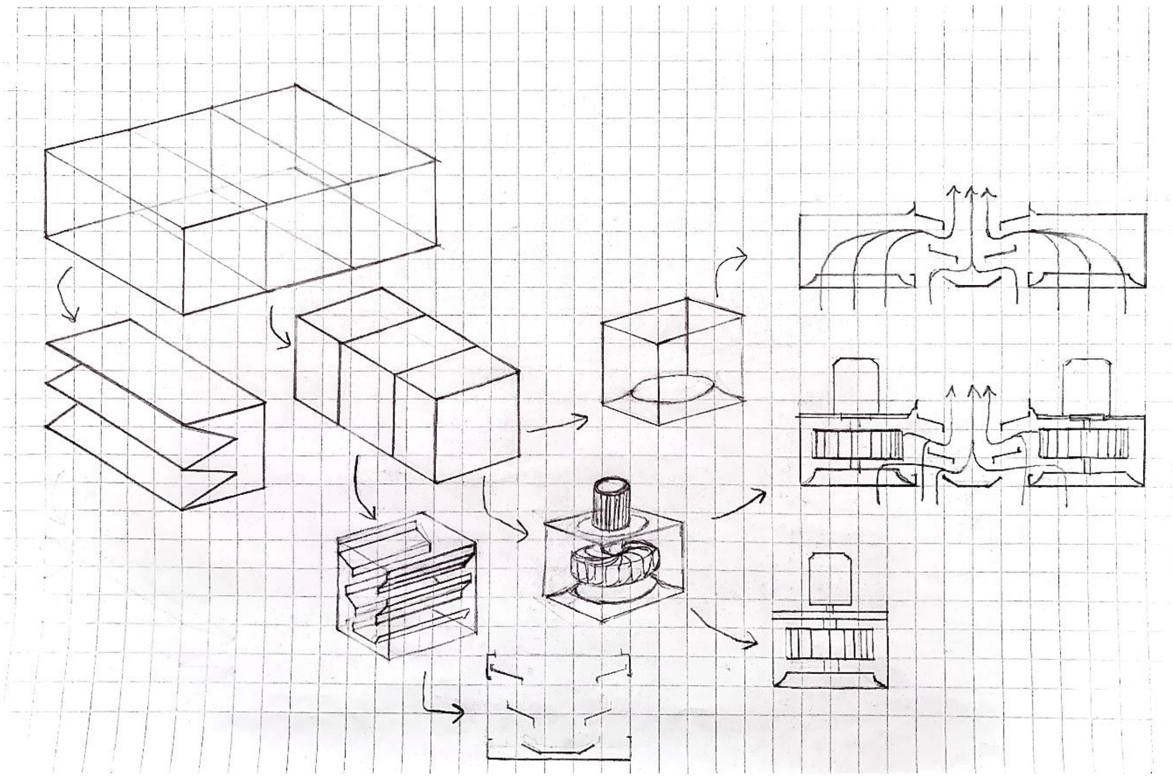

Figure 31. Open-air concept sketch.

As the figure above presents, these module variants could replace both open-air variants, a version for shaft mounted fan and version for external fan unit. On the right-hand side of the picture, the paths of warm air streams through the outlet module is visualized by arrows. One of the variants is equipped with external fan units, that blows the air stream through the drip guard outside the system. In another variant, the external fan units are replaced with air guide modules or maybe just sort of cover plates, that direct the warm outlet air stream out of the system.

The concept was sketched for air-to-water cooled technology as well. **Figure 32** shows how the concept could be implemented for that technology. The top-module could be divided into three modules, similarly, like in the open-air example. There could be two different inlet module variants, one for machines with shaft mounted fan, and another for machines with external cooling units. The first one could be just a single module, with a position for heat exchanger attachment. Another module could be a single module like the first one but equipped with three positions for external cooling units. Moreover, if needed, the module could be divided into three submodules, one for each fan motor.

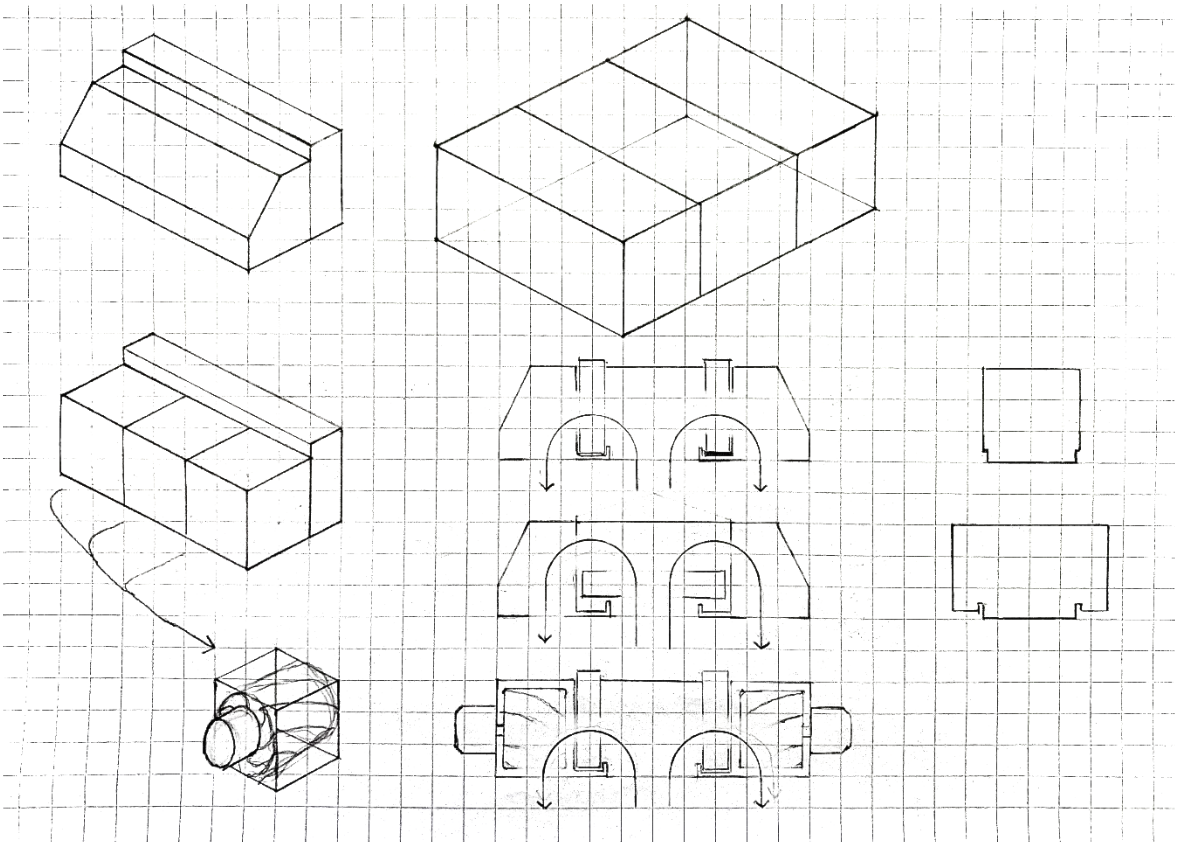

Figure 32. Air-to-water concept sketch.

