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IDENTIFYING MEANS TO IMPROVE THE MANUFACTURABILITY OF MARINE FEEDER-BOOSTER FUEL SUPPLY UNITS USING COMPETITIVE BENCHMARKING, REVERSE ENGINEERING AND THEMATIC INTERVIEW

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TIIVISTELMÄ

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Merialan polttoainekoneikon valmistettavuuden parantamiskeinojen tunnistaminen käyttäen kilpailijavertailua, käänteistä suunnittelua ja teemahaastattelua

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Tämä diplomityö on tutkimus laivan polttoainekoneikon valmistettavuutta parantavien menetelmien tunnistamiseksi. Toimeksiantajayritys Auramarine Oy tavoittelee tuotteidensa valmistettavuuden parantamista kilpailukyvyn kohentamiseksi ja tuotannon pullonkaulojen lievittämiseksi. Tutkimuksen tavoitteena on löytää suunnitteluratkaisuja, joilla polttoainekoneikon valmistettavuutta voidaan parantaa paikallisesti toimeksiantajan tilanteen, tuotannon ja tuotteiden ominaispiirteet huomioiden. Tutkimus on rajattu koskemaan ainoastaan toimeksiantajan valmistamia merialan polttoainekoneikkoja.

Tutkimuksessa käytetään kilpailijavertailua (benchmarking) ja käänteistä suunnittelua (reverse engineering). Menetelmillä tutkitaan vertailtavien tuotteiden eroavaisuuksia toimeksiantajan tuotteisiin ja tunnistetaan valmistettavuuteen myönteisesti vaikuttavia eroja tuotteiden suunnitteluissa. Havainnoinnin laajentamiseksi, analysoinnin syventämiseksi ja hiljaisen tiedon hyödyntämiseksi käytetään lisäksi teemahaastattelua. Haastateltavat ovat toimeksiantajan työntekijöitä eri osastoilta, joilla on laaja ymmärrys ja pitkä kokemus merialan polttoainekoneikoista.

Tutkimuksessa havaittiin eroavaisuuksiksi polttoainekoneikon sisään- ja ulostuloputkien yhteiden sijoittelu, koneikon rungon mittasuhteet, sähkökaappien toteutus ja asennustapa, lämmittimien asento, eristeet sekä syöttöpumppujen asennustapa. Lisäksi hiljaista tietoa hyödyntäen mahdollisiksi kehityskohteiksi tunnistettiin polttoainekoneikon rungon leveys, instrumenttien ja instrumentointilinjojen suunnittelu, tuotekategorioiden ja modularisoinnin soveltaminen koneikoihin, ehdot ja tavoitteet putkistosuunnittelussa sekä koneikon rungon rakenne. Tutkimustuloksena esitettiin ehdotuksia yhteisiin, rungon leveyteen, instrumentoinnin suunnitteluun, tuotekategorioiden ja modularisoinnin hyödyntämiseen sekä putkistosuunnittelun ehtoihin ja tavoitteisiin.

ABSTRACT

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Identifying means to improve the manufacturability of marine feeder-booster fuel supply units using competitive benchmarking, reverse engineering and thematic interview

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This master's thesis is a research for identifying means to improve the manufacturability of marine feeder-booster fuel supply units. The client company Auramarine Ltd. desires to improve the manufacturability of their products for better competitiveness and relieving the production bottlenecks. The research objective is to identify design solutions which can be used to improve the client's manufacturability locally considering their circumstances, production and the particularities of the products. The research scope is restricted to the client's marine feeder-booster fuel supply units only.

The research uses benchmarking and reverse engineering to study the differences between the client's products and the benchmarks and to identify the differences with positive impacts on the manufacturability in the designs of the products. For expanding the perceptiveness, deepening the analysis and utilizing silent information, thematic interview is also used. The interviewees are the client's employees of the from different departments, who have a wide understanding and long experience of the marine sector.

The differences identified in the research are the positioning of the inlet and outlet pipe connections of the feeder-booster unit, proportions of the unit's frame, implementation and installation of the electrical enclosure, orientation of the heaters, insulation material and installation of the feeder pumps. In addition, the width of the feeder-booster unit's frame, design of the instruments and instrumentation lines, usage of product categories and modularization with the units, pipe design limitations and objectives and the unit's frame build were identified as possible development subjects from the silent information. As a result of the research, suggestions regarding the connections, frame width, instrument design, usage of product categories and modularization and pipe design were made.

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LIST OF SYMBOLS AND ABBREVIATIONS

AMB	Auramarine feeder-booster
-M (together with AMB)	Marine
-Mc (together with AMB)	Marine compact
DFMA	Design for manufacturing and assembly
GMA	General Morphological Analysis
HFO	Heavy fuel oil
IMO	International Maritime Organization
MDF	Marine diesel fuel
MGO	Marine gas oil
SECA	Sulphur emission control area

1 INTRODUCTION

This research is a competitive benchmarking and reverse engineering research aiming to identify the means for improving the manufacturability of marine feeder-booster fuel supply units by developing the mechanical design of the pipelines and layout of the units. The research is commissioned by the fuel systems expert company Auramarine Ltd. (later "the client" or "Auramarine") who has recognized a need for better manufacturability of their products in order to enhance the competitiveness factors of the products in the market. Better manufacturability leading to simpler design of the feeder-booster units is also desired for improving the usability and service friendliness of the units.

1.1 Motivation for developing the manufacturability and design of the marine feeder-booster fuel supply units

The motivation behind this research is in improving the competitiveness of the products of the client company by optimizing the expenses and smoothness of the production phase. To achieve this, the manufacturability of the feeder-booster units is desired to be made better by simplifying the mechanical structure of the unit's pipeline and frame. Broader availability of manufacturing methods is an expected consequence, which in turn enables adopting the manufacturing method with the most suitable cost efficiency.

1.1.1 Introduction of the client company

The client company Auramarine Ltd. is a 45-year-old technology firm who specializes in fuel systems for both marine and power plant industries. The company is part of the Hollming group and has its headquarters located in Lieto, Finland, with an approximate of 50 people employed. Auramarine's fuel system hardware is used worldwide with over 14 500 units delivered so far and representative network extending all the way to 25 countries. (Auramarine 2019a.)

Auramarine was founded in 1974 as a subcontracting and design service collaborator for the shipbuilding industry and cargo handling. In the following years the operation shifted more towards auxiliary fuel supply units, resulting eventually to the discontinuation of mineral oil separators and cargo handling products in the 1980's. Major ownership of the company was acquired by the family company Hollming and a subsidiary company established in China in 2001 for closer customer relationships in the Asian market. By the autumn 2019, Finnish production has been outsourced to subcontracting companies, the and Chinese production facility focuses solely on assembly and testing of the products, while the parts manufacturing has been outsourced, as in Finland. (Auramarine 2019b.)

1.1.2 Different marine fuel oils and auxiliary units

The marine diesel engines can run on various types of fuel oils, which differ from each other by their chemical composition and properties affecting their processing requirements. Two typical fuel oil categories are the high viscosity heavy fuel oils (HFO), such as ISO 8217 standard residual fuels, and low viscosity, low-sulphur content marine diesel fuels (MDF), like ISO 8217 DMA often referred to as MGO (marine gas oil). The main differences between these two categories are their sulphur contents and viscosity levels in certain temperatures. The seaborne sulphur emissions are highly regulated in several areas around the globe known as sulphur emission control areas (SECAs). The viscosity of the fuel, in turn, must be carefully controlled by adjusting the temperature of the fuel in order to maintain safe and correct operation of the engine. Too low viscosity leads to trouble with injection pressure and lubrication properties of the fuel oil, while too high viscosity would cause trouble with the engine and components. (Auramarine 2018a, pp. 2-3.)

Regarding the sulphur emissions and the usage of sulphur-rich fuels, it must also be noted that a global emission cap has been directed by the International Maritime Organization (IMO). From the beginning of 2020 onwards, all ships must be run on fuel with a maximum of 0,50 % (mass-by-mass) sulphur content when outside of the even tighter SECAs. Alternatively, fuels with higher sulphur content may be used even after 2020, provided that the ship has an exhaust gas cleaning system, also known as “scrubbers”, installed. (International Maritime Organization 2019a, pp. 1-3.)

The products studied in this research are the marine feeder-booster fuel supply units (later “booster” or “booster unit”) often called simply “boosters” in the colloquial conversations. The products are skid-mounted auxiliary units that treat the used fuel to fulfill the strict condition requirements determined by the associated engine, such as viscosity, injection pressure and filtration degree (Auramarine 2019c). An example of an Auramarine feeder-booster fuel supply unit is illustrated in figure 1.

The booster units considered in this research are labeled as AMB-Mc or AMB-M, followed by a number indicating the unit size. In the abbreviations AMB stands for Auramarine feeder-booster, while M means marine and Mc is short for marine compact. Additionally, there are other auxiliary marine units produced by Auramarine, but not directly regarded in this research, such as cooling units (ACU), modular chilling units (AMC), fuel selectors (AFS) and the like. (Auramarine 2018b pp. 5, 9, 11.)

Figure 1. A marine feeder-booster fuel supply unit (AMB-M) by Auramarine (Auramarine marketing materials 2019).

In short, the booster units feed fuel to the engine(s) of the vessel, be it the main engine of the ship, an auxiliary engine, or both. For standardized units, the power limit of the supplied engine is 60 MW, although solutions for engines with power levels above that are available at custom request. In dual fuel usage (HFO and MDF), the fuel supply system first adjusts the intake to the selected fuel type using a three-way changeover valve. The fuel flows through a suction strainer to the first pump, known as feeder pump, which passes the fuel to the deaeration tank. There it is mixed together with the return fuel from the engines, equalizing pressure and temperature variations in the fuel. If the booster is built with a cooler unit (for MDF), it is installed to treat the fuel at this phase. Next in line is the booster pump, which pumps the fuel, further increasing its pressurization before flowing through the fuel heaters, where its temperature is adjusted to correspond the injection viscosity requirements. The heaters use steam, thermal oil or electricity as their source of heat. The final component of the system is the automatic filter, used to remove remaining impurities from the fuel before injection to the engine. The component comes with a pressure difference indicator to signify possible faults or clogging of the filter. Figure 2 demonstrates the fuel flow in a typical marine feeder-booster fuel supply unit. (Auramarine 2018b, pp. 4-9.)

1.1.3 Regulation in marine business

The maritime sector is heavily regulated, most importantly by IMO, Classification Societies and national or regional directives. IMO is a global agency operating under the authority of the UN and focuses on the safety and security of international shipping as well as the environmental wellbeing in the business (International Maritime Organization 2019b). The national or regional regulating is ruled by institutions like the European Parliament or local governments and appear in the forms of standards and directives, such as the Pressure Equipment Directive (PED). Finally, certain customers may have their own requirements or standards, which must also be satisfied according to what is agreed.

The Classification Societies, also known as “Class Societies” or simply “Class”, are local corporate bodies who focus on the condition and quality of sailing vessels. They also offer expert services and assistance to the maritime industry and other regulatory bodies in the field. The classification system was originally developed by insurers to evaluate and register the conditions of the vessels. The International Association of Classification Societies (IACS) is a union of twelve Classification Societies, who together class more than 90 % of all cargo carrying tonnage worldwide. IACS is also recognized as a consultative agent of IMO. (International Association of Classification Societies 2015, pp. 3-4, 16.)

In practice, the Classification Societies are involved from the design phase onwards through the full lifespan of a vessel. This includes inspection-like reviews and clarification requests at intervals, where elements such as the ship’s hull, anchors, chains and winches, cargo bay hatches and the like are subjected to assessment. Regarding the client company, the most important portion of the inspected systems is the propulsion, more specifically the engine and transmission, to which the fuel supply system and its piping belong as well. (Sillanmäki 2019.)

In the classifications, the fuel supply system is part of the engine’s piping system, which consists of the pipes and components together. The properties subjected to inspection within the fuel piping system are whether there are any leaks, proper functioning of the system, as in will it pump the fuel and treat it correctly, and the triggering of alarms under the right circumstances. One detail amongst others is the wall thickness of the pipes, the preconditions of which are in correlation with the used material. (Sillanmäki 2019.)

According to certain Classification Societies, the piping system must be subjected to the redundancy principle. For example, the Classification Society DNV GL (2018, p. 8; 2019, p. 46) defines this so that in the event of a system failure, the functioning of the system must be able to continue operating or restore its functionality within a set time frame. The redundancy types considered in the definition are divided into four categories based on lag times with an additional “not defined” -type for an undefined period of time. The redundancy requirement can be satisfied, for instance, by having two pump systems to switch between, or two fully independent systems for the same function. This is the reason some components are provided in pairs in figure 2: to maintain the safe functioning of the system in case of a component failure and during maintenance procedures, like the redundancy principle demands.

The fuel supply system is an essential appliance within the ship’s engine setup, since it affects whether the ship can be steered and controlled. Unlike the fuel supply system itself, however, its frame of the module isn’t that interesting to the classification societies or other authoritative parties. The piping, as it contains pressurized, flammable fuel, is of utmost importance. The frame on the other hand is a supportive structure, which is not regarded in the classifications. However, the customers could have their own specific requirements to the frame build, such as rigidity, welding class or paint layer thickness. (Sillanmäki 2019.)

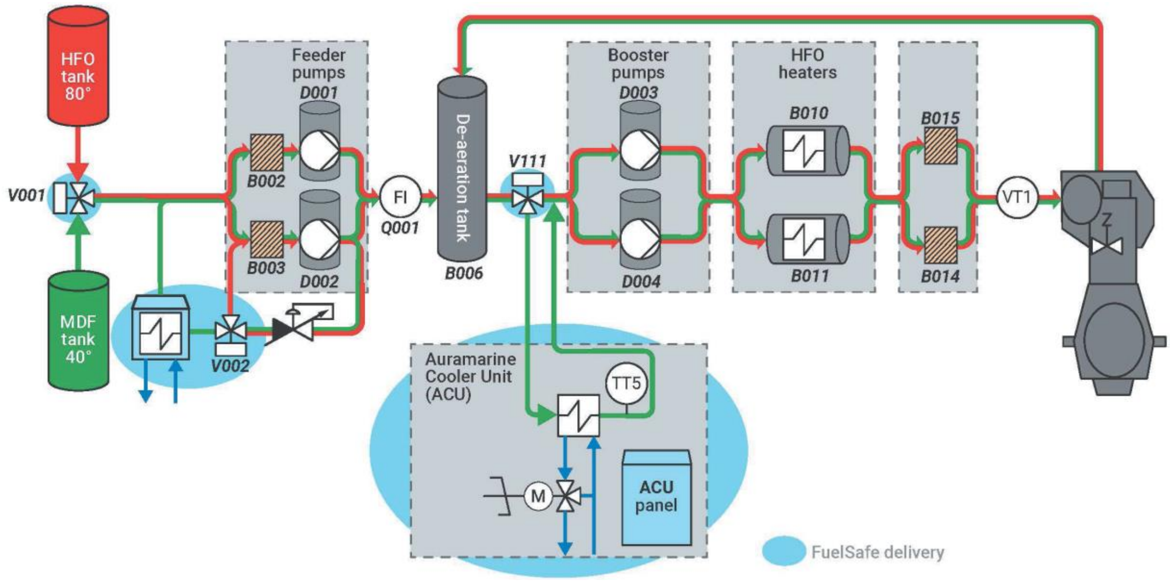

Figure 2. A process chart explaining the flow of different fuel types in a customary marine feeder-booster fuel supply unit (Auramarine 2018b, p. 8). Components provided in pairs are for maintaining the safe functioning of the system in case of a component failure and during maintenance procedures.

1.1.4 Recent development of the products in the client company

As the client has been selling skid-mounted auxiliary marine units for decades already, the development of the units has been ongoing for a long time. Therefore, adjustments have been made before this research as well and some of them even quite recently. The newest interventions affecting the mechanical structure and manufacturability of the products, to mention some, have been establishing the standard product category and, as a part of a recent booster redesign project, removing the dual-sided inlet and outlet pipe connections and designing a new sheet metal frame model.