There could be two different types of outlet modules, that are drawn in the right-hand side of the figure. The upper one is for the conventional machine, with two vertical heat exchangers. The other one could be designed for horizontal heat exchanger. The air stream through the top-module in different variants is visualized in the middle of the figure.

These top-module concept variants of both cooling technologies could be fitted to different frame sizes by providing several lengths of outlet modules, or alternatively by applying the ideas introduced earlier. For example, with adapters, or maybe just adding cover plates to gaps that must be covered to prevent air steaming to incorrect places.

These early stage sketches were compared, and their suitability for the purpose were considered. Sketches based on component-sharing and component-swapping modularity were seen to be potential for further development. In addition, the adapter idea was taken into further development. The idea based on sectional modularity turned out to be impractical in this application as the benefits that came from ability to mix and match modules in arbitrary way were not very advantageous. That was because of the strict limitations in component locations and combinations in ensuring proper cooling and functionality. Moreover, the features required by sectional modularity, such as identical interfaces between modules, would be problematic to implement. The properties of potential sketches were concluded into *Table 6* presented below

Table 6. Properties of potential candidates.

	Component-sharing	**Adapter idea**	**Component-swapping**
Frame fitting for different frame lengths	Changing middle section	Adapter fitting	Flexible frame
Differences between D- and N-end	Additional cover plate	Adapter	Additional cover plate
Fitment of outlet components for different frame lengths	Changing middle components	Same middle components	Changing middle components

Table 7. continues. Properties of potential candidates.

Variations for each cooling technology	Possible	Possible	Challenging
Potentiality for next stage of concept development	Potential with two variations: basic and adapter	Potential	Might be potential

3.5 Virtual models of the concepts

In further development, the sketches on paper were taken further, into 3D models. These models were simplified as the purpose was to create virtual models to obtain more information to be applied when analyzing the concepts. The 3D modeling started by creating a parametric model for the frame, which formed the base for the development work.

The first concept developed further was based on the component-sharing modularity. The idea behind the concept was to build the top-module around a variable length outlet module, while keeping the inlet modules in the same length. **Figure 33** shows variations for both cooling technologies, the upper ones are for open-air cooling and lower ones are for air-to-water cooling. The variations for shaft-mounted-fan machines are on the left side of the figure and variations for external fan units are on the right side.

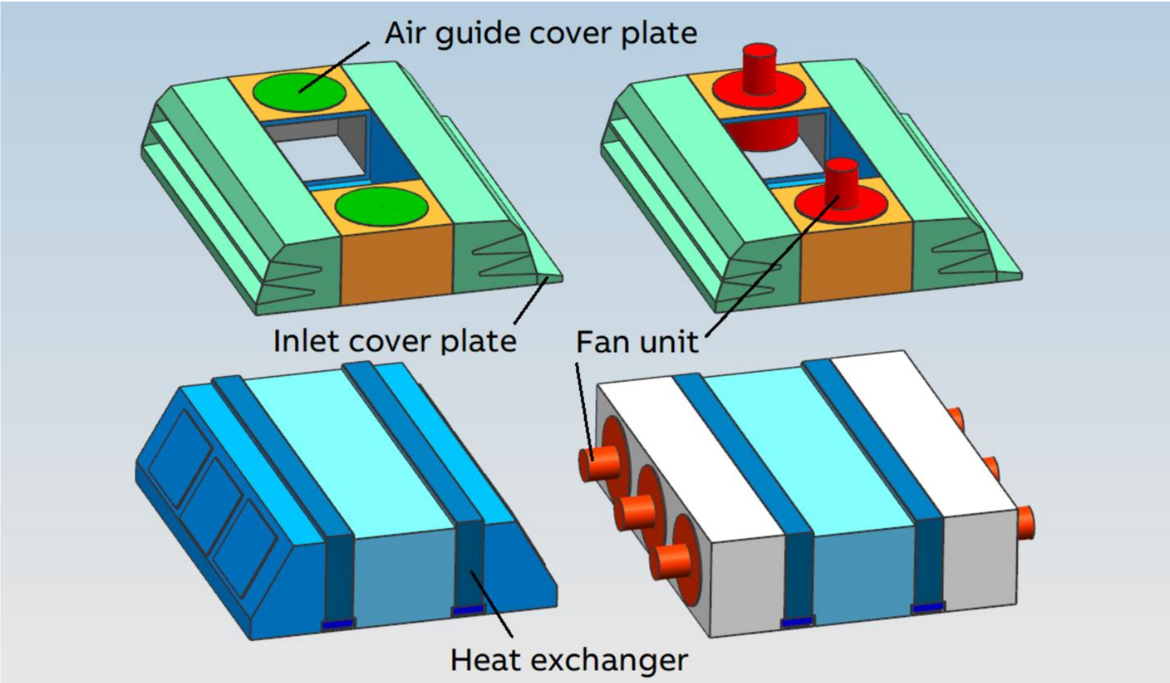

Figure 33. Component-sharing concept.

Open-air top-modules are based on an idea, that the same top-module could fit to both air stream generating technologies. Top-module for the shaft mounted fan could be converted into version for external fan units just by changing the outer sections of the outlet module, or alternatively, just by replacing air guide cover plates with external fan units. The extra space in stator frame N-end side is covered with additional inlet cover plate, which is attached on the N-end side inlet modules.

Air-to-water top-module variations are created around the same outlet module. There are two inlet module options, one for shaft-mounted-fan machines and one for external fan units. The extra space in N-end inlet channel is covered with additional cover plate as well, but it is not shown in this version, because it is located between the outlet module and N-end side inlet module. The **Figure 34** shows how the top-modules are divided into different modules and how different variations could be created.

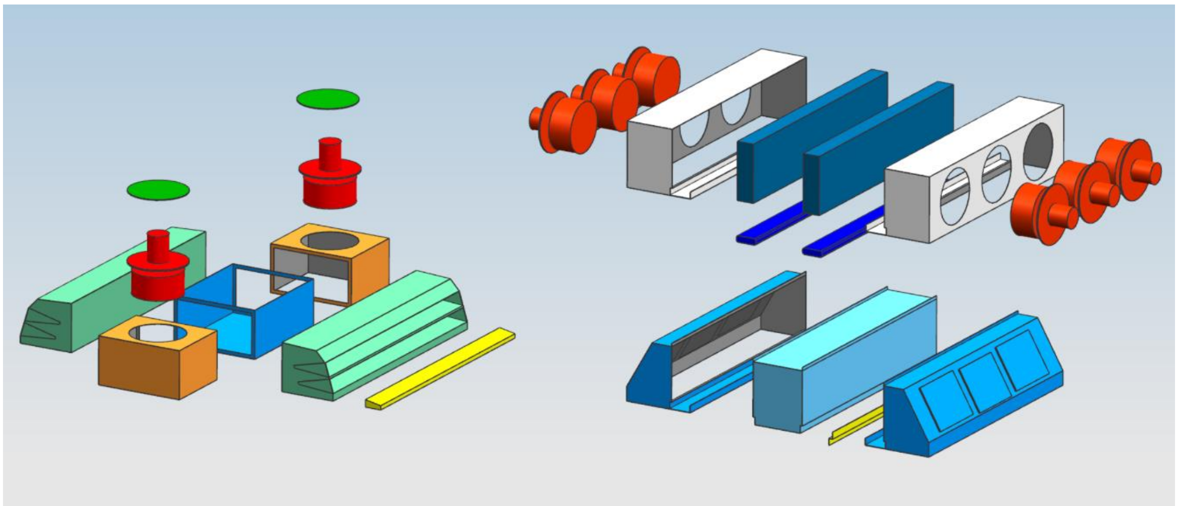

Figure 34. Exploded view of component-sharing concept.

The figure above shows the components for each cooling technology. As mentioned before, the outlet modules vary depending on the frame size. It does not appear in the figure, but the modules are practically similar, except for the length dimension.

Instead of having four cooling technology specific top-module variations for each five frame lengths, this concept benefits in keeping the inlet modules same. It will still require four different outlet modules for each frame size to function, but the total number of different parts will reduce significantly.

Another further developed concept was based on the adapter idea. Instead of splitting the top-module variations into different modules, the idea was to reduce the number of top-module variations by standardizing the current top-module variations and mounting them with adapters. The approach is totally different compared to the other concepts, but it seemed to be promising enough to deserve further development. The adapter concept is presented in **Figure 35** below.

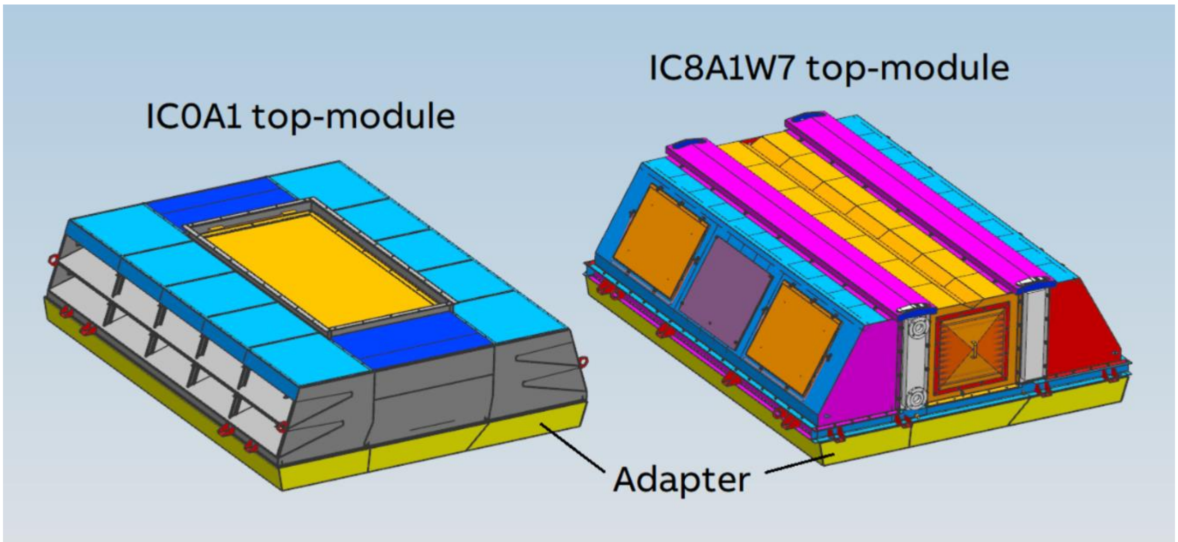

Figure 35. Adapter concept.

The figure presents the configurations for two different cooling technologies. On the left side of the figure there is a version of open-air top-module with external cooling units. On the right side there is an air-to-water top-module. The adapters are the yellow colored parts attached on the bottom of the top-modules. In addition to the ability to fit the top-modules into different frame sizes, the adapters will eliminate the fitting problems derived from asymmetric stator frame inlet channels, that were covered with external cover plates in the previous concept.

Choosing one specific top-module for each cooling technology, that can be mounted to all frame sizes using a specific adapter will reduce the number of top-module variations effectively. On the other hand, the concept requires adapters for all frame sizes that results in a huge number of different adapters. However, it might be still beneficial because the total number of components would remain lower.

The next concept is a combination of the two concepts introduced earlier. In practice, the idea is the first concept mounted with adapters. It may have potential to be applied if the earlier concept turns out inefficient. If the top-module turns out to be over dimensioned, and therefore too expensive for small frame length use, the configuration can be changed to more inexpensive one. The hybrid concept is shown in **Figure 36** below.

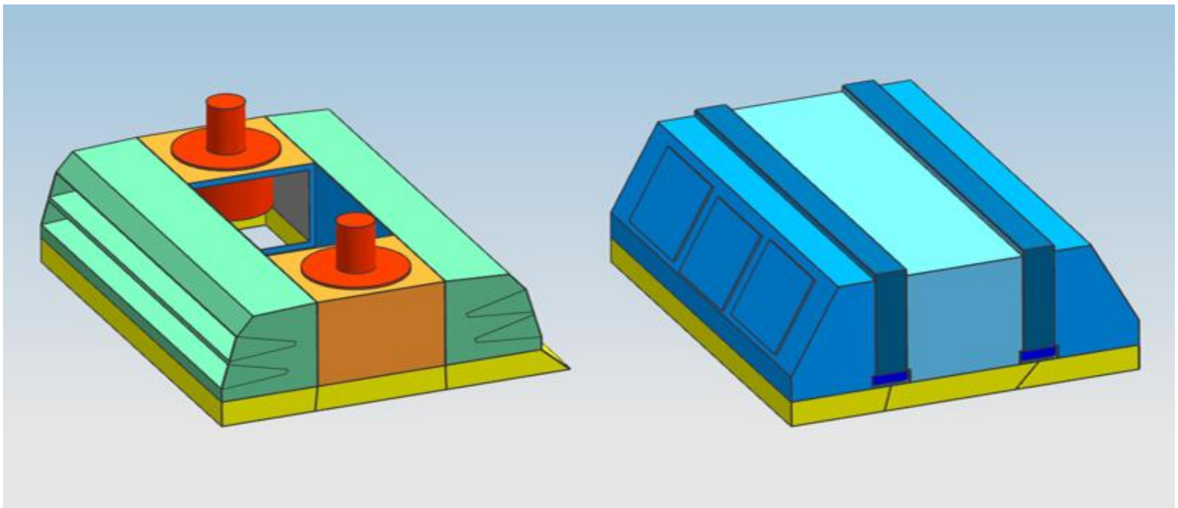

Figure 36. Hybrid concept.