The new product category, the planning of which begun in 2014, is a category for more standardized products sold by the client. This category was established to reduce the need for tendering documents to be accepted by associated designers each time an offer was made, but rather maintain accurate and up to date documents available on demand in the company's data systems. This development also led to some cultural changes in the company's working community and resulted in the first initial ideas of a sheet metal frame design to spark up. (Pair interview 2019.)

The dual-sided inlet and outlet pipe connections design consists of horizontal pipework stretching both ways across the booster unit at the bottom of unit, allowing the inlet and outlet connections to be installed from either side of the unit. This results in a neat look of the connections interface and eases the designing of the pipelines outside the booster itself. On the other hand, it increases the booster curb weight and costs related to the manufacturing of the pipes, since more piping material and branching is required. It can also result in excessive piping lengths, since in worst case scenario the shipyard may route the piping back right past the component from which the inlet or outlet pipe originates. It has also been noted in the client company that no competitor has similar dual-sided connections design, and, consequently, the first boosters without the said design were made by Auramarine in 2019. (Pair interview 2019.)

The sheet metal frame is a frame design made using sheet metal parts. This design takes advantage of modern manufacturing methods, such as laser cutting, resulting in less parts and reduced weight. This change was devised and implemented concurrently with removing the dual-sided inlet and outlet pipe connections design, from 2016 to 2019. (Pair interview 2019.)

1.1.5 Past events leading to the need of improving the manufacturability of the marine feeder-booster fuel supply units

The manufacturing efficiency of the piping of the products in the client company took a huge leap towards better in 1997, when innovative branching and bending technologies got taken into use (Auramarine 2019b). Since then, the pipelines have been made using special tools and machinery with positive experiences and results. By utilizing these sophisticated methods, the need for later processing stages, such as welding and finishing, was reduced and they were made less laborious.

However, as time has passed and the approach to the booster unit production has evolved, the manufacturing of the units has been outsourced increasingly. With a diverse array of collaborators and the desire to expand the selection of subcontractors ever more, comes the growing pressure to make the manufacturability better and less demanding. Almost as to emphasize the mentioned pressure even further, an unforeseen failure of a critical production device recently took place. This forced the client to react swiftly to the situation and take rapid actions to maintain smooth production despite the setback. With limited range of contractors and piping design which requires extensive finesse in manufacturing, this proved to be no easy task.

Meanwhile, monitoring the competitors has also brought to awareness the contrast in the mechanical appearance between some of the rivaling products and those of Auramarine's. There seems to be different feasible designs for structure of the booster when compared to the ones used at the client so far. Together with the intent to prevent complications like the one described above from incurring again in the future, this has led to the decision to research the potentialities for improving the manufacturability of the boosters with competitive benchmarking and reverse engineering.

1.2 Research problem

The core issue to be researched is the potentiality to improve the manufacturability of the marine feeder-booster fuel supply units of the client company. Since the possibility of refinement seems conceivable, this possibility is now aspired to be researched with scientific confidence. In the research, the focus should be directed towards the simplicity of the booster's mechanical structure in order to uncover the most production friendly and flexible design(s), while also bearing user friendliness and serviceability in mind. It can be stated that this is a design for manufacturing and assembly (DFMA) research.

The research questions to be answered are as follows:

1. What are the identified differences between the booster units of the client company and the products studied with benchmarking and why?
2. What are the potential areas of development identified from the silent information that could improve the manufacturability of the booster units of the client company and why?
3. Which of the identified designs would improve the manufacturability of the booster units of the client company and why?

The intention of DFMA is to decrease diversity in production and increase the usage of standard parts in order to allow for using common technologies and shared modules for different products. The general recommendations include the use of either symmetrical or clearly asymmetrical features and as few parts as possible. Also being able to feasibly use different manufacturing methods for the same design is advised. (Miles & Swift 1998.) These characteristics shall therefore be the ones pursued in this research as well for manufacturability improvements.

The research is to be carried out by benchmarking the structures and piping configurations of the client's boosters using competing products as points of reference and will consist of investigating the competitor products from available photographs, catalogues and online brochures complemented by thematic interviews with the client's employees to utilize silent information. Reverse engineering methodology is then used to learn from the identified differences and apply the results in the client's boosters. A morphological analysis is planned to be made to review and rank the identified improvement options in an orderly fashion.

One challenge in the research is the domain of the results. This means recognizing the impact of the findings both locally and globally. Solutions that are generalizable as improving manufacturability globally could be unsuitable to the client's boosters, already in use at the client or require so comprehensive research and conceptualization effort that they fall outside the scope of this research. On the other hand, solutions that can be found improving the manufacturability locally at the client can't be generalized to improve the manufacturability globally. This research focuses on solutions and results improving the manufacturability locally at the client company within their production framework.

1.3 Objective

The objective of this research is to identify the adjustments which can be implemented to the client's booster units to achieve better manufacturability regarding the mechanical construction of the unit frame and its piping. Also, if possible, enhancing user friendliness and serviceability in the process is a welcome subsidiary result. In the benchmarking, it is important to examine products from multiple competitors to retain the scientificity of the research and refrain from false conclusions due to inadequate research data. In order to perceive the findings of the benchmarking comprehensively, the observations must be verified with experts from different departments in the client company, such as mechanical design, process design, sales and purchasing.

Once the differences are recognized, they are analyzed using reverse engineering in order to fully understand the influence the differences make to the boosters. The analysis will be done in collaboration with professional designers in the client company to heed all the affecting aspects and limiting factors, such as serviceability and regulations, properly. Positively influencing perceptions shall be recorded and recited in a morphological matrix for easier comparison and evaluation of the findings.

The research is expected to result in well-grounded, validated concept level suggestions of realistic and applicable ideas regarding how to improve the manufacturability of the boosters. The research should be carried out in high enough detail to enable the formulation of the report with proper credibility, so it can be used as a support for decision making in the client company. This written thesis will also serve as the report provided to the client.

1.4 Research methods

In this research, benchmarking is used to identify the relevant differences between the products of various manufacturers and reverse engineering is then applied to the findings in order to understand what’s there to learn and take heed of. The preliminary results are then validated with professional designers using thematic interview and the final results are reviewed with morphological analysis to properly contemplate them.

1.4.1 Competitive benchmarking

The word “benchmark” itself means “a term used in surveying and means a fixed point, i.e. a point – often red – marked out in the bedrock or some other immovable mass. It is used as a reference for establishing altitudes and locations for buildings, and other construction work” (Karlöf & Lövingsson 2005, p. 28). Hindle (2003, p. 8) in turn defines benchmarking as “a way of determining how well a business unit or organization is performing compared with other units elsewhere” and the process, according to his book, is categorized into four classes: internal, competitive, industry and best-in-class benchmarking.

In this research, competitive benchmarking is used, since it positions rivaling companies as reference points. Similarly to what Hindle (2003, p. 9) describes Xerox had done in 1980’s during their famous benchmarking process, also this research is about analyzing the competing products and pursuing new ideas about changing the client’s boosters for better.

Benchmarking is used to identify the factors in the competing products which can be learned from.

1.4.2 Reverse engineering

Reverse engineering in its simplest is duplicating an existing object without any drawings or computer models, using only the object as a source of information. It is basically the opposite of forward engineering, which in turn means the traditional engineering process of designing and implementing a concrete, functional system beginning from abstract, conceptual ideas. Reverse engineering methodology can be used in several disciplines of engineering, such as computer programming, industrial design or manufacturing. (Raja 2008, p. 2; Page, Koschan & Mongdi 2008, p. 12.)

Reverse engineering should not, however, be understood as a synonym to copying a competitor's products. Reverse engineering defines the way information is gained but does not determine what the gained information is then used for (Thayer 2017). The source product is also a subject of choice, depending on the need: whether the project executor's own product is reviewed in order to upgrade the design with the latest technology, or that of a competitor's is used for deriving new ideas and design options (Otto & Wood 1998, p. 231). In this research, reverse engineering is used to gain information and insight for further developing the manufacturability of the client's boosters by recognizing more manufacturing friendly design principles and configurations from competitor reviews.

1.4.3 Thematic interview

Thematic interview is an interview method neither structured nor unstructured, though it is closer to the latter of the two. It is one kind of semi structured interview revolving around key themes instead of pre-made questions or mutual, arranged experience shared amongst the interviewees. The benefit of this method is the detachment from the interviewer's perspective and centralizing on the sentiments of the interviewees instead. The "thematic interview" -term is not popularly used in English language, and the closest similar interview methods are "general interview guide approach" and "focused interview". (Hirsjärvi & Hurme 2015, pp. 47-48.)

The expression “thematic interview” is therefore an informal translation made by the researcher. Thematic interview is used in this research for gaining broader knowledge and understanding of the benchmarking and reverse engineering results as well as the eligibility of the new design ideas on behalf of different departments of the client, such as design and sales. Additionally, this method is also used for gathering and making use of the silent information possessed by the Auramarine employees.

1.5 Scope

This research aims in delivering the means for improving the manufacturability by new design ideas and principles. The research does not directly consider things like manufacturing method decisions, materials used in the booster units or the units’ function definitions. Therefore, the expected result of this research is limited to suggestions and justifications, which need to be regarded together with other influential matters, such as labor and material costs, when ruling future company policies regarding the manufacturing and design doctrines.

It must also be noted that the results of this research are limited to consider the mechanical structure of the pipelines and frame of the booster units. Focusing on finding the means for improving the manufacturability with changes only in the mechanical design of the units, other fields, such as electrical design or process design, are not included in the scope of this research. The views of these fields are taken into account during the research and conclusions, but the research focuses on mechanical design and mechanical engineering. Additionally, the subject of the research is restricted to the casual boosters only. The research does not consider highly customized solutions or products outside the AMB family, be it marine or otherwise.

1.6 Contribution

This research is of notable value to the client company in their decision making and this is also the dominant intention behind the research. The scientific contribution this research provides to the global community, however, is limited, as the research problem is very detailed, and the premises are set decisively by the client company with the current design of their boosters. The results are partially applicable in other products with similar pipework and limited available space, but this must be evaluated case by case.

2 REVIEW ABOUT UTILIZING BENCHMARKING AND REVERSE ENGINEERING FOR IDENTIFYING MEANS FOR MANUFACTURABILITY IMPROVEMENTS

This chapter is a review assessing the usage of the chosen research methods and their applicability for studying the research problem at hand. The review is carried out based on existing literature describing the usage of benchmarking and reverse engineering for comparative investigation considering competing products within a shared field of industry. At the end of the chapter is a summary with the conclusions of the researcher about the suitability of the methods.

2.1 Design for manufacturing and assembly

Design for manufacturing and assembly is a design philosophy that focuses improving the manufacturability and assemblablity of a product by ameliorating its design as well as production plans. It has been estimated that design decisions determine roughly up to 70 % of a product’s manufacturing costs in terms of work time and material usage as well as complexity of the manufacturing phase. Therefore, applying DFMA techniques can greatly influence the profitability of the manufacturing. There are a number of different tools for aiding the implementation of DFMA, such as general design guidelines and dedicated computer software. The guidelines applicable to almost all DFMA situations include rules such as reducing the number and variety of parts and fasteners, using easily distinctive geometries and materials, preventing incorrect assembly by design choices and avoiding excessively accurate tolerances and finishes. (Bogue 2012, pp. 112-114.)

For DFMA to be a fully functional process, besides reviewing a product or its design data, improvement ideas are also needed. In addition to generic ideas originating from general guidelines and design rules, product type specific design solutions should be applied. This research aims to gather inspiration for fresh ideas specific to marine feeder-booster fuel supply units by employing benchmarking and reverse engineering.

2.2 Using benchmarking and reverse engineering for identifying manufacturability improvements

Benchmarking and reverse engineering are used complementing one another in this research. Looking for literature and previous researches regarding the subject, this research is not the first to combine benchmarking with reverse engineering methodology (Vojak & Hatakeyama 2006, pp. 287-288), although a research closely similar to this one could not be found. Finding previous researches combining benchmarking and reverse engineering was expected, since both methods are conceived as redesign process steps (Otto & Wood 1998, p. 226).

Otto and Wood present a redesign methodology to support product evolution and state that reverse engineering is an additional step in product redesign process when compared to designing a new product. The methodology also incorporates benchmarking as a part of the reverse engineering procedure: using similar products or technologies as a point of reference yields, on its part, the information required for forming the engineering specifications. The article eventually concludes in claiming this kind of structured approach to redesign being beneficial and supporting collaboration amongst experts and that it should therefore satisfy the industrial companies' need for an effective product development practice. (Otto & Wood 1998, pp. 226, 237, 242.) Vojak and Hatakeyama in turn proclaim reverse engineering as a substantial component of competitive benchmarking, and as such, a notable tool for improving a company's products and / or processes (Vojak & Hatakeyama 2006, p. 288).

Lefever and Wood recognize reverse engineering most commonly used as a redesign method. However, they also list benchmarking, competitor evaluation and cost reduction, amongst others, as possible purposes for applying reverse engineering, and design for manufacturing or assembly as a valid focal aspect of the design process. They ultimately conclude the deep comprehension of the product being concealed within the product and unveiling this comprehension a key asset to redesign activities. This is where reverse engineering comes to play: as a tool to begin the unveiling with. (Lefever & Wood 1996, pp. 2-4, 26.)

2.3 Conclusion of the suitability of the methods

Based on the publications referred above, it can be reasoned that the selected methodology should address the research problem in a systematic and convincing manner. Benchmarking and reverse engineering have been used in numerous different fashions in the past, and there aren't any strict defining boundaries how these methods should or should not be used. One thing can be found in common, however, with all the reviewed writings: the reason for resorting to benchmarking and reverse engineering, which is to discover information a product or a manufacturing process encloses within and gain or supplement the insights for design or redesign activities. As this research is exactly a competitor review with the aims in improving the manufacturability and cost efficiency of a concrete product, the description suits this research in every respect.

Although some the cited materials are dated as of today, more modern references could not be found where benchmarking and reverse engineering had been used together for finding means for improvement of a product. However, the methodology presented is still valid for applying for a research such as this one. This review proves that these methods can be used together for complementing each other.

3 METHODS FOR IDENTIFYING MEANS FOR MANUFACTURABILITY IMPROVEMENTS

The research is planned to be carried out by benchmarking the client's marine feeder-booster fuel supply units and their competitor's products and studying the differences with a reverse engineering approach to gain fresh insights for product development purposes. The resulting findings are reviewed and verified using thematic interviews with the client company's employees for harnessing expert insights developed along years of professional working. Also silent information about the development parameters for improving the manufacturability is sought after from the interviews. For better reviewability and to ensure no detail is being ignored, a morphological analysis will be utilized when contemplating the findings. This chapter explains the methodology used in this research in more detail.

3.1 Benchmarking

Benchmarking is the act of comparing one's own performance against that of the others, in a subject area mutual to all parties considered in the comparison. The Merriam-Webster online dictionary defines the verb benchmark as "business: to study (something, such as a competitor's product or business practices) in order to improve the performance of one's own company" (Merriam-Webster Inc. 2019). Improvement and learning must indeed be borne in mind when it comes to benchmarking, lest it might degenerate into meaningless comparison without any real effects or regard towards consistency, pretending progress was made. (Karlöf & Lövingsson 2005, pp. 29-30). It should be noted, however, that the target issue of the benchmarking procedure is not strictly outlined in any sources. In fact, very different things, such as a business' customer service practices, the gaming performance of a custom personal computer setup or a CAD program's nesting algorithm efficiency can be subjected to benchmarking.

Benchmarking can also be described as relative performance evaluation used to learning and discovering fresh perception towards one's own operations. Broadly speaking, it is the comparison of production entities, which can be whole organizations, departments, teams, projects or individuals: anything that transforms similar resources into alike products on a corresponding level. A notable detail is that benchmarking is not limited to comparison between organizations, but rather, internal comparison is a widely used mode of benchmarking as well. (Bogetoft & Otto 2011, pp. 1-2.)

Overall, different sources express slightly different orientations to the idea of benchmarking. The information and research content provider iSixSigma (2019) in turn makes a distinct difference between benchmarking and competitor research, although both are considered equally useful. They see benchmarking as a wider process going on for longer, while competitor research is a one-time arrangement addressing a certain issue. The division between these two is portrayed in table 1.