Instead of having five different outlet modules for each frame length as in the first concept, this configuration could be implemented with two different outlet modules, the second smallest and the largest options for example. In these cases, the top-modules could be mounted without adapters. They would be required only in situations where the frame length is the smallest, mid-size or the second largest.

The last concept's idea was derived from component-swapping modularity. Instead of creating the top-module around the outlet module, the outlet module could be created around inlet modules. The outlet module itself consist mainly sheet metal plates, that forms the outlet channel between the inlet modules. The idea turned out to be impractical because components inside the outlet channel should be frame length specific and therefore the benefits gained from adjustable frame would disappear. Theoretically, the concept might work in air-to-water purposes which do not require components inside the outlet module. The concept idea was abandoned in early stage of 3D modeling. The abandoned concept idea introduced in **Figure 37**.

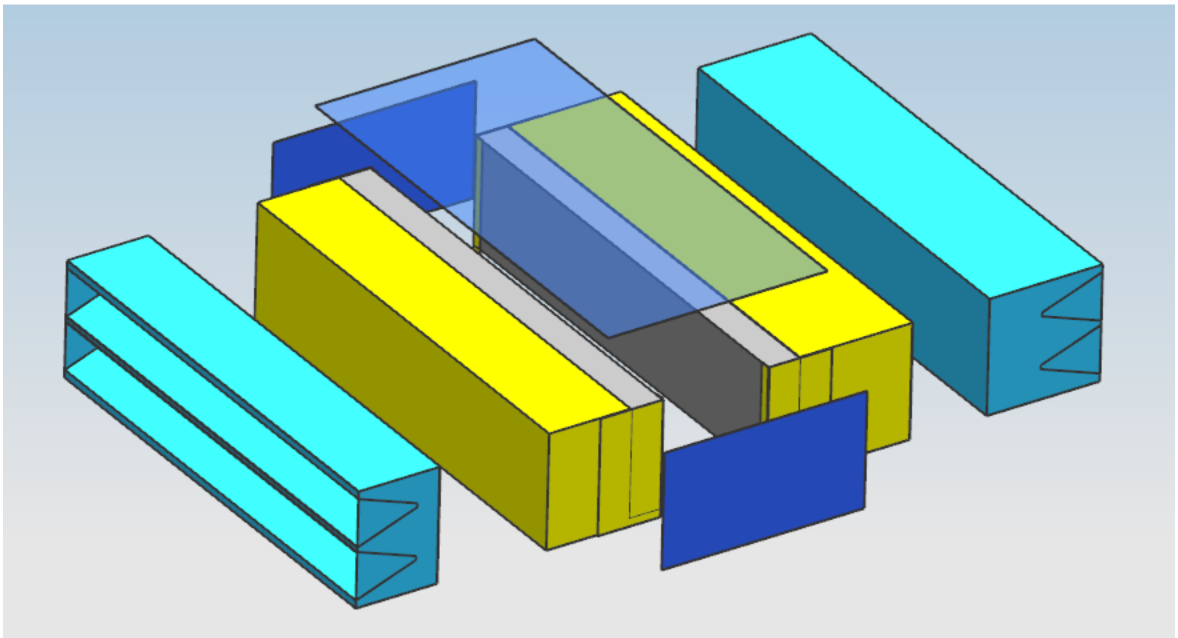

Figure 37. Exploded view of abandoned component-swapping concept idea.

Figure 37 shows inlet module options for both cooling technologies. Light blue colored modules are for open-air cooling and yellow colored are for air to water cooling. The blue colored cover plates are dimensioned to be used in all frame lengths.

Technical specifications of the concepts are presented in appendix. Table contains general data about concepts, for example numerical data of modules, module items, interfaces etc. that are needed to analyze the concepts. Also the concepts are combined in exploded view drawing that is presented in appendix.

3.6 Numerical results

The virtual models were made to provide numerical data that can be used to facilitate the comparison between concepts. Simplified 3D models do not provide accurate numerical values but can be used to make an approximation for value estimation.

Design of new concept structures are close to the original top-module structures, and therefore enabled the utilization of pre-known values to estimate corresponding values for new concepts.

To ensure that the comparison results will be valid and reliable, it was important to measure right things, in the right way. The literature review concluded that variables, such as part count and item count, provides very useful information that correlates directly to important factors behind customer requirements. Item, in this context, means an individual component, with its own manufacturing drawing. The explanation for a part is simpler: it means a single component manufactured by any manufacturing drawing. Reducing the number of part items will increase the economics of scale, which, in turn, benefits in various factors explained in the paragraph 2.5Costs. Another important variable, the number of parts, has similar influence on benefits, but provides also other useful information: how efficiently these part items are used. DFMA aspects advocate to minimize the number of components to obtain the maximum benefit.

To measure those variables in a right way, the whole product family with all frame lengths must be considered. It is important to examine single top-module variants to ensure that they are suitable and meet the requirements. But to see the overall influence, it is necessary to look the numbers for the whole product family. The benefits of modular product architecture stand out when the whole product family is examined.

Design of the component-sharing concept is based on pre-known top-module versions: both new open-air variants are based on the original version with external fan units and air-to-water variants are based on the top-module version without external fan units. The numerical data for these were derived from existing BOMs (Bill of Materials). The air-to-water top-module with external fan units does not exist yet in generator product family, but the values for it were derived from comparable version from motor product family. The adapter concept utilizes the original top-module versions, so numbers for them were derived from existing BOMs.

The data derived from original versions were gathered and estimations for new concepts were approximated. The part counts for single variants remained almost the same, except that additional parts, such as cover parts and adapters were added to the concept. In addition, splitting the original top-module into modules increased slightly the number of components. Results for single variants compared to the original one in a scaled form are presented in *Table 8*.

Table 8. Scaled results for single cooling technology variants.

	IC0A1	IC0A6	IC8A1W7	IC8A6W7	TOTAL
Original					
Part items	1	1	1	1	**1**
Parts	1	1	1	1	**1**
Component-sharing					
Part items	1	1,077	1,043	1	**1,029**
Parts	0,465	1,057	1,014	1	**0,884**
Adapter					
Part items	1,036	1,038	1,022	1,027	**1,029**
Parts	1,006	1,014	1,003	1,007	**1,006**
Hybrid					
Part items	1,036	1,115	1,043	1,027	**1,051**
Parts	0,472	1,071	1,014	1,007	**0,888**

The data for the whole product family were estimated by approximating how many parts and part items are required in a product family to create any top-module variant needed. The original top-modules are individual welded structures for each cooling technology and their frame length, but they are sharing some of the components, especially between different frame lengths. These components are called as *shared components* in this study.

Finding out the exact values for shared components for each cooling technology would be challenging, due to the huge amount of data. Moreover, some of the versions do not even exist in multiple frame lengths. The problem was solved again by approximation. The number of basic components were approximated by comparing BOMs of two different frame length variants. The numbers of parts and part items were counted for both variant, and the coefficients of shared parts and part items were calculated. Coefficients for shared components between cooling technologies were approximated as well. In open-air technology, the top-module is the same, except the fan unit, which replaces the air guide unit in the component-sharing concept. The coefficient of shared components between both open air cooling variants was derived by comparing the number of fan related components to the total number of components in open air top module. In air-to-water technology, the inlet modules are different. Those inlet modules cover half of the module items and one third of the numbers of modules overall. These modules are not dependent on frame length, which means that they were not considered in calculations of frame length variances. Coefficients presented in *Table 9*

Table 9. Coefficients for shared components.

Shared components	**Part items**	**Parts**
Between frame length	0,357	0,314
Between cooling technology (open-air)	0,088	0,084
Between cooling technology (air-to-water)	0,5	0,67

Due to the similarities of product design between different cooling technologies, these ratios were estimated to correlate along different technologies. These coefficients were utilized to estimate the corresponding values for new concepts as well, so the overall part counts and part item counts were approximated. Different cooling technology variations for component-sharing and hybrid concept were combined due to their high component sharing rate. Results for the whole product family is presented in*Table 9 Table 10.*

Table 10. Scaled results for product families.

<table>
<tr><th>Original</th><th>IC0A1</th><th>IC0A6</th><th>IC8A1W7</th><th>IC8A6W7</th><th>TOTAL</th></tr>
<tr><td>Part items</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>Parts</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>Component-sharing</td><td colspan="5"></td></tr>
<tr><td>Part items</td><td colspan="2">1,172</td><td colspan="2">1,446</td><td>0,708</td></tr>
<tr><td>Parts</td><td colspan="2">1,146</td><td colspan="2">1,344</td><td>0,709</td></tr>
<tr><td>Adapter</td><td colspan="5"></td></tr>
<tr><td>Part items</td><td>0,485</td><td>0,491</td><td>0,457</td><td>0,468</td><td>0,472</td></tr>
<tr><td>Parts</td><td>0,457</td><td>0,475</td><td>0,451</td><td>0,459</td><td>0,457</td></tr>
<tr><td>Hybrid</td><td colspan="5"></td></tr>
<tr><td>Part items</td><td colspan="2">0,744</td><td colspan="2">0,836</td><td>0,422</td></tr>
<tr><td>Parts</td><td colspan="2">0,723</td><td colspan="2">0,788</td><td>0,421</td></tr>
</table>

3.7 Concept evaluation and selection

The concepts were evaluated by applying methods from MFD and DFMA procedures. Due to various evaluation criteria, the priority for different criteria was solved by applying QFD (Quality Function Deployment) matrix by weighting their importance. The concepts were scored from 1 to 5 for each criterion and scaled with a weighting factor. At the end, the points were summed for each concept, to find out the concept with highest score.

First, the evaluation criteria were defined. Most of the criterion were derived indirectly from customer and functional requirements, to ensure the right aspects to be considered in the evaluation. Criteria were intended to be accurate enough to achieve reliable results, but not too specific to ensure that all important aspects will be covered. The values for criteria were based on the data in previous chapter and appendix. Some of the criteria were not suitable to scored directly based on quantitative data: these qualitative types of criteria were scored by estimations made by experts. The evaluation criteria are presented and explained in the following sections.

The number of part items, in this context, means the number of manufacturing drawings in an entire product family. The smaller the number is, the better. The criterion itself tells about economics of scale, where reducing the number of part items increases production volumes. In addition to that, the smaller number of items is easier to manage overall. The number also describes the future level of investment in product development.

Number of parts is close to the earlier criteria, but in this context it means the minimum number of parts needed to create any variation of the concept in the entire product family, including all frame lengths. It measures slightly different properties than the previous one, i.e. it is a measure of installability, and the lower the number of parts indicate for a lower number of phases required in the final assembly.

Number of interfaces means how many interfaces are included in each concept. It includes the interface between a stator frame and top-module, as well as interfaces between modules or top-modules and adapters. Like the previous one, this criterion tells about installability.

Manufacturability measures the concept from the perspective of manufacturing. It tells about difficulty of processes, number of manufacturing phases and overall lead time in manufacturing. The easier and less time consuming the manufacturing phases are, the better the manufacturability is. Manufacturability scores are estimated by experts, based on previous experience gathered from top-module manufacturing.

Serviceability measures the physical maintenance properties of the concept, in case of a maintenance. It tells about the accessibility to essential components during maintenance and correlates often with the number of problematic interfaces.

Logistics measures the transportation and storage properties of the concept. It is estimated by the number, size, and shape of the modules. The less modules need to be stored, the better logistical properties the concept has. The size affects also the transportation mode as complete top-module requires extra properties from transportation.

Weight means the total weight of variants in product platform. The modules are mostly made of sheet metal, so the weight correlates directly with the amount of material used in the product platform. Weight can be estimated by number of parts and part items, combined with visual inspection of virtual concept models.

Cooling power scalability measures how well the cooling properties are handled in the product family. If the variations between frame-sizes shares the same cooling related components, they might be over-dimensioned. The benefit achieved from sharing components between frame-sizes may disappear if the cooling properties are too expensive. This situation exists only in concepts with adapters.

Sealability measures the sealing properties of the concept. Especially long interfaces, that must be sealed in the final assembly are often problematic and therefore increase lead time. Sealability is estimated for each concept by visual inspection of virtual models.

Appearance measures the visual look of the concept and may have positive or negative influence on customers. Visual inspection creates an image of the product and may reveal quality or functionality related properties.

Novelty of solution measures the rate of new ideas, technologies or other new solution applied in the concept, compared to the pre-known, often solutions already in production. Pre-known solutions are usually more reliable and safer to use, due to the previous experience. On the other hand, the lack of new solutions limits the technological development. Points for this criterion are estimated by the designer.

The weighting factors for each evaluation criterion were derived from QFD matrix, where every criterion is compared to other criteria by their importance. In comparison, the more important criterion is graded with value 1, and the less important criterion gets value 0. There may occur situations, where both criteria are equal. In this study, both criteria are then graded with value 1. Each criterion is placed on its own row and column in the table forming a matrix with diagonal row of values 1, where a criterion is compared to itself. QFD matrix is shown in *Table 11*.