Table 1. Differences between benchmarking and competitor research (Mod. iSixSigma 2019).

Benchmarking	**Competitor Research**
Focuses on best practices	Focuses on performance measures
Strives for continuous improvement	Bandage or quick fix
Partnering to share information	Considered corporate spying by some
Needed to maintain a competitive edge	Simply a “nice to have”
Adapting based on customer needs after examination of the best	Attempting to mirror another company/process

However, while competitors can be used as the benchmarks in the research, an important notion must be kept in mind: with benchmarking, the orientation should be towards inspiration for creativity and ideas, not imitating and mimicking the competitors. This would be a waste of human intelligence. At its best, the scope of comparison acts as a role model motivating the desire to improve, while the thought of competition induces the enthusiasm and evokes interest in the learning process, leading to effectiveness and competitive spirit. The improvement by benchmarking is pursued by the process of learning. In the learning process, understanding the causality behind the events is of utmost importance. It is not enough to see that someone is doing better, but to understand why and how this is, is the key to initiating true learning. (Karlöf & Lövingsson 2005, pp. 29-30, 32, 35.)

The types of benchmarking can be divided according to the object and the scope of the comparison, like presented in figure 3. The object of comparison describes what part of the company's operations are focused on in the benchmarking process: whether it's the company's performance on a certain sector, measuring how successful strategy a company has or if there is room for improvement in certain process(es) within the company. The scope of comparison on the other hand defines the selection of participants to be compared, which could be between departments inside the organization, amongst leading competitor companies, between all companies involved in a certain function within an industry or generally amidst the best practitioners of a process regardless of the field of industry. As there are such different orientations to it, the correct approaches to carrying out a benchmarking project cannot be limited to just one. (Rostek 2015, pp. 33-34.)

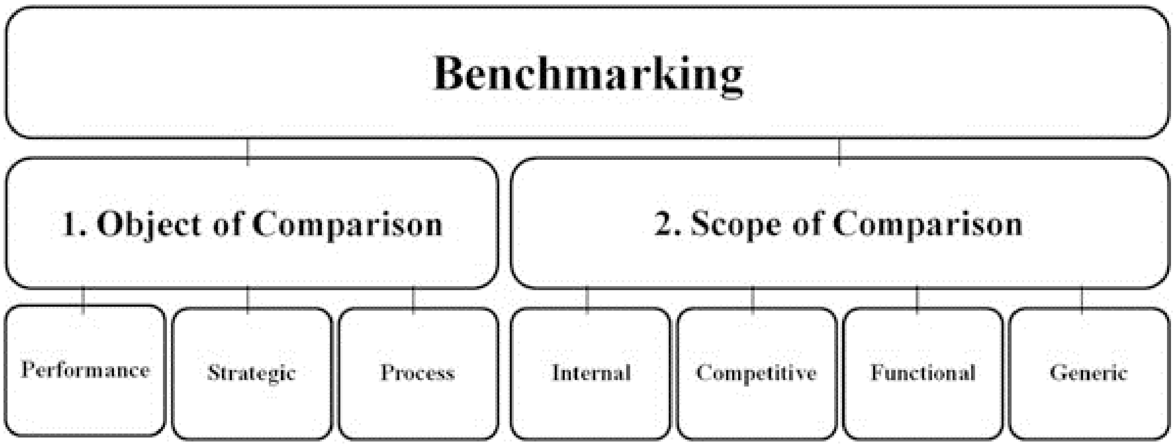

Figure 3. Different benchmarking classes (Mod. Rostek 2015, p. 34).

Rostek also displays benchmarking as a cyclical process comprising of six phases, demonstrated in figure 4. These phases are (Rostek 2015, pp. 35-36):

- Goals planning: Defining the targets and how the successfulness is measured.
- Data gathering: Collecting the required information and specifics for analysis.
- Data analyzing: Systematically going through the outcomes of the previous phase, then validating and verifying the results.
- Changes planning: Based on the outcomes of the previous phase, planning the changes to be implemented.
- Changes implementing: Executing the changes planned in last phase.
- Results reviewing: Evaluating the success of the process according to the measures from the first phase and weighing the next process iteration.

In the definition by Rostek, the inceptive thought and goal of benchmarking is continuous improvement: to always reach for the best practices. In the center of benchmarking is the desire for identifying the highest existing standards regarding the owned products or activities, with the intention to fulfill these standards on one's own behalf. The ultimate goal of the process, then, is the improvement of efficiency, productivity or quality by adapting to the optimal approaches and methods proven by the benchmark group leaders. (Rostek 2015, p. 34.)

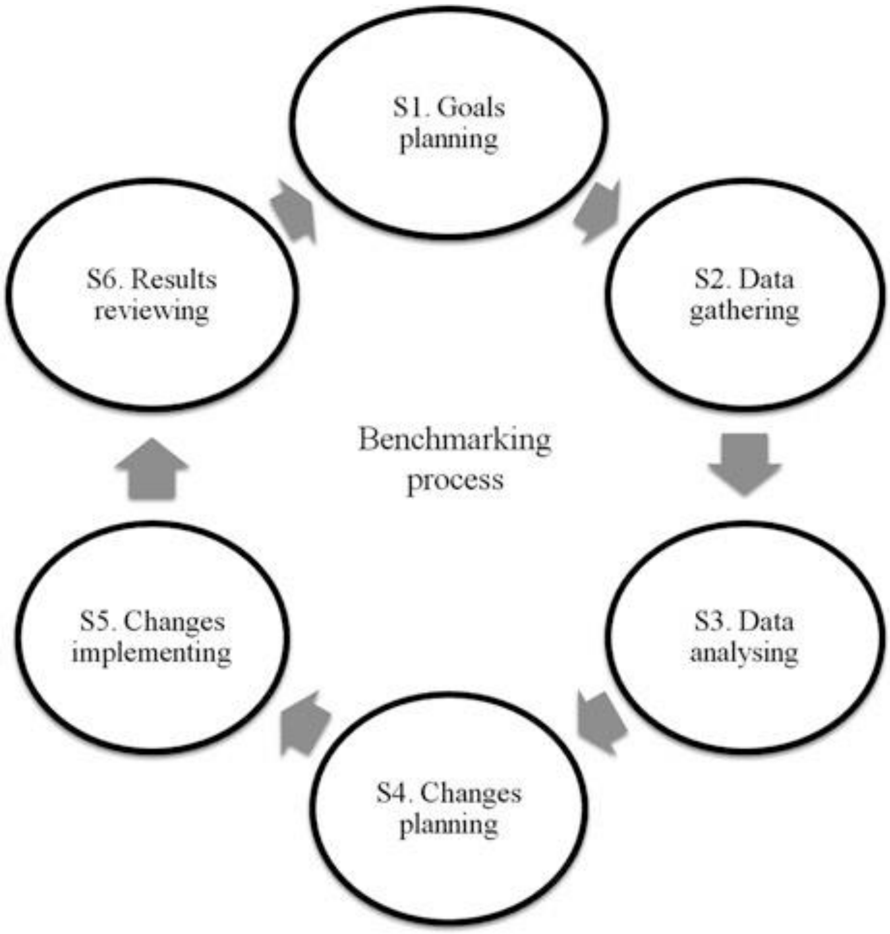

Figure 4. Benchmarking process (Rostek 2015, p. 35). Note that the process is a closed circle and does not finish at the last phase, but rather starts again according to the continuous improvement doctrine.

3.1.1 Overview of using benchmarking in this research

This chapter describes how benchmarking is implemented to reach the goals in this research. As different sources use and emphasize slightly different characteristics while defining benchmarking, each of the above-mentioned definitions are to some extent adopted to this research, while none will be used entirely as described above. Conforming to the sorting visible in table 1, this research uses a combination of benchmarking and competitor research, since the planned research method is not completely consistent with either of the classes. The focus is on best practices and designs, continuous improvement is pursued, but no partnering with any of the benchmark companies is planned. On the other hand, the results shall not be just a bandage or quick fix, as maintaining a competitive edge is unconditional and the primary attempt is to use other companies as a mirror for the improvement of the client's activities.

The inspiration for creativity and process of learning emphasized by Karlöf & Lövingsson are sought after from the benchmarking materials. The goal for this creativity and learning is to identify the means for improving the manufacturability of the client's boosters. For understanding how and why the solutions used in the benchmarks are better, reverse engineering is used.

Of the categorization presented in figure 3, the object of comparison is process, as it aims in improving the manufacturability of a product. The scope of comparison is then competitive, as corresponding processes of competing companies are set as benchmarks. This makes sense, since the client's request is to focus on the manufacturability of the boosters, which for its part is a quite narrow target, and comparable similarities are primarily found within competing products only.

Regarding the Rostek's cyclical process displayed in figure 4 and explained in the listing, the goals planning has already been made in collaboration with the client's representatives. The data gathering shall be conducted by scouring the archives of the client company and seeking and reviewing competitor materials from their publications and websites. Phase 3: data analyzing will be implemented following reverse engineering procedures and morphological analysis. The expected result of this research is suggestions and ideas of product development changes for the client's use, leaving phase 4: changes planning to be done in a follow-up project and phases 5 and 6 falling outside the scope of the research.

3.1.2 Benchmarking materials

Being the easiest to access, specification papers, brochures and other marketing material published by the competitors are a good source of benchmarking data. Available online and collected by the employees of the client on fairs and expositions, the materials contain clean and presentable images of the competing products accompanied by limited technical information, such as performance values and indicative exterior dimensions. While this data is not very detailed and directly usable in technical sense, differences with the client’s boosters are perceivable. Thereby the material can be used as a source of inspiration for design updates, as long as the reasons for the used designs can be analyzed and understood from the materials. Also, other materials collected by the client company, such as of notes and photographs from visits to factories, collaboration companies and vessels, are used for observation if available.

The selection of viable competitors to be considered in the benchmarking process is determined by the client, since they have extensive experience and knowledge of the operators in the business. The raw data and perceptions made from it will be arranged in an orderly fashion for easier analysis later in the research. Also, public materials released by the client won’t be viewed for the benchmarking, since more detailed and informative sources are available in form of non-public photographs and CAD models.

As the researcher is somewhat unfamiliar with the client’s products as well, getting acquainted with them is also in place. This would be most practical by reviewing the ones built at present in Finland, once they have been manufactured and tested but not yet shipped to a customer. The availability of such reviewal event is, in turn, dependent on the state of ongoing orders, as in what and when is being manufactured locally during the research. Photographs and notes shall be taken of the product, should such event take place.

3.2 Reverse engineering

Like with benchmarking, the definitions for reverse engineering from different sources are not entirely congruent. The principal idea of reverse engineering is using an existing product as a source of information for understanding the motives behind its design resolutions. This is also the reason for concluding reverse engineering as a fitting method for this research, since the description is exactly what this research is about: finding fresh inspiration for means to improve manufacturability by surveying similar products with dissimilar designs.

Reverse engineering produces engineering design data by carefully analyzing the target objects. The objective of the process is to compose representations of the system delineating its elements and their compositions and interrelationships. A reverse engineering process is hence carried out conversely to the steps of conventional engineering, starting from a complete product and finishing with the design data encompassed within. This is also the reason the method is known as reverse engineering, as opposed to forward engineering, which is the regular design process advancing from plans to product. (Vijaya Ramnath et al. 2016, pp. 995-996.)

The reverse engineering methodology has several fields and subjects it can be applied to, from computer code deciphering to creating a replacement for a broken part belonging to an old machine outdating computer aided design (Hunwick 2017, p. 41). Raja (2008, p. 3) lists multiple reasons for using reverse engineering, of which the most notable ones regarding this research are analyzing competing products for their advantages and disadvantages as well as finding new ways for improving the functioning of a product. One of the benefits of reverse engineering is shortening the time spent on the product development process by recording the geometry and other properties of a prototype and utilizing them in the redesign process aiming for further improvement (Raja 2008, p. 2).

One purpose for using reverse engineering is to reduce redundancies by carefully analyzing a product and identifying superfluous parts and structures (Lefever & Wood 1996, pp. 9-10). For this, Otto & Wood (1998, pp. 231, 233) introduce a special subtract-and-operate procedure. By operating the product with and without each part or subassembly and comparing the results, it can be determined whether the part is necessary or redundant and understand its subfunction. When tearing down the product, its assemblability is also appraised in the process. (Otto & Wood 1998, pp. 231, 233.)

Lee et al. (1993, pp. 321-322) in turn see reverse engineering as inferring the design process of an existing product, acquiring knowledge about its original design process and using it as an aid for (re)design purposes. They propose using reverse engineering in three stages, which are knowledge acquisition, reconstruction of a default design plan and case-based redesign. Knowledge acquisition is gathering design information that isn't available in documents, but by experiencing the product by oneself. In the reconstruction of a default design plan, a conceptual degree default plan, which is a result of probabilistic series of well-grounded decisions that took place during the actual design, is created. Lastly, the case-based redesign consists of tracking design problems to their origins in the design plan as well as looking for and adapting a similar case from the past to the present problem. (Lee et al. 1993, pp. 321-322.)

3.2.1 Overview of using reverse engineering in this research

This chapter describes how reverse engineering is implemented to reach the goals in this research. None of the definitions for reverse engineering presented above are completely congruent with another. Even so, each description most certainly has something to contribute for carrying out this research, since as much as possible is desired to be learnt from the various designs of the benchmark products. The research data found and narrowed down in the benchmarking phase is subjected to reverse engineering procedures found suitable, depending on the nature, depth and quality of said data. Using visual perception from images and photographs combined with available technical details, design information is extracted from the designs of existing products and its suitability for tackling the design problems in the client's design is evaluated. Appropriate and justified suggestions for improvements are then made based on the reverse engineering results. Keeping design for manufacturing and assembly in mind is pivotal while judging the design information.

From the benchmarking observations, the elements of the products and their compositions and interrelationships are recognized with reverse engineering. Although physical products for geometry recording, disassembly and analysis are not available, the redundancy of the boosters' elements is carefully evaluated. Redundant elements and features of the boosters' mechanical structures are then proposed for removal for improving their manufacturability.

Regarding the definition by Lee et al., finding ingenuity from existing products is at the core of the research. While reconstructing a full design plan would not be worthwhile in this research, understanding the design problems tackled with the used designs on available benchmarks is remarkably important. Also applying the previously used solutions to freshly manifested problems is one of the main intents in this research.

3.3 Thematic interview

The employees of the client company have long and broad expertise of the boosters and the competition in the business, unlike the researcher. Being aware of this, the expertise and silent information possessed by the employees are planned to be drawn from. Silent information could appear in the form of, for example, knowledge derived from experience, professional competence or established practices (Eskelinen & Karsikas 2014, p. 87).

For having the silent information available to be used in the research, it must first be made perceivable by the act of reflecting. This is important for harnessing the latent resources already existing within the company, which can be done in several ways. The methods for reflection include, amongst others, interviews and colleague observation. The interviews, then, can be carried out by using structured interview, semi-structured interview, unstructured interview or group interview. (Eskelinen & Karsikas 2014, pp. 84, 88.)

Interviews in general are well-suited for a variety of research purposes. On the downside, they also generate plenty of irrelevant data and require sufficient preparation and post processing to be reliable. The difference between an interview and a regular conversation is that an interview aims at collecting information in a target-oriented fashion, while the purpose of a conversation could be purely social connection. Characteristic for an interview is that it takes place on the interviewer’s initiative, who also leads the situation and is deliberately curious, even to the point of asking weird questions, while the interviewee can trust the confidentiality of the situation. (Hirsjärvi & Hurme 2015, pp. 34, 36-37, 42-43.)

Semi-structured interviews aren’t defined in a uniform manner, but there are definitions for different kinds of semi-structured interviews, such as the focused interview or the general interview guide approach. Thematic interview also fits into this category, as it is based on the focused interview. By not being limited to just one kind of research, be it quantitative or qualitative, or dictating the required number of interviews made, the thematic interview is well-suited for different kinds of researches. The method emphasizes proceeding around pivotal themes, which liberates the interview from the perspective of the interviewer, allowing for better discerning the views of the interviewees. In thematic interview, the interpretations of matters and meanings given to things by the interviewees is considered important. (Hirsjärvi & Hurme 2015, pp. 47-48.).

Although not referring directly to any specific interview method, Miles, Huberman & Saldaña also justify interviewing with little pre-planned structures and specific instruments in qualitative research, while considering the context important. The risk in detailed arrangement of the interviews is blinding the researcher and obliviously excluding the most important points from the preparations. (Miles, Huberman & Saldaña 2014, p. 38-39.) In thematic interviews, the focus revolves around fixed topics, while the exact questions and their order can vary between individual interviews. However, all the same themes must be worked through with every interviewee and the interviews recorded for later processing. The method well suits cases where the set-up can be revised and redirected by asking more detailed questions as the research progresses. (Eskelinen & Karsikas 2014, p. 85.)

3.3.1 Overview of using thematic interview

This chapter describes how thematic interview is implemented to reach the goals in this research. Firstly, the target is to better understand and perceive the benchmarking materials as well as to detect and find details and differences that would otherwise go unnoticed. This is made possible by the experience of the industry the interviewees possess and the different perspectives the interviewees have due to their positions in different departments of the client company. Secondly, the goal is to utilize the silent information of the interviewees, which they have accumulated in their careers, relations with other professionals and by participating in different projects in the maritime industry. Additional improvement parameters and ideas are sought after from the silent information.

As the interviewees are from different departments and represent different fields of professionalism, it is constructive to emphasize different perspectives with each person. For example, the salesperson has better knowledge of the customer interface and their wishes, while the mechanical designer knows best the details and reasons behind the current design of the boosters and the production representative can share deeper insight about the effects on manufacturability and related issues. This will lead to somewhat different questions being asked from the individual people. However, the intention is to gain as wide knowledge and apprehension as possible of the client's boosters and the benchmark products and their manufacturability and therefore none of the subjects must be ignore or discounted with any of the interviewees.

Finally, after the benchmarking and reverse engineering materials have been investigated thoroughly and the individual interviews carried out to the point that no relevant additional information is available, the results are planned to be verified with a group interview. The interviewees of the group interview consist of the employees from different departments of the client company to widely represent the different perspectives. The goal of this group interview is to validate the preliminary results analyzed from the previous phases of the research and disclose possible missed details that have remained hidden by allowing the interviewees an opportunity to comment, criticize and support each other's views in a dialogic situation.

3.3.2 Silent information

Several of the client's employees possess information of the business in maritime sector accumulated along their careers. This information appears in forms of personal knowledge gained through experiences in their occupation, including participation to company visits, trade fairs and such. These sources should provide information not available by any other means, adding to the amount of potential improvement parameters.

The purpose of the interviews is to expand the profundity and depth of insight in terms of identifying the most useful research data and analyzing it to the fullest. The interviews are planned to be made throughout the whole research, from gathering additional research data possessed by the employees to studying and analyzing the data and making conclusions of the findings.

3.4 General Morphological Analysis and Morphological matrix

Understanding the motivation behind different designs by reverse engineering, the found product data is expected to yield a number of design principles and solutions for different design problems. Different improvement parameters and solutions are also gathered and recorded from the silent information. To review and inspect the findings in an orderly manner and determine the most suitable options for each situation, they must be arranged in a structured way. For this, the General Morphological Analysis (GMA) is selected as a means.

The idea of morphology emphasizes structure and arrangement: how the parts of an object, be it physical, biological, social or mental, create a “Gestalt”: a “whole” that is more than simply the sum of its parts. That being said, the General Morphological Analysis is a method focusing on the structures and relationships between the parts of a problem complex, where each part is assumed to be related to everything else and therefore cannot be ignored per se. GMA has very wide field of applications, being applicable all the way from astrophysics to organizational structures and rocket propulsion systems development. The method is founded on the scientific process of consecutive analysis and synthesis. It can therefore be used for inspecting problems, that cannot be quantified and subjected to mathematical methods, in a reasonable way. If performed correctly and thoroughly, GMA should unveil every solution for each subproblem without favoring one over the others, assisting in recognizing relationships that would have been otherwise ignored as well as the extreme boundaries of the divergent options. (Ritchey 2011, pp. 7-9, 17.)

GMA at its simplest can be implemented by listing the system attributes and subjecting them to consistency checking (Ritchey 2011, p. 4, 11). For implementing GMA in this research, the morphological matrix, also known as “morphological box”, is employed. Morphological matrix, visible at figure 5, is a tool, in which the factors of the problems are registered, and different compilations are reviewed for drafting possible solutions (Moschytz 2019, p. 230). Widely cited Pahl, Beitz, Feldhusen & Grote (2007, p. 94-95) use the morphological analysis as an example of a classification scheme, which they state to be a useful method in design process, as it encourages in finding all the possible solutions comprehensively and assists in noticing the characteristics and combinations of viable overall solutions. A certain realism must be kept in mind when using the classification scheme, however, as not all solutions are necessarily compatible with each other (Pahl et al. 2007, p. 104). To counteract this, they list instructions for proper combining of the solutions in the chart (Pahl et al. 2007, p. 105):

- “Combine only compatible subfunctions.
- Pursue only such solutions as meet the demands of the requirements list and fall within the available resources ---.

- Concentrate on promising combinations and establish why these should be preferred above the rest.”

The description concludes in stating the method being suitable for compiling multiple subsolutions into overall solutions. It can be used for several purposes in different phases of design and production, from constructing working principles at the conceptual phase to planning assemblies at the embodiment phase. (Pahl et al. 2007, p. 105.)

Para-meters	***Possible solutions*** **Element Alternatives**				
Support	Wheels	Air cushion	Tracks	Slides	Spheres
Steering	Turning wheels	Rails	Air thrust		
Stopping	Reverse power	Brakes	Block under wheels	Drag a weight on the floor	
Moving	Air thrust	Power to wheels	Hauling along a cable	Linear induction motor	
Power	Electric	Bottled gas	Petrol	Diesel	Steam
Trans-mission	Hydraulic	Gears and shafts	Belts or chains	Flexible cable	
Lifting	Screw	Hydraulic ram	Rack and pinion	Chain or rope hoist	
Operator	Seated at front	Seated at rear	Standing	Walking	Remote control

Figure 5. A morphological matrix filled with Forklift Truck parameters (Moschytz 2019, p. 237). Note the colored circles denoting compiled sets of possible solutions.

3.4.1 Overview of using morphological analysis in this research

In this research, different design parameters of the boosters’ elements are filled into the morphological matrix based on the benchmarking and silent information findings and proposed solutions based on the reverse engineering results. The problem parameters could be, for example, different frame or layout designs, instrument pipe routings or the positioning and orientation of certain components. The solutions concluded most beneficial in this research are then suggested for implementation and the justification why they are considered most beneficial explained. By finding the optimal combination of alternatives, a refined solution to the problems can be achieved. Also, in addition to studying the solutions found prepared from the benchmarking, room for brainstorming and creativity must also be left when plotting the final resolution. This is because the morphological method does not replace open-mindedness and professional skill (Moschytz 2019, p. 231).

Based on the descriptions in this chapter, the selected methodology suits the needs of this research. The methods complement each other and using methodological triangulation increases the reliability of the methods. Justified and pragmatic means for improving the manufacturability of the client's boosters can be found with these methods. The full research methodology and it's intended usage is visualized in figure 6.

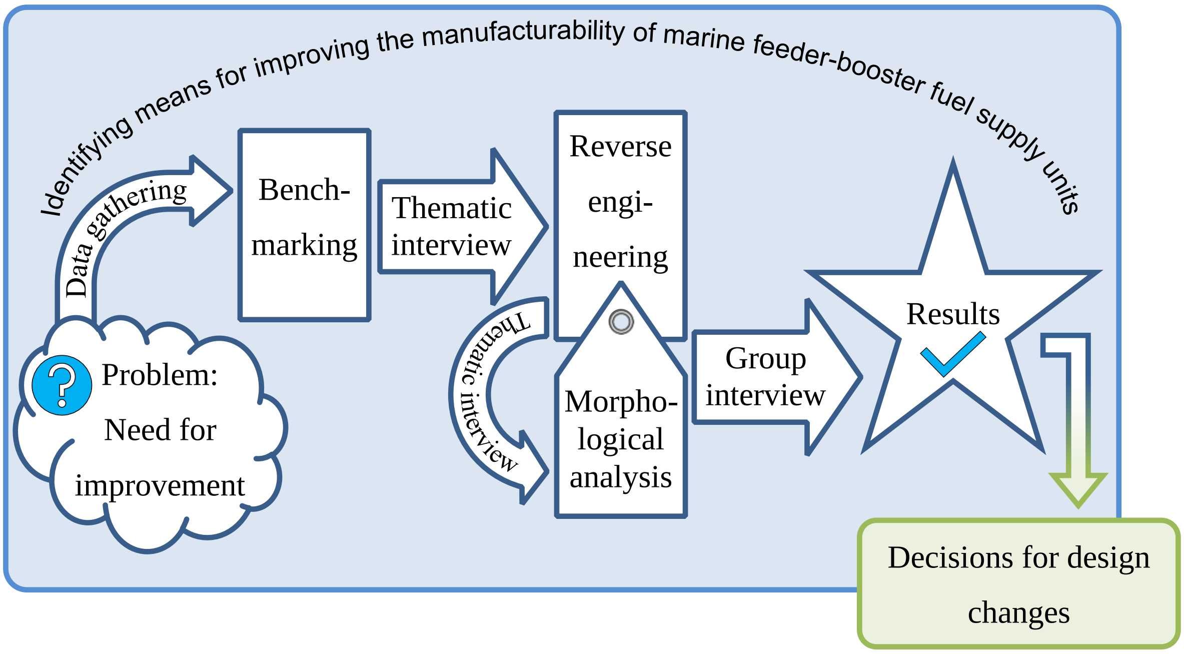

Figure 6. Usage of the chosen methodology in this research. Blue color marks the scope of this research, while green color indicates the launch of expected chain of actions succeeding this research.

4 RESULTS

The research begun with gathering the available benchmarking data. Using the available materials, comparable yet dissimilar details were recognized from the products of several competitors. The findings were then analyzed with reverse engineering and morphological analysis, and finally the analysis was evaluated and validated with a thematic group interview amongst a multidisciplinary team of professionals, all of whom were employees of the client company.

4.1 Benchmarking points of references

The available benchmarking data consisted of perceptions, photographs and video materials gathered by the client company upon factory visits, company visits and vessel visits, such as maintenance and retrofitting checkups, including products from unknown manufacturers, of which only photographs with no reference information from visits were available. Also public marketing materials, such as brochures and visual images, released by the competitors in the past as well as currently available during the research were considered in the benchmarking phase. Thus, the amount, quality and relevance of the materials varies notably between different benchmarks. Following is a short preview of the most notable benchmarks.

Alfa Laval is a Sweden-based company acting in the fields of heat transfer, separation and fluid handling since 1883, their products being used to handle water, carbon emissions, energy usage and food transporting. Their most notable products are utilized in a large scale of applications, from food and pharmaceuticals to mining and refinery, including the marine sector. The company has 42 major production units and more than 17 000 employees around the globe. (Alfa Laval 2020.)

GEA is a company founded in 1881 and headquartered in Germany. The company is known particularly for its food processing technologies, and works in other industries as well, such as pharma, transportation and marine. They have activities worldwide and employ over 18 000 people in total. (GEA 2020.)

Nantong Navigation Machinery Group Co. is a Chinese company with a history dating back to the year 1973. The company manufactures products for several industries, including shipbuilding, electricity generation and metallurgy. Items such as filters, valves and marine modules are both designed and produced by the company. (Nantong Navigation Machinery Group CO. 2017).

4.2 Competitor benchmarking findings

In the benchmarking materials, several comparable subjects with different implementations were found. While detailed comparison between products with precisely similar specifications and properties could not be made, dissimilar design principles and fresh solutions to certain aspects of the client's boosters could be perceived. Of these parameters, the practical ones are also included in the morphological matrix at the analysis phase.

4.2.1 Electrical cabinets and upper frame

The most noticeable difference amongst the comparable products is that not all the benchmark units have an upper frame for electrical cabinet mounting like the Auramarine boosters do. The upper frame is a beam structure with welded mounting plates for electrical cabinets, cables and instruments. This allows for installation of the said equipment above the other components of the booster, also giving it a very distinctive appearance. Figure 7 displays an Auramarine booster unit with the upper frame colored and the rest of the unit grayed out.

While the distinctive upper frame application was not unique to the Auramarine boosters only, other solutions for electrical components arrangement were found in the in the benchmarking materials, too. These solutions are to either mount the cabinets on an independent cabinet rack or redesign the whole electrical assembly into a standalone console installed on the floor level of the unit. These implementations, as seen in a benchmark unit, are demonstrated in figure 8. Different versions of all three ideas were used in the benchmark units, but in general, these were undeniably the observable trends.

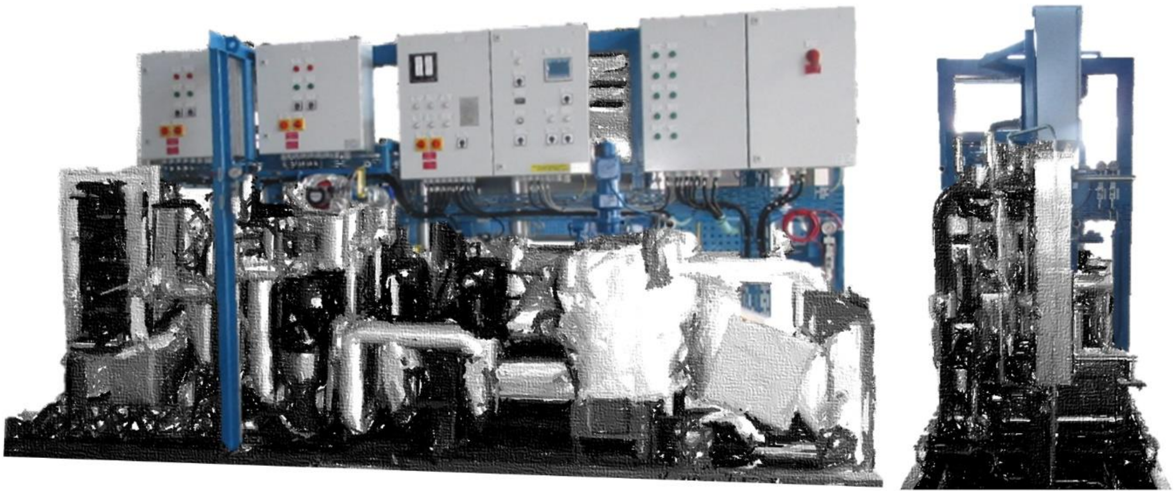

Figure 7. An Auramarine feeder-booster fuel supply unit with the upper frame colored, front and side view (Mod. Auramarine internal archives 2020a).