Table 11. Example of QFD matrix

	Criterion 1	Criterion 2	Criterion 3	Points	**Weighting factor**	**Standing**
Criterion 1	1	0	1	2	**0,67**	**2**
Criterion 2	1	1	1	3	**1**	**1**
Criterion 3	0	0	1	1	**0,33**	**3**

After scoring, the total points for each criterion can be calculated by summing the points in the columns of the row. The weighting factor is obtained from the average of the row. At the end, the criteria are ranked by their importance on standing column.

The QFD matrix was performed by a group of three product development engineers to achieve multi-perspective evaluation and therefore improve the validity of the results. The results are presented in *Table 12*

Table 12. QFD matrix and results.

	Number of part items	Number of parts	Number of interfaces	Manufacturability	Serviceability	Logistics	Weight	Cooling power scalability	Sealability	Appearance	Novelty of solution	Points	Weighting factor	Standing
Number of part items	1	0	0	0	1	0	1	0	1	1	1	**6**	**0,545**	**7**
Number of parts	1	1	0	0	1	0	1	0	0	1	1	**6**	**0,545**	**7**
Number of interfaces	1	1	1	1	1	0	1	0	1	1	1	**9**	**0,818**	**3**
Manufacturability	1	1	1	1	1	0	1	0	1	1	1	**9**	**0,818**	**3**
Serviceability	1	0	1	0	1	0	1	0	1	1	1	**7**	**0,636**	**5**
Logistics	1	1	1	1	1	1	1	1	1	1	1	**11**	**1**	**1**
Weight	0	0	0	0	0	0	1	0	0	0	1	**2**	**0,182**	**10**
Cooling power scalability	1	1	1	1	1	0	1	1	1	1	1	**10**	**0,909**	**2**
Sealability	0	1	1	0	1	0	1	0	1	1	1	**7**	**0,636**	**5**
Appearance	1	0	0	0	0	0	1	0	0	1	1	**4**	**0,364**	**9**
Novelty of solution	0	0	0	0	0	0	0	0	0	0	1	**1**	**0,091**	**11**

Logistics was considered the most important single criterion by defeating all other criteria. Another highly important criteria were the cooling power scalability in the second place and manufacturability and the number of interfaces, which shared the third place standing. The three most unimportant criteria were the novelty of solution, weight, and appearance.

The weighted factors were exported to the concept scoring table, where each concept was scored. The grades were given compared to the original, current top-module versions, which facilitated the scoring by benchmarking the scaling. Other scaling methods were also tested to verify the results, but the results remained similar. The concept scoring table with weighted scores is presented in *Table 13*.

Table 13. Results of concept evaluation.

Aspect	Importance	Component-sharing		Adapter		Hybrid		Original	
		Points	Score	Points	Score	Points	Score	Points	Score
Number of part items	0,545	4	2,18	5	2,725	5	2,725	3	1,635
Number of parts	0,545	4	2,18	5	2,725	5	2,725	3	1,635
Number of interfaces	0,818	2	1,636	2	1,636	1	0,818	3	2,454
Manufacturability	0,818	4	3,272	3	2,454	3	2,454	3	2,454
Serviceability	0,636	3	1,908	3	1,908	3	1,908	3	1,908
Logistics	1	5	5	3	3	4	4	3	3
Weight	0,182	3	0,546	2	0,364	2	0,364	3	0,546
Cooling power scalability	0,909	3	2,727	1	0,909	2	1,818	3	2,727
Sealability	0,636	2	1,272	1	0,636	1	0,636	3	1,908
Appearance	0,364	3	1,092	2	0,728	2	0,728	3	1,092
Novelty of solution	0,091	3	0,273	2	0,182	2	0,182	3	0,273
	Total points	**36**		**29**		**30**		**33**	
	Weighted score		**22,086**		**17,267**		**18,358**		**19,632**
	Rank	**1.st**		**4.th**		**3.rd**		**2.nd**	

1 = clearly worse than the original, 2 = worse than the original , 3 = equal to the original, 4 = better than the original , 5 = clearly better than the original.

The results indicate that the component-sharing concept was clearly more potential compared to the others, by achieving the highest weighted score and total points. Moreover, the component-sharing concept scored better than the current version, which makes it potential for further development. The original version was scored better than the hybrid concept, which in turn, took the third place with slightly higher weighted score than the adapter concept.

3.8 Recommendations for utilizing alternative jointing methods

The implementation of the component-sharing concept requires new design, which in turn provides an opportunity to replace welding with alternative jointing methods at the same design process. The implementation of alternative jointing methods would require more detailed virtual models. Therefore, a complete implementation can-not be done in this study, due to its limited timescale and scope as a master's thesis. However, recommendations for replacing welding in further development can be given.

As shown in the literature review welds can be replaced with mechanical joints. Also, hybrid jointing can be recommended in situations, where waterproofness was required. Mechanical joints turned out to be strong and durable enough to be applied in an entire structure, except in few highly loaded components, such as lifting lugs and mounting brackets, where the welding is the optimal solution. Overall, screw and rivet joints turned out to be the most optimal solutions for the structure. The screw joint is better for situations where the space requirements for assembly are stricter, and the rivet joint is better in situations where the space requirements for fastener head size are stricter.

In further development, detailed design should be implemented to support the properties required by alternative jointing methods. Components have been welded before, should be designed for the specific jointing method. For example, edges of the metal sheet can be welded together without special design, but the mechanical joints recommended in this study require at least holes for the connector, and often a separate flange for the hole.

Reducing the number of joints was proved to be beneficial. It can be done by applying the basic principles of DFMA, reducing the number of components and maximizing the use of the manufacturing processes. In some cases, two separate sheet metal components could be manufactured from a single metal sheet more cost effectively. The time lost in more advanced design pays off in faster installability.

Recommendation for further design is to utilize mechanical jointing methods in a detailed design procedure. Modules can be designed to support either rivet joints or screw joints, depending on the situation. The properties of the joints can be improved with adhesives if waterproofing is required. Connecting the modules together was recommended in previous study by screw joints due to its property of requiring less space in assembly. Moreover, in case of disassembly, the screw joint is easier to open.

4 ANALYSIS

The results presented in previous chapter are analyzed in this chapter. In addition, the cost estimation for component-swapping concept is introduced and the fulfillment of the requirements and objectives of the study are presented.

4.1 Development process and results

The concepts developed in this study were modular by their own way. Some of them came outside the conventional approach, for example the adapter concept and the abandoned component-swapping idea. Most of the concepts did not fit perfectly to their modularity typology, but however, the ideas of potential candidates were derived from them. The restrictions for design were so strict that totally new solutions could not be developed. However, three considerable concept ideas were developed and one of them turned out to be clearly more potential than others, including the current solution.

The requirements for the design were set carefully at the beginning of the work, which resulted into situation, where aspects like numbers of components, modules, interfaces and general overall simplicity were considered as a guideline and measure of successful design. These drivers were considered to reflect automatically in other important aspects, such as logistics, manufacturability and installability.

The importance of comparing the importance between these criteria was understood after the concepts were developed, and therefore some of the aspects were weighted too much in the design. The literature review emphasized little too much the importance of pursuing the increased volume advantage from modular product architecture, which turned out to be relatively less important in this application. The result probably would not be different if the importance between criteria were defined earlier, but it could have been useful information during the work.

The comparison between evaluation criteria were carried out by a group of experts. Important application specific perceptions were found out. The importance of facilitated logistics turned out to be greater than assumed in this application, and therefore relatively great benefits can be achieved with improved logistical properties. Achieving equally large benefits with other approaches would require a lot more effort in design.

The scoring method turned out to work well. In addition, comparing the concepts to the original solution turned out to be beneficial. It facilitated the comparison by providing a clear concrete reference. At the same time, easily comparable points were obtained for the current solution as well. This reference-based scoring method also facilitated the scoring process in situations, where the evaluation criteria were not based on quantitative results. In these situations, where the decisions had to be done based on qualitative results, the scoring was easier due to concrete reference. The evaluation criteria proved to be appropriate and they covered all important areas well. The scoring process was implemented also separately from current solution with other scaling scale. The results remained the same, except the distribution was slightly different. According to that, the validity of scaling can be assumed to be reasonable.

Three most important evaluation criteria were logistics, cooling power scalability, manufacturability, and the number of interfaces. The component-swapping concept gained the best points from all these three criteria, compared to other concepts. The concept which can be divided into reasonable size and shape modules gets proper score on logistics. In terms of cooling power scalability, the structure with frame-length specific modules guarantee an optimal scalability. In terms of manufacturability, all concepts are roughly similar, except that the component-sharing concept and hybrid concept provides an opportunity to utilize alternative jointing methods for welding. Component-sharing differentiates positively from others by its adapter free structure, which does not require any cumbersome adapters.

The greatest decrease in the number of part items and parts were obtained by both concepts that were equipped with adapters. These criteria turned out to be not as important as expected during the design process. These aspects were expected and also proved to provide better logistics, manufacturability, etc. as side-benefits, but the effect was small.

The overall results showed that the component-sharing concept was scored clearly the best, which proves that the concept is the most potential concept compared to others. Moreover, scoring better than the current solution proves that the component-sharing concept has potential for further development. The difference in scoring between the two other concepts were relatively small but clear. It may be assumed that the ranking between these two adapter equipped solutions might be ended differently if the evaluation would be implemented differently.

Overall, the methods were suitable for this study, but required little freedom for the designer due to the need to remain inside its boundaries. The concept development process, defining the numerical results and comparison of the concepts were partly based on assumptions. Therefore, in further development these assumptions could be investigated more precisely.

4.2 Filling the requirements

The requirements for design and concept were defined in early phase of this work and explained in paragraph 3.2. The design process followed pre-defined guidelines, which were derived from literature review and applied to this subject as far as it was possible. The boundaries covered general requirements to be followed in machine properties, standards, and classifications as well as material properties and surface treatment.

The requirements for machine properties were followed and the concepts were developed to meet these requirements. The standards and classifications were followed in general level by considering these functional properties, such as cooling, and protection in design. Fulfilling these IP classifications and IC codes exactly would require more detail design, which was not possible in the scope of this study. Anyway, the designs are close to current solution, which has proved to fulfill these classifications.

Materials and surface treatment were considered shortly in this study due to the early phase of the concept development. Dimensional requirements were followed by keeping the dimensions close to the original concepts, including the concepts equipped with adapters, whose total heights were a bit higher, but still at an appropriate level. The component specific requirements were followed by using their real dimensions in virtual model.

4.3 Cost estimation

Making an accurate cost estimate for a single top-module is a huge process, so the cost estimate made in this work was a simplified, indicative estimation, based on findings from literature review, experience from original top-modules and tacit knowledge from experts.

A general opinion from the field of welding technology is that engineering costs cover more than half of the total costs of the product. The share of other costs is challenging to estimate. Therefore, in this cost estimation, the other aspects were assumed to share the rest 50 % of the costs by dividing it evenly into five parts, which were costs for materials, manufacturing and assembly, surface treatment, packing, and logistics.

This first half of the product costs was estimated to decrease 30 % due to modular product architecture. That is a moderate estimate according to the literature review, which showed that the change between part-by-part built product and modular product decreased lead time 30…60 % with a median of 45 %. This assumption is supported by the decreased number of part items. The number of overall part items decreased nearly 30 % in component-sharing concept, which correlates directly to the number of part items needed to maintain and manage by engineers.

The material costs could be estimated to decrease 6 %, according to the literature review, where estimates of a change varied between 3 % of increase and 10 % of decrease, with a median of 6 % decrease. The assumption was supported by the reduced number of parts. In the component-sharing concept, the results estimated that the number of parts will decrease over 10 %, which can be expected to correlate with material costs.

The manufacturing and assembly costs can be estimated to decrease 20 % due to the reduced number of parts and part items. The reduced number of parts for single top module decreased over 10 %. Therefore, it can be assumed that the overall manufacturing and assembly costs would decrease 10 % as well, due to the decreased number of parts needed to be manufactured and assembled. The entire product family requires 30 % less part items, due to a higher component sharing rate. This can be assumed to increase production volumes and therefore, decrease the manufacturing costs. The reduced number of part items facilitates the assembly as less unique tools, fixtures etc. are required for the assembly.

The costs for surface treatment, such as painting, could be estimated to decrease 50 % due to a modular product architecture, which provides a possibility for using powder coating, instead of spray painting. A complete top-module is too large for powder coating, but the problem could be solved by coating the modules separately. The powder coating is known to be less expensive than the spray-painting. The spray-painting process requires at least two and usually three layers of paint, when the powder coating can be made with single layer. Moreover, the post processing is simpler in powder coating.

The effect on packing costs can be seen in the easier handling of the modules, instead of handling a complete top-module. On the other hand, packing single modules takes more effort and packing materials. The costs for packing are difficult to define, therefore the changes in packing costs are ignored in this cost estimation.

The largest effect on costs were estimated to appear in logistics, by 67 % of decrease. The modular product architecture allows a product to be transported and storage in pieces, which requires less room and is therefore less expensive. Transporting a complete top-module requires extra wide transport, which is approximately three times more expensive than standard sized transportation. The overall cost estimations are summarized and presented in *Table 14*.

Table 14. Cost estimation for component-sharing concept.