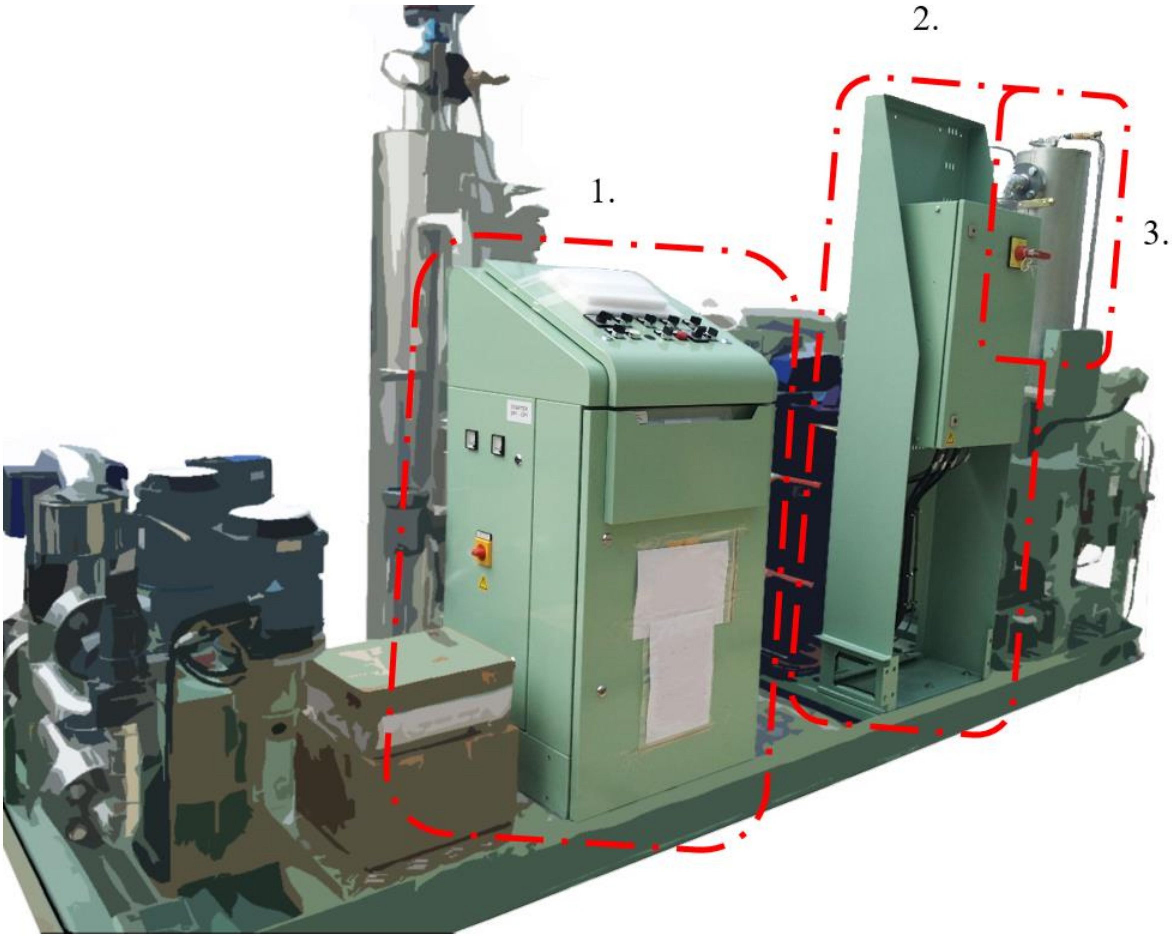

Figure 8. A benchmark unit with standalone electrical console (1), independent cabinet rack (2) and vertical heater components (3) (Mod. Auramarine internal archives 2020b).

4.2.2 Heat insulation

Some of the pipelines and components handle heated media and are therefore insulated. The differences in the used insulation materials caught the eye of many interviewees when the benchmarking materials were shown to them. In short, the insulation material could be divided into soft and hard materials. In the client’s boosters, mainly hard, plate covered insulation is used, although soft insulation also has its applications. In the benchmarking materials, similar hard insulation was used, but also different types of other materials were seen. Figure 9 displays the hard and soft types of insulation used in Auramarine boosters, while figure 10 shows other types of insulation materials found in the benchmarks.

Figure 9. Soft and hard insulations as used in Auramarine feeder-booster fuel supply units (Mod. Auramarine internal archives 2020b).

4.2.3 Heater orientation

In the marine booster units, heaters are used to regulate the temperature of the used fuel in order to achieve desired viscosity. In the studied units, heaters are long, cylindrical components with pipes running to and from them. In each studied unit there were at least two heaters, usually provided in pairs due to the redundancy principle. However, one unmistakable difference in the benchmarks was the orientation of the heaters; vertical or horizontal. In most of the client’s boosters, the heaters are designed horizontally, while in certain benchmark units, they were positioned in a vertical orientation. Figure 11 shows horizontal heaters in an Auramarine booster, while in figure 8 vertical heaters can also be seen.

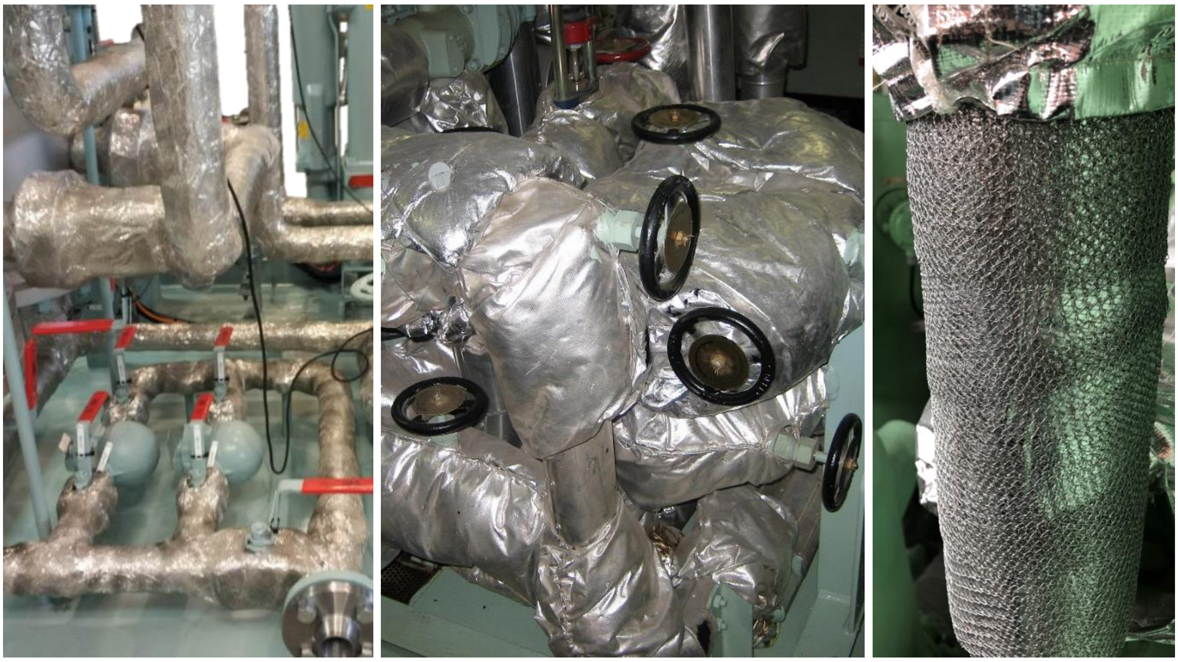

Figure 10. Various insulation materials, different to the ones in Auramarine feeder-booster fuel supply units, as used in the benchmark units (Mod. Auramarine internal archives 2020b).

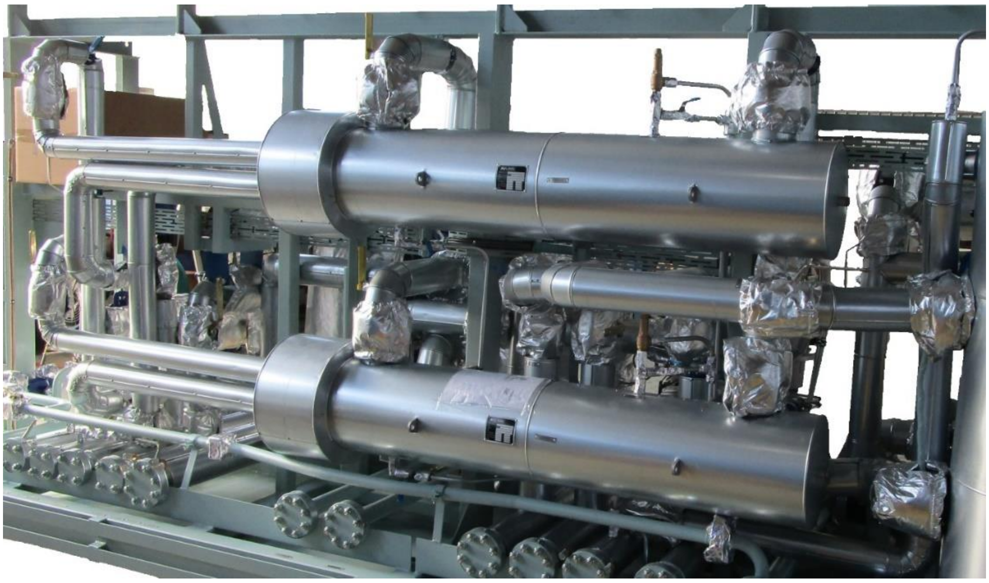

Figure 11. Horizontal heaters (the two horizontal cylinders) in an Auramarine feeder-booster fuel supply unit (Mod. Auramarine internal archives 2020c).

4.2.4 Locations of the inlet and outlet pipe connections

Since the client's boosters are auxiliary skid-mounted units often delivered as a single product, flanged connections must be made for all the medias flowing in or out of the system. Even though a decision has been made to remove the dual-sided inlet and outlet pipe connections design, it turned out in the interviews that boosters with dual sided connections are still produced in the client company and there's no clear standing order as when it should be designed and when it should be avoided (Kaataja 2020b). The dual-sided connections design combined with bringing all the connections to a horizontal row at the bottom of the booster unit is another distinctive feature of Auramarine's units.

Bringing the connections to a neat row is not something the benchmark companies do, however. In the benchmarking materials the connections were not made 2-sided like the with the client's design, and they are often located on varying positions in both horizontal and vertical directions. In some cases, the connections are even distributed on several sides around the unit, sometimes left at the connection of the final component or even what appears to be directly below the unit, although the last-mentioned option could not be verified with certainty. Figure 12 shows a typical application of two-sided connections in a row, with the other side closed with blind flanges, as used in an Auramarine booster, while figure 13 displays some of the benchmark units with less systematic connection designs. A row of connection flanges as used in Auramarine boosters can also be seen in figure 11.

4.2.5 Feeder pump installation

The feeder pump installation of one of the benchmark units caught the eye of an interviewee. In Auramarine boosters, the feeder pumps are installed to a pump block mount, with suction strainers located separately before the pumps. In the said benchmark unit, in turn, it seems as if the strainers are built in with the pump assembly.

4.3 Reverse engineering results

By studying the findings of the benchmarking with reverse engineering supported with the interviews of client company's employees, an account of the prerequisites and effects of each element was made. As concrete products for disassembly and hands-on studying were not available, the professional insight provided by the employees became exceedingly important. Following is a review of what are the key differences of each finding and how influential they would be, should they be chosen to implementation by the client.

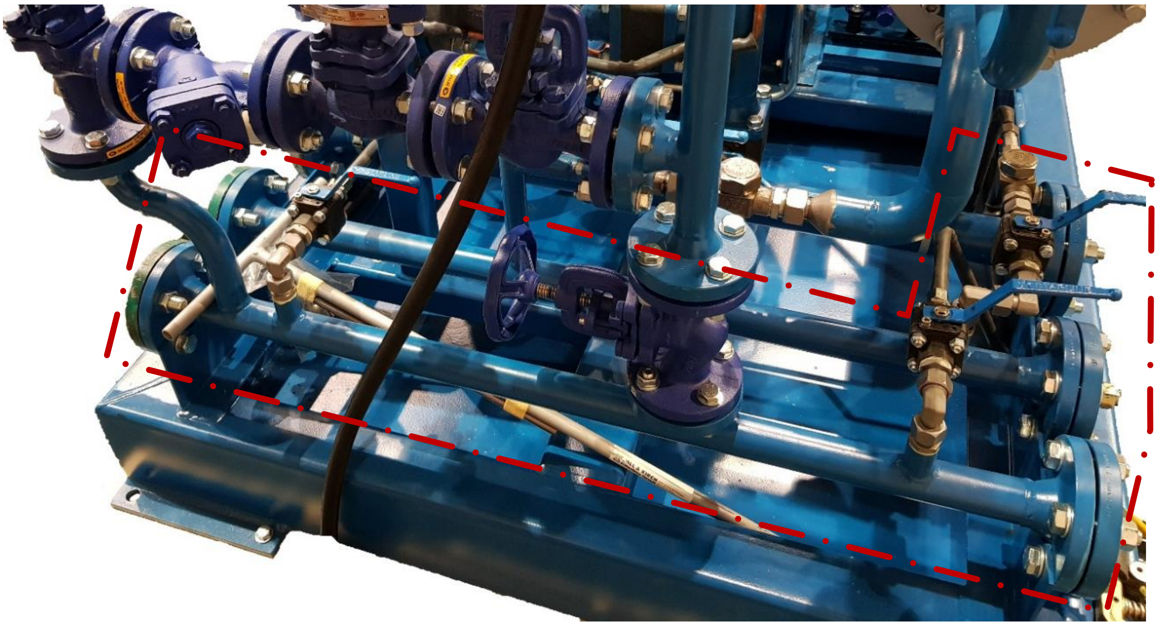

Figure 12. Dual sided row of connections as used in an Auramarine feeder-booster fuel supply unit, marked with red.

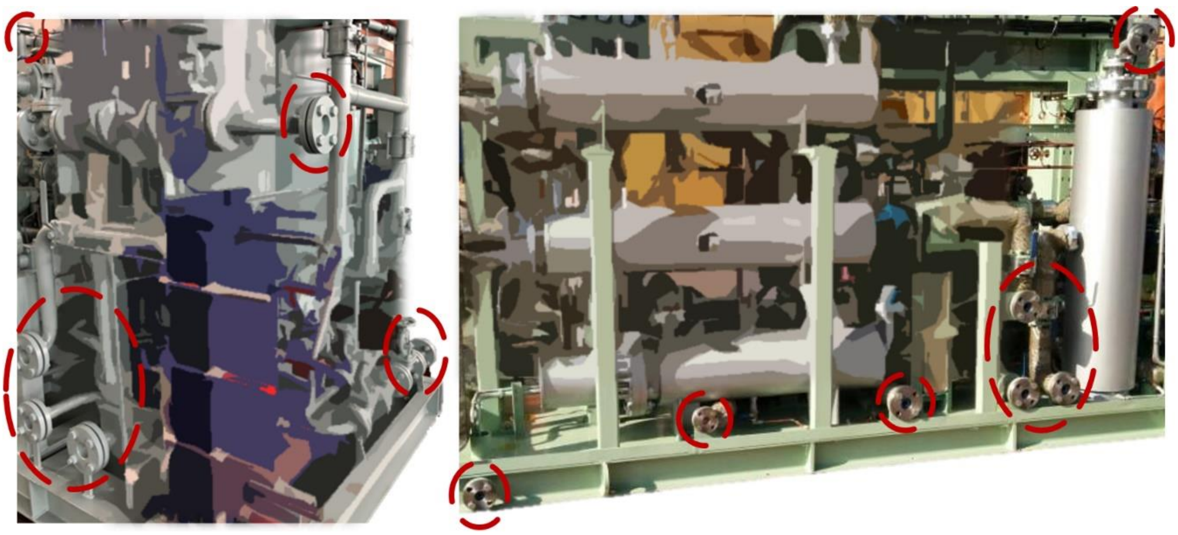

Figure 13. Connections in various positions as found in the benchmark units, marked with red (Mod. Auramarine internal archives 2020c). Note on the left, the connections are in four directions. On right, connections are at several heights, and the top right flange is left at the inlet of the component.

4.3.1 Electrical cabinets and upper frame

In the interviews, it was found that the electrical cabinet design with the upper frame mounting has several impacts on the booster unit and its manufacturability. The main reason for using this solution for electrical components placement is, in addition to a long-term practice of doing so, to save the footprint of the unit. If the upper frame was to be removed, the electrical cabinets, which could amount up to seven or eight individual cabinets in total, would have to be placed somewhere on the main frame of the booster, which consumes footprint. (Silvennoinen 2020a; 2020b.)

During the interviews, it became clear that in addition to footprint usage and electrical component locations, the upper frame can also be used to support any tall components which could resonate to the vibrations caused by the vessel’s engine (Henriksson 2020). Such components are, for example, vertically mounted heaters or pipes running down from atop of a component. Additionally, in this research, it has been concluded that the upper frame also allows for more expansive fixing of the inlet/outlet pipe connections, should they be located elsewhere than the bottom level of the booster. For this, the upper frame should be positioned and constructed so that supports for the connections could be easily attached to it without the need for overly long and complicated support beams.

On the other hand, in the interviews it was also found that the upper frame has its downsides as well. One of the downsides is that it adds the weight of the booster (Kaataja 2020a). This increases the manufacturing costs for its part, but then again, if the electrical cabinets were installed on the booster’s floor, the main frame must be lengthened, which could negate the cost savings achieved by removing the upper frame (Julin 2020b). Also, although the upper frame acts as a support for tall components, high installations of the electrical enclosures could also be prone to resonating to vibrations when compared to lower installation location (Silvennoinen 2020b). The vibrations of a vessel are very difficult to predict, as they depend on the engine, transmission, hull and many other factors (Henriksson 2020).

The electrical cabinets themselves also lead to certain dilemmas when mounted on the upper frame, it turned out in the interviews. In some cases, they are located too high, so that people with below average stature have trouble accessing the user interface, even to the point of the client having to make platforms below the cabinets for better usability (Julin 2020a). Another thing to note is that when the cabinets are installed up, there are always components, such as electrical motors, below them, and in the most extreme cases the cabinets complicate the maintenance of these components (Silvennoinen 2020b). With the cabinets installed high and next to each other, and most of the other components low across the bottom of the booster, also comes the need for extra cabling, as the electrical lines run down from the high mounted cabinets as well as from one cabinet to another (Tevaluoto 2020). Lastly, the amount and size of the cabinets has been increasing in the past, with the consequence of the space in the upper frame growing increasingly limited, and if this trend doesn't change in the future, new arrangement for the electrical cabinets has to be devised at some point (Kaataja 2020b).

To summarize the upper frame and electrical cabinets issue, although the current solution has its downsides, none of them are too overwhelming when compared to the conveniences of the design. It can't be unambiguously stated which one of the electrical enclosure options found in the benchmarking is the most beneficial in total, in terms of manufacturability or otherwise, without further, deeper study of the subject including new electrical designs and different cabinet options. Changes to the electrical enclosures and their locations would also require significant amount of redesign and reorganization work from both electrical design and purchasing departments (Kaataja 2020b). Searching means for improvement in these fields were ruled out of the research scope in the research problem. All things considered, this portion of the benchmarking results is not included in the morphological analysis, but rather recommended for further research complete with concept-level prototypes of the different designs.

4.3.2 Heat insulation

In the interviews it was found that the difference between hard and soft insulation materials is whether they can be simply wrapped around the insulated object as soft coating, or if it has to be molded into hard shape according to the object outlines (Vieno 2020). The advantage of the soft material is that it is easy to remove and reinstall, since it is tightened simply with steel wire, almost like lacing a shoe (Henriksson 2020). Most of the customers of the client company would consent to the use of soft insulation, should it be decided. However, the benefits of such decision to the client company would be questionable, since the whole insulation procedure at the production phase has been outsourced, and the subcontractor can't be expected to lower the already agreed prices. (Tevaluoto 2020.)

In this research, it has been concluded that the insulation process has minor effect on the manufacturability of the boosters. This combined with the fact that the used material choice is more of a purchase issue than a mechanical engineering one, this proportion shall not be considered in the morphological analysis either. However, this is another auspicious recommendation for further research within the relevant department.

4.3.3 Heater orientation

Similarly to the electrical cabinet mounting, both heater orientation options have their advantages and disadvantages, it turned out in the interviews. With relation to manufacturability directly, the effect of the heater orientation is minor, however (Silvennoinen 2020b). Instead, the heater orientation has significant impacts on the other aspects of the booster unit: different orientations allow for different physical structures, and by changing the orientation type, roughly half of the design choices with the whole unit are ruled out as it is (Kaataja 2020b). In the research, it was also concluded that another thing affected by the heater orientation is the serviceability of the unit.

During the interviews, it soon turned out this matter has been discussed and contemplated upon in the past already, but the subject was closed in the client company up due to fear of vertically aligned heaters starting to vibrate (Kaataja 2020a). Word had it that some competing products with vertical heaters had regular problems with vibrations, while the horizontal construction used by the client is more robust, not quivering easily (Anttila 2020). Another trouble that must be looked out for with the vertical installation of the heaters is the height of the booster, which usually isn't allowed to exceed 2 meters by a lot (Henriksson 2020). Additionally, some customers specifically request a horizontal heater, while the vertical heaters have never been a prerequisite for an order (Julin 2020a).

In the interviews, it was also found that the major asset of vertical heaters is saving footprint when compared to the horizontally installed ones (Silvennoinen 2020b). In addition to footprint, the vertical alignment also reduces the pipeline meters, with horizontal heaters requiring more piping (Tevaluoto 2020). It has been estimated that at least 1,5 m extra piping is required for the horizontal heater design (Julin 2020b).

Regarding the footprint usage, it should be noted that not only do the horizontal heaters take more space due to their dimensions, but they also require specific maintenance space besides that. This is because of the way the heaters are serviced: horizontal heaters are treated in place by opening the heater’s tube casing and sliding the heater element out, whereas vertical heaters are detached from the booster as a whole and serviced elsewhere. In some instances, this has resulted in almost two meters of empty space next to a horizontal heater that cannot be used for anything else. Now, the horizontal heater can also be detached for maintenance at another location, but this requires additional working space behind the booster unit, whereas the vertical heaters can be dislodged easier, especially if located at the periphery of the unit. However, the flip side of this is that maintenance in-place is much more convenient, since the component itself doesn’t have to be deinstalled and moved at all. (Julin 2020a; 2020b.)

As it turned out during the interviews, both designs have their pros and cons, and it is not self-evident which one to use in what kind of products (Kaataja 2020b). All in all, it was concluded in the research that the whole heater issue is not a simple question with one solution being explicitly better than the other. Like with the electrical enclosure design, concept prototypes with different designs should be made for further research and analysis of the total effects of each design, together with dynamic analysis to ensure satisfactory vibration resistance of the components. Meanwhile, with horizontal heater designs it is recommended to locate the heaters with their maintenance lid at the edge of the booster unit, so that the space reserved for maintenance purposes only within the unit is minimized.

As the effects of the heater orientation on other properties of the booster supersede its impact on the manufacturability in great measure, it was decided to not include the parameter in the morphological analysis either. Rather, it is also a recommended subject for deeper research and conceptualization. If new concepts regarding the heaters are decided to be made at some point, an interesting idea that appeared during the interviews should be kept in mind: a redesign of the heaters themselves. By using shorter, barrel-like heaters with larger diameter, better designs could be achievable (Silvennoinen 2020b).

4.3.4 Locations of the inlet and outlet pipe connections

Designing the connections at the front bottom edge of the booster unit is most of all a result of 40 years of design work, and a residue from the time before computer aided design. Similar history pertains to the dual-sided inlet and outlet pipe connections design, where the connections are brought to the front and back of the unit at the same time: before computer aided design it was a selling point to have flexible design with standard locations the for connections. Although originally designed a long time ago, having the connections at the bottom front edge still has its merits that are advantageous even today: a more or less standard location of the connections is a distinctive feature typifying Auramarine products, and the location allows for easy and simple supporting of the flanges. The connections must be supported at the neck of the flange to avoid bending of the pipes when installing the booster in a ship. (Silvennoinen 2020a; 2020b.)

However, this kind of connection design doesn’t really have very strong technical justification, it was found in the interviews. The pipes that connect to the booster can emerge from anywhere in a vessel. Although it is not necessarily practical to scatter the connections all around the booster, there is no need to bring them in a neat, dual-sided row, unless specifically requested. This is of course something that shipyards could have their own preferences about, but for example a local shipyard has expressed that for them, it is of little importance where the connections are located. (Henriksson 2020.) Also, since none of the benchmark companies have similar uniform practices for the connections, it can be assumed that the shipyards are accustomed to changing designs (Anttila 2020).

On the contrary, in this research it was concluded that always leading the pipes to the bottom edge of the booster is most of the times futile, and even more so to make the connections dual sided, as the unused side is completely profitless in the end. Not only does this require extra piping meters and complicate the connecting pipes, as they have to be brought down to the bottom and then bypass the components, but it also takes up additional space at the bottom level of the booster, where most of the components are installed. Additionally, it unfolded in the interviews that in the most extreme cases, the connection are brought a long distance from a component to the bottom edge of the booster, only for the connecting pipe at the vessel to go back past the said component (Silvennoinen 2020a).

4.3.5 Feeder pump installation

In one of the interviews, it turned out specific pump blocks are being used for pump installations in the client company. In practice, this means that the pumps are installed on a machined block part, to which the pipes are then connected. An alternative is to connect the pipes directly to the pumps. On the other hand, pump installations with built-in strainers comparable to the ones found in the benchmark unit are also available from certain suppliers. However, the pump block and strainers as they are currently are of the client's own design and buying them as a complete product from outside the company likely has a substantial negative impact on the manufacturing price. This would mean a total change to the structure that is used today. (Henriksson 2020.)

In the course of the research, it begun to seem that this doesn't affect the manufacturability of the boosters very much. Also, the issue should be reviewed at the purchasing department more than design. For this reason, the matter isn't included within the morphological analysis, but should still be kept in mind when considering development options for the products.

4.4 Additional development parameters unfolded during the interviews

During the interviews, several aspects to be considered in the analysis that could not be seen from the available data came to prominence. The aspects include ideas that either had been thought of already in the past or were brought to the mind of the interviewees by the benchmarking materials. This is exactly the kind of silent information that was intended to be found with the interviews.

4.4.1 Width of the booster's frame

Although technically visible in the benchmarking materials, the frame width was only brought to attention via the interviews with the Auramarine personnel. The width of the frame has been designed to certain standard measures corresponding to the capacity of the booster and the size of its components. During the interviews, it was confirmed that this has resulted in the booster having an oblong shape, being somewhat narrow and long, unlike some the competing products (Anttila 2020). While considering the products of certain competitors in general, units with greater widths are made as well and there's nothing unusual about it (Julin 2020a). For clarity, figure 14 visualizes which dimensions are meant with length, width and height.

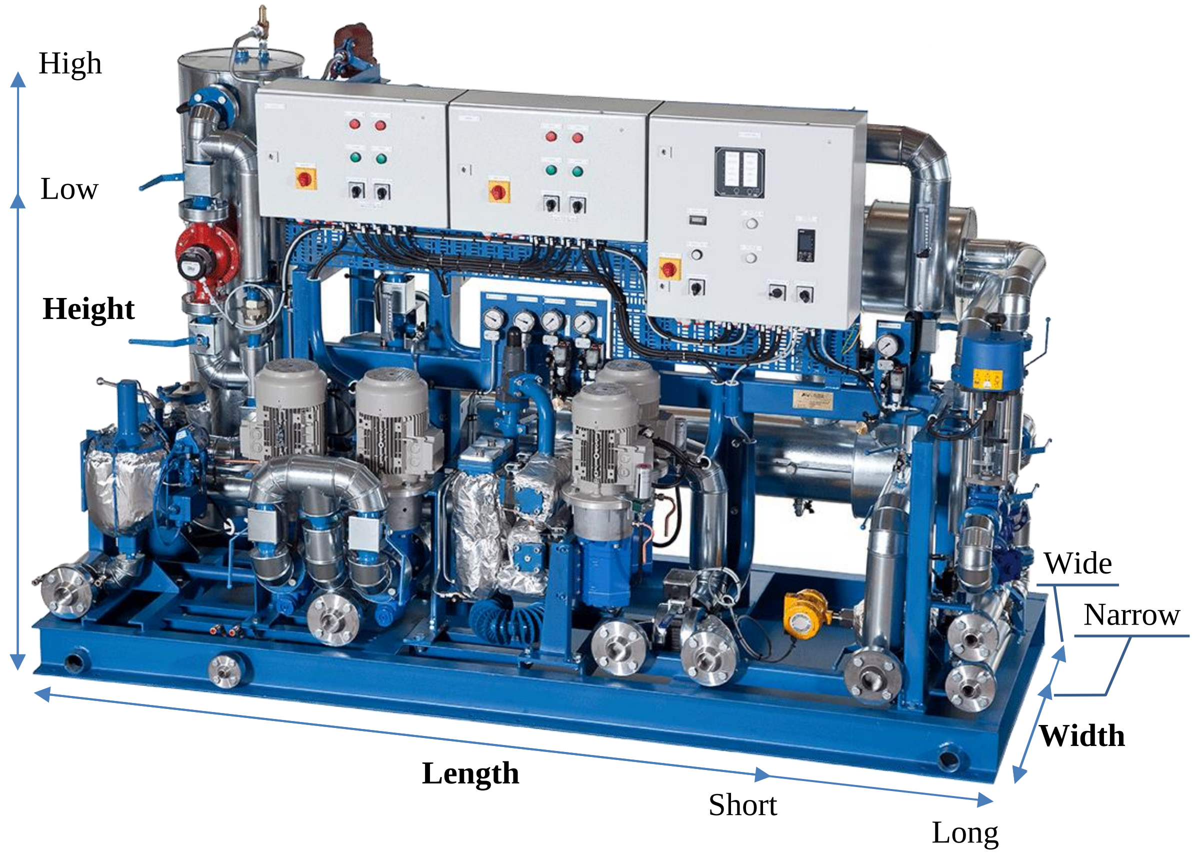

Figure 14. The terms used to describe the dimensions of a feeder-booster fuel supply unit in this research (Mod. Auramarine 2020).

In the manufacturing it has come along that there are difficulties with the narrowest booster units regarding manufacturability and serviceability. Due to the narrowness of the units, additional welds and curves must be made in the piping in order to fit everything inside the frame, and in certain instances some pipes even pass on the outside of the frame boundaries. This shouldn't be the case, but rather the frame should protect its contents in the event the unit knocks into something during transportation or maintenance. Similar problems haven't been present with the wider boosters of greater capacity, that are 50 % wider. (Julin 2020a; 2020b.)

In the interviews it became apparent that generally the width of the frame isn't much of a problem. The length, on the other hand, turned out to be over the preferred limits from time to time, but in 16 years of working with the Auramarine booster units, only a few comments have been about the width of a unit. (Julin 2020a.) The justification behind the currently used frame widths is the flow of the processes within the unit: doing the mechanical design of the booster according to the P&ID charts leads smoothly into the widths as they are. This is also, like with the connection locations, a distinctive feature of Auramarine productline, which is regarded as a good productline. Changing that is laborious and would result in Auramarine product family looking different. (Silvennoinen 2020b.)

Indeed, the changes on the appearance of the boosters would be notable, and the customer's attitude towards the changes should be carefully examined, it was found in the interviews. Since Auramarine has been producing booster units using the current width for the last 20 years, a sudden increase to the width of the units should be first discussed with customers, as the company is not in a position to dictate the dimensions or layout of a vessel's engineroom (Kaataja 2020b). However, it was also estimated in the interviews that by increasing the frame width, the manufacturability and serviceability of the narrowest boosters could be improved. While decreasing the length of the frame by increasing the width could prove extremely troublesome, it would still make using standard pipes much easier. Some 16 - 25 % increase in the width of the narrowest boosters should be enough. (Julin 2020a.)

Considering all the aspects, one concern justifiably raises in the research: What would be the effects of such change on the manufacturing costs of the boosters? By increasing one dimension without decreasing any other, more material is required, and the weight of the booster increases. Even so, according to a recent internal study conducted at the client company, the frame only constitutes 3,51 % of the material costs of all Auramarine boosters in total with the current design (Auramarine 2019d). Hence it is can be concluded that the increase in the frame costs could be surpassed by the progression achieved by improving the manufacturability and serviceability.

4.4.2 Applying modularization and new product categories to boosters

In the interviews it was found that there have been plans in the client company for a new product category between the standard products and custom products, of which the latter currently includes all the boosters (Kaataja 2020b). Modularization on the other hand is something that has been attempted before, with unsatisfactory results. However, this was at least partially due to unfitting starting configuration and requirements. (Tevaluoto 2020). Minimizing of product variants has also been difficult due to exercising partial optimization in too great detail (Julin 2020a). Experience has shown that optimization and standardization are two totally different things, even to the point of opposing each other (Silvennoinen 2020a).

In this research, it has been concluded that part of the idea in modularization is to decrease the variety of components and parts used. As a result, optimal space usage must be partially given up, since modules of varying sizes and dimensions have to be made compatible with each other, but it could result in better management of components and parts supply. This conclusion also got support from the interviews: Keeping the optimized footprint of the booster unit unchanged is in contradiction with interchangeable modules (Tevaluoto 2020). According to Henriksson (2020,) one thing that must be accepted with modularization is the inevitable increase in the size of the unit. However, by using the same components more, suppliers can be informed better about the client’s needs, increasing the suppliers’ stocks and lowering the purchasing costs (Julin 2020a).