	Share [%]	**Savings [%]**	**Result [%]**
Product development	50	30	35
Materials	10	6	9,4
Manufacturing and assembly	10	20	8
Surface treatment	10	50	5
Packing	10	0	10
Logistics	10	67	3,3
Total [%]	**100**		**70,7**

As the table below shows, the total costs were estimated to decrease almost 30 %, which is a significant change. However, it is important to emphasize that this cost estimation was an indicative assumption, but despite that it shows the potential of the concept for being developed further.

In addition, modularity provides other benefits, that are important to consider. The product family of component-sharing concept includes common modules and variation modules. These common modules, that are shared between frame lengths could be standardized and outsourced in batches. Facilitated transport properties allows outsourcing from emerging markets, which would decrease the manufacturing costs even more. Moreover, if the new concept could be implemented without welding, or at least reduce the amount of welding, the product family would be even more inexpensive to manufacture.

In this cost estimation, the market demand was assumed to be equal between variations. In case of further development of the concept, the variance must be considered. The modularity is mostly beneficial if the marked demand is distributed evenly between variations. If the market demands are weighted mostly on few variations, the modular product architecture may be inefficient when considered to integral product architecture. In such cases, more detailed cost estimations are recommended and keeping the original integral product architecture-based versions in product assortment should be considered.

4.4 Discussion

The restrictions for the platform were strict and therefore limited the freedom of design and novelty of solutions. It is not very surprising due to years of product development work behind the original product assortment. These well-functioning top-module versions are designed by applying integral product architecture and are therefore high-performance products, with relatively high price. Applying modular product architecture into a top-module product assortment turned out to be challenging, but a potential concept was found for further development.

The literature findings were useful in the process of generating the concept idea by offering considerable approaches from typologies of modularity, as well as offering a systematic procedure for concept development. The part of alternative jointing methods resulted in a brief recap of earlier study and pointed out few new details to be considered in the implementation of this concept. Overall, the findings formed a supportive foundation for the development work. Applying the MFD procedure and the integrated framework for modular product development remained shorter due to the limited scope of this study but guided the design for the right direction from the beginning to the current phase.

The concepts developed in this study were reasonable, but only one of them turned out to be truly potential. All the concepts were estimated to decrease the number of components in product family, but the importance of decreasing the number of components turned out to be less important than expected. The requirements for design were defined carefully before the concept designing started, but their importance should be defined as well. It probably would not have let to different results but could have been useful during the work. The results analysis pointed out that this study missed one important criterium related to costs. That is the measure for required engineering work to maintain the product family. It was included in the number of items criteria, but it should have be separated into an individual criterion to provide an individual perspective. However, the highest points would probably have gone for component-swapping emphasizing the concept's ascendancy.

The results show that the component-swapping concept is potential for further development, which can be recommended to start from defining the distribution of top-module market demand. How evenly the market demand for each top-module variation distributes, and are there clear differences? The answer should be considered before further development. If one top-module variant is clearly best-selling, keeping that variant in the product assortment may be reasonable. The development of this concept may be continued by following the next steps in MFD procedure and integral framework for modular product development. In addition, a deeper analysis of concepts and cost estimations would be recommended with a greater number of interdisciplinary experts to ensure the reliability.

5 CONCLUSIONS

The aim of this study was to develop a modular top-module platform concept that could be used as a base for further development. The study introduced a potential concept that meets these requirements. Moreover, according to cost estimations, the concept would decrease the total costs effectively. Another objective of this study was to define how the alternative jointing methods could be utilized to replace time consuming welding from top-module manufacturing. This study was made for finding answers to research questions listed below.

1. How the modular platform concept would reduce total costs?
2. How the modular platform concept should be implemented?
3. How the alternative jointing methods should be utilized to replace welding?

The answers for research questions were found. The modular platform was able to reduce the total costs by improving the product assortment towards a product family with an easier management, the total costs are reduced due to decreased lead time in product development, manufacturing, and assembly. Increased economics of scale will reduce also material costs and the modular product architecture provides significant benefits in surface treatment and logistics. Overall, the costs were estimated to decrease by 30 % using this concept.

The modular platform concept should be implemented by splitting the top-modules into reasonable size and shape modules, with simple and clear interfaces, without harming the functionality. It can be done by applying component-sharing modularity typology to original design, with changes that increase the component sharing rate and facilitate the manufacturing by replacing welding.

The alternative jointing methods should be utilized to replace welding in further development by designing the sheet metal parts suitable for mechanical joints. Screw joint and rivet joint were selected to be suitable for most of the joints. In some special cases, welding may be the optimal solution. The implementation should be made by following the basic principles of DFMA to achieve the maximum benefit. The effort put in more advanced design will pay off in improved installability properties.

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Technical data of concept designs

	Original				**SUM**
Data for single top-module	IC0A1	IC0A6	IC8A1W7	IC8A6W7	
Module items	1	1	1	3	6
Modules	1	1	1	7	10
Interfaces	1	1	1	3	6
Adapters	0	0	0	0	0
Additional cover plates	0	1	0	0	1
Data for product family					
Variations (top module)	5	5	5	5	20
Module items	5	5	5	6	21
Modules	5	5	5	7	22
Adapters	0	0	0	0	0
Additional cover plates	0	1	0	0	1
	Component-sharing				**SUM**
Data for single top-module	IC0A1	IC0A6	IC8A1W7	IC8A6W7	
Module items	3	3	2	2	10
Modules	5	5	3	3	16
Interfaces	5	5	3	3	16
Adapters	0	0	0	0	0
Additional cover plates	1		1		2
Data for product family					
Variations (top module)	5	5	5	5	20
Module items	16		7		23
Modules	17		9		26
Adapters	0	0	0	0	0
Additional cover plates	1		1		2

Technical data of concept designs

	Adapter				**SUM**
Data for single top-module	IC0A1	IC0A6	IC8A1W7	IC8A6W7	
Module items	2	2	2	3	9
Modules	2	2	2	4	10
Interfaces	2	2	2	4	10
Adapters	1	1	1	1	4
Additional cover plates	0	0	0	0	0
Data for product family					
Variations (top module)	1	1	1	1	4
Module items	2	2	2	3	9
Modules	2	2	2	4	10
Adapters	5	5	5	5	20
Additional cover plates	0	0	0	0	0
	Hybrid				**SUM**
Data for single top-module	IC0A1	IC0A6	IC8A1W7	IC8A6W7	
Module items	4	4	3	3	14
Modules	6	6	4	4	20
Interfaces	6	6	4	4	20
Adapters	1		1		2
Additional cover plates	1		1		2
Data for product family					
Variations (top module)	2	2	2	2	8
Module items	5		4		9
Modules	6		6		12
Adapters	3		3		6
Additional cover plates	1		1		2

APPENDIX II

Exploded view of concepts