One idea that emerged in the interviews was that the mechanical design of the boosters could follow more a philosophy of building blocks. There are certain elementary functions that are always found in every booster. These could compose the base booster unit, to which extra functions, such as cooler units, homogenizators or viscometers, would be added as independent building blocks. (Julin 2020a.) With modern systems, the management of the boosters’ designs and frames is uncomplicated, as the design data is updated and transferred at the push of a button. This way, the frame can be customized to fit each product variant with ease, as opposed to the old principles, where everything had to be fittable to a single frame. (Silvennoinen 2020b.)

It has also been recognized at the client company that making the boosters more uniform would be wise, and some standardization has already been made. However, there are occasions where a repeated product of an old booster unit is ordered, and to save time, it is designed the old way with minimal changes, which sometimes does seem like clumsy design. (Silvennoinen 2020b.) Still, it’s not only the repeat cases that carry on the old design choices, and even the repeat units could well be improved with new manufacturability preconditions. The prices for repeat units are nonetheless recalculated for new offers, so the risk of shrinking profit margins because of the redesign is also minuscule. (Julin 2020b.) The customer on the other hand could not be less interested in the exact contents and layout of the booster itself, so long as it is made with the agreed components and connection positionings (Kaataja 2020b).

Regarding the product categories, a conclusion was made in this research that it is possible to combine the new semi-customized product category with the modular design. In addition to that, the possibility of extending the boosters even to the standard product category as well should also be kept in mind. By implementing the modularization with the core booster and predesigned modules, the most commonly ordered configurations can be designed into more optimized standard products if their request rate is high enough.

4.4.3 Requirements of the design of the booster’s piping

Both while studying the client’s boosters as well as along the interviews it turned out that in the pipeline design, several different angles and bends are being used. While this has its advantages, it might be viable to limit the design options and orientate more towards the use of standard pipes and limited variety of angles where feasible, even at the expense of the width of the frame (Julin 2020a). That being said, standardizing the pipes is something that has been attempted before at the client company together with the modularization and with equally displeasing results, leading to very complicated labeling of pipes with scarce repetitiveness (Silvennoinen 2020b).

In the interviews it was found that like with minimizing the product variants, one reason behind the number of unique pipes is the aim for optimizing the pipes. The mechanical design is balancing between optimizing and standardizing the pipes, as components are desired to be located right next to each other and pipe lengths are attempted to be minimized. This has led the Auramarine boosters to be compact relative to the other manufacturers’ units. (Silvennoinen 2020a.) Then again, similar building block thinking could be applied with the pipe design as with the function modularization. By using regular angles more, the bending machines do not need to be reconfigured as often. The irregular bends should be avoided if possible, even by widening the booster’s frame if needed. (Julin 2020a.) One thing concluded in the research is that with standard curve dimensions, that being 45° and 90° curves, weldable curve parts can also be used instead of forming the pipes if deemed profitable. Curve parts with these angles are widely available for purchase (Henriksson 2020).

A deficiency regarding the pipe design recognized during the interviews is the scarcity of determined development work with the designing of pipes, which is at least partly due to tight resources at the design. For example, there are cases where a component with an excessively large outgoing pipe diameter is used, which is then separately reduced into a smaller diameter, whereas a component with smaller outlet diameter could be used instead. (Silvennoinen 2020b). Another reason for the current practices in the pipe design is the tool used for designing the pipes, which allows for effortless creation of new pipes. The result is numerous closely similar pipes with minor differences, even in cases where one standard pipe could be used in place of all the different ones. (Julin 2020a; Tevaluoto 2020.)

4.4.4 Instrument modules and design of instrumentation lines

One thing that became a topic in the interviews was the locating of instruments and the design of instrumentation lines. It turns out the instrument lines are not being designed at all, which usually results in even a series of theoretically identical boosters to have dissimilar appearances. It also leads to partial distortion of the cost structure of the boosters, as some instrumentation lines need to be trace heated, and the heating cable is rather costly. (Julin 2020a.) Also, by having the instrumentation lines modeled ready for production, the mechanics installing the lines do not have to plan the route for the lines individually, which saves time and allows for picking of the fastening parts and supports in advance (Tevaluoto 2020).

Another thing that came up in the interviews was the instrument modules, meaning subassemblies containing the most typically used instruments in pre-assembled, organized panels. Currently the instruments aren’t always being designed in the models, leading to the mechanics implementing the instrumentations as they see fit according to parts lists and process chart only (Silvennoinen 2020b). These panels could on the contrary be assembled when no booster units are at the assembly line, allowing for faster installation of instruments when a unit arrives, reducing the lead times (Julin 2020a). Turns out this kind of panels are already being used in a few instances, and some standardization regarding the instruments has been going on for years (Tevaluoto 2020; Silvennoinen 2020b).

4.4.5 Booster frame build

The frame build has been recently renewed with sheet metal design, making use of modern manufacturing technologies like laser cutting. However, a perspective regarding the sheet metal design surfaced in one of the interviews: the used sheet metal applications could have been more drastic, exploiting the stiffening of sheet metal by bending and cross braking (Tevaluoto 2020). Even so, it was concluded in the research that elaborating this would require vast amounts of planning, training in sheet metal design, redesign work and strength calculations, and therefore it is not included with the analysis part of this research. Rather, the profound sheet metal construction of the frame is again a recommendation for further development regarding the boosters and their DFMA.

4.5 Group interview results

A preliminary morphological matrix was formed based on the findings from the benchmarking, reverse engineering and silent information. Presenting this matrix, a discussion and group interview was arranged in order to validate the preliminary ideas and spark up conversation that were left hidden in the individual interviews. The group interview helped in making the final decisions for the morphological analysis and better justify the recommendations.

The most central new points that emerged during the discussion concerned the instrument modules and the effects of the frame width changes. In addition to the pre-assembling of the instrument modules at the off-peak times, another notion made in the group discussion was that by having them fully designed, they could also be purchased as ready subassemblies, should the volumes be high enough (Booster workshop 2020). This could, for its part, be used to alleviate the rush times at the production as well.

In this research, it has been concluded that in addition to allowing easier installation of components, more painless maintenance and the use of more simple pipes, slight increase in the frame width could also reduce the number of claims received regarding the boosters. The group interview revealed that there have been some cases where a handle could not be turned, or a piece of insulation was difficult to fit in position due to the density of the components within the booster (Booster workshop 2020). Therefore, it can be concluded that by increasing the width of the narrowest frames, more space is left also between the objects within the frame boundaries. Additionally, should the width of the booster's frame be increased, a practical limit for the extreme maximum width was constrained in the group interview: the booster must fit in a marine container (Booster workshop 2020). According to Logistiikan maailma (2020), the inside width of a marine container is 2330 mm, and some tolerance must be left for the loading procedures.

4.6 Morphological analysis on the results

This chapter contains the morphological analysis and the final morphological matrix regarding the results of this research. The analysis constitutes of the rationale of the suggested design choices described and reasoned more deeply in the subchapters. The morphological matrix, visible at table 2, is shown at the end of this chapter.

In this research, it has been concluded that changes to the frame width and locations of the pipe connections by themselves are not of intrinsic value to the manufacturability. Still, by allowing design changes to these parameters, simpler pipes of better manufacturability can be achieved with very minor actual hindrance to the less critical aspects of the boosters. The usage of more standardized pipes is therefore closely related to the frame width and pipe connection locations. Also, in the interviews it was found that the modularization of the boosters is not an easy task in the end, but it could lead to changes in the piping design that could be implemented soon already (Julin 2020a). This is an exemplary case of morphology: how the total result is more than just the sum of its parts. Considering the interdependence of these parameters, it is conspicuous that the manufacturability improvements in the morphology greatly stress the piping and its design.

The reason for concentrating on the manufacturability of the piping is, as was confirmed in the group interview, that the way it is currently, the pipes form a bottleneck at the production sometimes and there have been some quality issues with them as well. It would be easier to find subcontractors for larger batches of more uniform pipes, and each weld also adds the dimensional inaccuracies of the pipes. (Vieno 2020; Booster workshop 2020.) In addition to hampering lead times, the cost effects of the piping are also multiplied for several reasons.

The complexity of the pipes affects the raw price of the pipes themselves, their assembly costs, as well as the insulation and tracing costs. Faulty pipes that cannot be installed due to accuracy errors must also be sent back to the subcontractor for fixing, cleaning, finishing and so on. Finally, 50 % of the weld seams must be inspected with non-destructive testing. (Julin 2020a; 2020b.) It should be noted that by decreasing the number of designed curves, the amount of welding can also be reduced, since some of the curves in the pipeline are manufactured with welded curve parts.

4.6.1 Locations of the inlet and outlet pipe connections

In the interviews it was found that the connections should only be brought to a specific place if it is certain that it’s on the way to the connecting pipe of the ship. Otherwise they should be left to a logical position close to the last component. (Silvennoinen 2020a.) The end of the booster (meaning the “width” side in figure 14) should also be considered an option for locating the connections, unless forbidden by the customer (Henriksson 2020). A determinative factor in locating the connections, in addition to the last component’s location, would be a suitable mounting position for support. If every connection was brought to the outer boundary at a straight line from the last component, each of them would require a separate support beam, which would result in the whole booster being full of support beams here and there. Few additional frame members might be profitable to be inserted, though, if it leads to enough reduction of the piping. (Julin 2020b). In this research, it has been concluded that, in practice and considering the boosters of the client company, this would mean to no longer aim for leading the pipes to the bottom edge of the booster, but rather accepting a less congruent placements for the connections.

Any dual-sided connection structure, in turn, should be undone by default, as was rationalized in the interviews. A dual-sided connection should be available for additional price at most, so long as the customer is allowed to choose which side the connections are brought to (Anttila 2020). The dual-sided connections could still be offered as a deviation, but in the end, the price is often what matters the most (Tevaluoto 2020). An effort should also be made to recognize which connections are most frequently requested on varying sides, usually at least the fuel in and fuel out are. Creating the designs so that those pipes can be easily mirrored on either side would then negate the need for a dual-sided interface. These connections would also have to be designed at the bottom of the booster, since a mirrored connection is more difficult to make at an elevated height. (Julin 2020a.)

However, in the interviews it was clearly stated that the connections in general should primarily be still brought to the outmost boundary plane of the boosters (Henriksson 2020). The connections must be located so that when installing the connecting pipes, there isn't anything in the way that could be damaged. It is better to be able to work outside the booster unit than within the boundaries of the unit's frame. On some specific cases, leaving a connection deeper in the booster can be allowed, though, provided there is enough space around the connection for trouble-free installing. (Julin 2020b.) Still, slight differences from the outer boundary of the booster and even overlapping flanges should be allowed if they wouldn't fit next to each other on a common plane. Additionally, the connections can be designed closer to each other than they are with the current design. (Henriksson 2020.)

In the matrix, the suggested "Anywhere, front or back side" option refers to allowing the pipes to be left at any given location on the outer plane of the booster unit on the long sides; in other words, on the front or back of the unit. This way, having the last component of a fluid line on the backside of the booster wouldn't be a problem connection-wise, and the number of complicated inlet or outlet pipes would decrease, while the connection sides and orientations would generally remain the same. Where practicable, mirroring the connection pipe could be made available with no additional costs, and specific lines could be designed to a desired location at a customer's request.

The suggested long-term design "At the outlet of the last component" then refers to having no separate outlet pipes at all: the connections in the ship would have to be brought all the way to the component connection. This would be very drastic and installation-wise unfriendly as well, since some of the components are located deep in the booster structure, leaving the connection to very inconvenient place considering the connection pipe fixture. Should this design be taken into usage at some point in the future, exceptions would have to be made with the most deeply located components. However, in this research, the suggested direction is to strip the booster units from unnecessary connection pipes where possible, and this solution could even be partially effectuated immediately, as was revealed in the interviews: The deaeration line and return line could be left right at the mixing tank where they are connected to with small changes to the tank itself, should these changes be approved by the customer, and retain the possibility to bring them to the front of the unit as an option (Julin 2020b; Booster workshop 2020).

Part of the long-term suggestion is that where the lines can't be left at the last component, they should be allowed to be located at all borders of the booster unit, even above or below, unless the customer insists otherwise. This would require special arrangements with the unit design, though, as the drip tray located at the bottom of the unit would have to be punctured and create a protrusive edge around the puncture to keep fluids from draining through the opening. Additionally, it was found in the interviews that the booster would have to be lifted for maintenance procedures with the pipes underneath (Henriksson 2020).

Simple demonstrations of these solutions are displayed at figures 15 and 17. On figure 15 is the cooling water inlet and outlet, where in the original design, one of the pipes is made with two curves and the other with three curves. By changing the traditional setting of the connections, the pipes can be swapped crosswise, resulting in only one and two curves respectively, and most importantly, with 90° curves only, instead of the non-standard angle currently designed at the outer pipe. The downside is that both flanges of the pipe with more curves would have to be carefully positioned at an irregular angle in proportion to the curved part of the pipe, demonstrated with a red arrow in figure 16 for clarity. Still, as was found in the interviews, a proficient welder has no problems making this kind of welding and it requires less effort than an additional bending with an irregular angle (Henriksson 2020; Julin 2020a). Additionally, taking the suggestion even further, the connections could also be set pointing the opposite way, resulting in even fewer curves and shorter length of the pipes ending on the backside of the booster. However, due to the surrounding components and scarcity of space near the pipes, both solutions would require some repositioning of the nearby components. Even so, it is implementable.

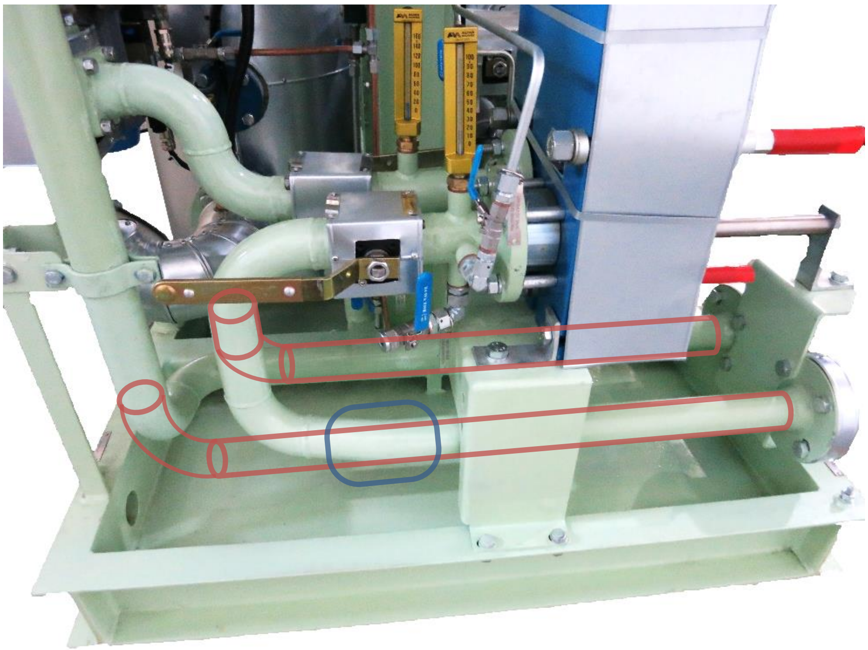

Figure 15. Pipes in an Auramarine feeder-booster fuel supply unit that can be done with less curves by changing the conventional connection arrangement (Mod. Auramarine internal archives 2020d). Suggested new pipes drawn with red, while blue accents the irregular curve in one of the original pipes that can be avoided using the suggested design.

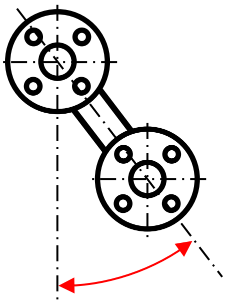

Figure 16. Irregular weld angle resulting from the suggested design, drawn with red arrow.

Figure 17 then displays an S-shaped MGO/MDO outlet pipe with two curves. The only reason for these curves is to bring the connection down to the bottom edge of the booster. By lifting the connection up, the support for the pipe would have to be changed, but the pipe could be done with no curves, using only straight pipe instead. Finally, it must be noted that these are not the only articles with potential for manufacturability improvement by more liberal connection locating, but the idea for the design change suggestion is made clear with these examples.

Figure 17. A connection pipe of an Auramarine feeder-booster fuel supply unit with two curves in the original design and no curves in the suggested design drawn with red and made possible by changing the traditional connection arrangement (Mod. Auramarine internal archives 2020d).

4.6.2 Width of the booster's frame

Regarding the frame width, the suggestion only means the maximum limit of the smallest booster units. In other words, all units do not have to be made unnecessarily wide only because of the widened limit, but rather the idea is to no longer imperatively pursue the traditional minimum width at the cost of having to design complicated piping. It was found in the interviews that as it is currently, the smallest booster units are being designed with the traditional minimum width even without a customer's request, and also the units with recently developed design improvements face similar manufacturability issues due to intricate piping that could be avoided by more spacious frame (Julin 2020b; Booster workshop 2020).

In the interviews it was also revealed that there already is extra space in the boosters for being able to use standard pipes (Silvennoinen 2020b). However, based on the research, it appears that by increasing the width, not only could the pipes be made simpler, but the usage of standard pipes could also be increased. In addition to the manufacturability of the pipes themselves, this would also improve the assemblability and serviceability of the booster units, as was confirmed in the interviews: By having more room in the frame of the unit, there would be more room for installations and assembly (Booster workshop 2020). By having more room between the components and the piping of the booster, the maintenance operations performed on the components are made more pleasant, as with the current design, the pipes must be passed by and over during maintenance (Julin 2020a).

As to the morphological matrix, it is difficult to set any measurable limit suggestions without first drafting prototypes of the units. The +25 % suggestion is mainly based on the interviews and validated in the group interview as well. It was estimated in the interviews that by increasing the width by a maximum of 25 % extra, the manufacturability and serviceability could be notably improved, while it shouldn't be an issue for the customers (Julin 2020a; Booster workshop 2020). Since the suggestion isn't to change all the smallest boosters unconditionally to +25 % width, the most suitable measure would be found and settle with time, as the new design based on a wider frame becomes more commonplace. At that point, any narrower boosters ordered and produced should be custom products only. Additionally, any long-term goals for this issue are even more difficult to suggest, since it is impossible to predict how the space requirements change as new components are released to the market and the whole industry evolves.

4.6.3 Design of instrument blocks and instrumentation lines

Although the first idea regarding the instrumentation piping that came up during the research was to have the all the lines modeled for manufacturing in advance, it was made clear in the group interview that it is not entirely practicable. The longer lines have to be formed in place, as it would be impossible to insert the long, curved lines in the middle of the booster as pre-shaped parts, and by crafting them on site, the risk of erroneous forming is reduced. Still, there are also certain simple instrumentation pipes with little bends that are used regularly, and which could be profitable to design so that they could be manufactured to stock. (Booster workshop 2020.)

With respect to the morphological matrix, the design of the simple and repetitive pipes as well as the more expensive traced pipes and including them in the parts listing is justifiably recommended. This would lead to the possibility of pre-manufacturing the repetitive pipes as well as being able to better predict the full production costs of the boosters. Continuing and finishing the development work initiated with the instrument modules is likewise recommended. The modules, repetitive pipes and traced pipes would be a good milestone for the manufacturability improvements which to aim at first. It was estimated in the group interview that 80 % of the used instrument modules could be designed quite swiftly (Booster workshop 2020). Then, should the standard and semi-standard product categories be implemented fully with the boosters, the instrumentation pipes used regularly in the boosters fitting these categories are also suggested to be designed and modeled for the same reasons. These pipes could later be purchased along with the frame from the frame supplier as well (Booster workshop 2020).

4.6.4 Applying modularization and new product categories to boosters

Combining all the presented thoughts about modularization and categorizing the booster products, a bold idea can be drafted in conclusion to this research: to apply the standard product category in addition to the new semi-standard product category to the boosters as well. Together with the frame width changes, limiting pipe variety and focusing on standardization rather than optimization, modularization can be implemented with better results, provided that the configuration and requirements are set more realistic and forgiving than in the previous modularization attempt.

Then, should the modularization be implemented profoundly, it must also be decided exactly how to implement it. In the group interview, it was confirmed that as it is currently, only theoretical design modules are being used, not mechanical production modules (Booster workshop 2020). In this research, it was concluded that as the booster is built on a single frame, the use of design modules is reasonable. Although mechanical modules could be manufactured and preassembled to stock, the separate frames would result in increased weight, frame costs and less rigid build. The premanufactured modules would also have to be installed on the ends of the base booster, keeping the core of the booster mostly unchanged and simply connect the frames as more modules are added. In the interviews it was found in turn that as the fluids in the booster unit flow generally from left to right, this would in many cases result in excessively long piping going back and forth in the unit as the added functions need to be connected in between the ones already designed at the core unit (Kaataja 2020b). In this research, it was also concluded that although with mechanical production modules the management of component positioning is a bit easier in some instances, as the additional modules are assembled on their own rectangular frames, it doesn't justify the inconvenience resulting in manufacturing the frames and pipes. In the group interview, it was also revealed that this is where the modularization project failed previously: the mechanical production modules turned out to be difficult to implement in the client's products (Booster workshop 2020).

The advantage of the design modules on the other hand is the ability to better follow the process chart flow of the booster unit, adding the extra modules at the most logical position in the middle of the unit and keeping the pipe lengths also reasonable. This can be carried out by lengthening the frame and moving the other components accordingly as groups. However, in the interviews it was found that additional modules designed on their own frames could still be utilized in tight spaces. The standard "core" booster unit could be delivered on a compact frame containing only the necessary functions, and extra functions could be installed nearby in locations where there is more room, and then connected to the core unit with separate lines (Julin 2020a). Although this is a viable option, these kinds of instances should be regarded strictly as special products.

What comes to the morphological matrix solutions, it is suggested to extend all the product categories to pertain the booster family as well, as is using the design modules together with standalone function modules in special products. In the semi-standard booster units, these modules can then be added to the unit where practical on the unit's frame, by stretching the frame and moving the existing modules as sets if needed. As long-term goals, the standard and semi-standard product categories should be the primary focus in the future to allow for more standardized and more predictable manufacturing of the boosters. However, regarding the modularization of the boosters, sustainable reasoning for attempting the physical production modules could not be found within this research. The conclusion is that production modules have their uses in other industries, and even with other products in the marine industry, but considering the client's boosters and manufacturability locally, no substantial benefit is anticipated by implementing them.

In addition to the morphological matrix suggestions, one thing that must be constantly assessed regarding the modularization is the positioning of the modules and functions. In the interviews it was found that in the past, there have been instances where thoughtless locating of components has occurred. The emergency pumps that are an optional extra function to the booster units have sometimes been designed at the opposite end of the unit as the fuel inlet connection, resulting in a long, unnecessary pipeline running across the booster, whereas the pumps could simply be located at the same end as the fuel inlet (Julin 2020a). In the boosters where the recently developed design has been used, this issue has been fixed already (Silvennoinen 2020b). However, the reason why this example was pointed out is that continuous improvement and development work is recommended, and the improved solutions should be taken into use throughout the full booster product range. Figure 18 displays the traditional and newly developed design of the emergency pumps.

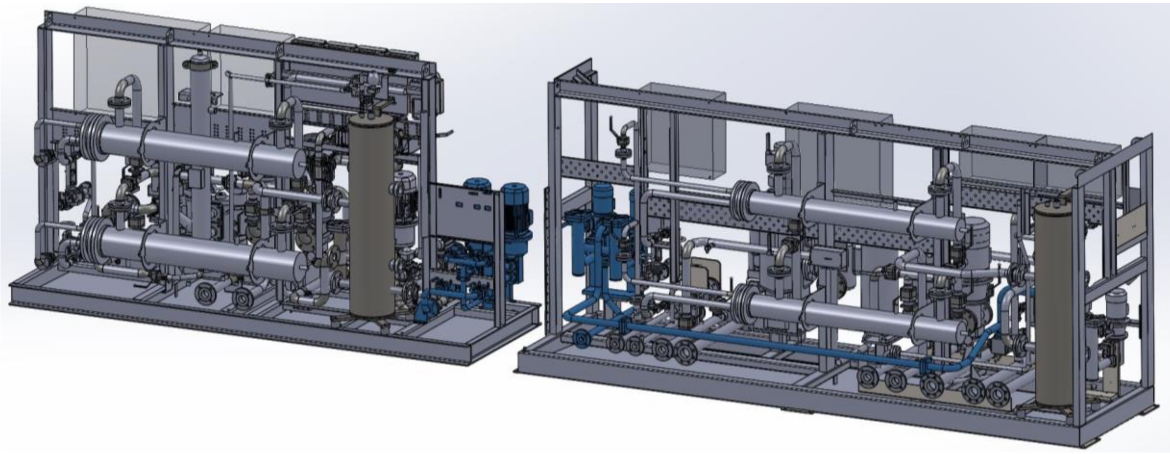

Figure 18. The old-fashioned (on the right) and recently developed (on the left) designs of the emergency pump positionings (Silvennoinen 2020c). The emergency pump functions and pipes are highlighted with blue color.

4.6.5 Requirements of the design of the booster’s piping

The pipe design is presently an optimized solution with the current booster arrangement and the constraints it sets. However, by relinquishing some of the factors limiting the pipe design, such as the frame width or end connection locations, more production friendly solutions are attainable. It was found in the interviews that being able to produce the boosters with 90° and 45° pipe curves only would be the best, since irregular curves always slow down the production (Henriksson 2020). It would also allow the use of purchasable curve parts, which would in turn set clear rules for the design and simplify the pipe manufacturing, as only straight pipeline would have to be cut in given lengths and then take all the parts to welding (Tevaluoto 2020).

Additionally, by changing the limits in the pipe design, the use of more standard pipes is possible. It was found in the interviews that a lot of standard pipes are already being used at the client, especially numerous pipes that consist of flanges only or flanges and curves only welded together without actual pipeline meters at all, that are used for connecting two components (Silvennoinen 2020b). In this research it was concluded that affecting the manufacturability of these pipes is very difficult, since the used components define the kinds of flanges used and partially the orientation of the connections within the booster as well. The suggestions concerning the standardization of the pipes in this research therefore focalize the pipes where actual pipeline material is used, as the above-mentioned types of pipes are already as standard as they can be.

It was also revealed in the interviews and verified in the group interview that standard pipes with actual pipeline are also being used already in the client company, and less than half of the pipes are of new design in each new unit (Silvennoinen 2020b; Booster workshop 2020). The conclusion made in this research is that the number of new pipes in new units should be attempted to be decreased, but an exact target percentage is hard to set. However, this could be used to measure the successfulness of the standardization of the pipes, should it be decided to pursue the standardization in more detail than currently is.

What comes to the suggestions in the morphological matrix, it is a good idea to set simple constraints in the use of the pipe curve dimensions. Especially should the standard and semi-standard booster products be introduced, a limited number of different curves is suggested to be used in them. In the matrix, only 90° and 45° angles are mentioned, but this is not necessarily unconditional. Still, the amount of different angle measures should be kept very limited, save for the most special cases, where for example small footprint is of utmost importance. But these should in turn be very strictly special products only.

Table 2. The morphological matrix of the results of this research.

Parameters:	**Possible solutions – element alternatives**					
Pipe connec-tions	Dual-sided bottom row	Bottom row, front side / mirrored	Anywhere, front side / mirrored	Anywhere, front or back side	Any-where, all sides	At the outlet of the last component
Frame width, smallest units	Current smallest		+16 % of smallest	+25 % of smallest	Current largest	2 300 mm (marine container width)
Design of instruments and -lines	Single instru-ments only		Instrument modules	Modules, repetitive & traced pipes	Modules and all instrumen-tation pipes	
Product categories	Custom boosters only		Customs and semi-standard	All product categories	All, primarily standards & semi standards	
Modulariza-tion	Design modules only		Design & standalone skid-mounted modules		Integratable and standalone modules on frames	
Pipe design	Unrestricted		90° & 45° curves, more in special cases only		90° & 45° curves only, no specials	
Subjects for further research and reviewing						
Electrical enclosure	Upper frame		Cabinet rack		Standalone enclosure	
Heater orientation	Horizontal		Vertical		New heaters - new orientation	
Insulation	Plate covered		Hard mesh covered		Soft	
Pump installations	Block		Separately		Integrated strainers	
Frame build	Beam profile		Sheet metal profile		Sheet metal with stiffening	
Traditional design of the client company	Recently developed new design of the client		Suggested immediate changes		Suggested long-term goals	

In the matrix, the leftmost column with blue shading contains the selection of improvement parameters from the benchmarking and thematic interviews. Each row then displays the different options and ideas found throughout this research for the parameters, respectively. The lower, greyed-out section of the matrix contains the improvement parameters and their design options that were not included in the analysis based on what was defined in the research problem due to their nature, due to their minor concluded impact on the manufacturability of the client's boosters, or because of their need for excessive redesign and conceptualization work before justified suggestions can be made. The bottom row contains the legend of the markings used matrix. Blue dots indicate the traditional design of the client's boosters, while green dots indicate the recently developed design not yet applied to all units. Yellow dots indicate the suggested immediate design changes for manufacturability improvements, while red dots indicate the suggested long-term goals of the design parameters. These long-term solutions have been concluded too bold and drastic for the time being, so that customers might question the new designs, or they require great amounts of design work for proper implementation at production. Therefore, these options should be set as goals for which to aim in the future development projects, which are expected to result in conspicuous new designs and require plenty of design work in any case. Meanwhile, the suggested immediate changes are estimated to substantially improve the manufacturability of the boosters with tolerable visible changes and resource requirements.

5 DISCUSSION

This research was carried out to find the means for improving the manufacturability of the marine feeder-booster fuel supply units. The problem this research solved was the client's need for improving the manufacturability of their products by changing the mechanical design of the products. The objective was to identify design solutions that could be applied to the boosters for improving their manufacturability. This chapter discusses the conducted research.

5.1 Reflexion of the research

Since comparable researches with same methodology are not available for points of reference, reflecting this research against earlier ones would not be very fruitful. Benchmarking, reverse engineering and thematic interviews used together were beneficial in this research. The methods complemented each other very well, especially on a subject that was unfamiliar to the researcher in the beginning of the research.

In addition to the results of this research, this research also yielded a model for the client company for carrying out similar researches in the future. Benchmarking was originally selected due to the client company's request and soon became accompanied by reverse engineering as the research plan made progress. The same methodology can be used for studying similar subjects, be it about improving manufacturability or something else. If proper benchmarks can be set and enough suitable data gathered, other subjects can be researched following the model produced in this research.

The results are well-grounded and comprehensive, and the analysis culminated in feasible applications which will lead to improved manufacturability. Objective, critical attitude towards different sources of information was maintained in the research. The resulted recommendations can be trusted to lead to the desired outcome, should they be implemented in the client company. Convincing arguments were used to justify the resultant suggestions.

5.2 Objectivity, reliability and validity of the research

Objectivity has been a guiding factor though the whole research. In the benchmarking, points of reference were gathered from as widely as possible. Companies from various countries and continents, products with very different designs and source materials from both the client company as well as the benchmark companies were taken into consideration. Although critical thinking was striven to be upheld all the time, it must be admitted that the analyzing the benchmark products is always a subjective process, especially with no physical product to study. The reverse engineering process derives from the background of the researcher, and another person with different background could have ended up with dissimilar results. To counter this, the thematic interview was used during the reverse engineering as well, for expanding and verifying the findings of the researcher. Several people were questioned for the interviews and during the initial interviews, open-mindedness was maintained. The interviewees also were not led to any desired conclusions or statements. When the results of the research begun to take shape, the follow-up interviews were then carried out with more detailed and fixed topics for unveiling all the details concerning each discussed parameter and verifying the understanding achieved based on the preceding research phases. Also, even though many people from different backgrounds and professions were selected as interviewees, they were all employees of the client company working with the Auramarine products for living. This affects and steers their views and thinking to some extent and having other interviewees will result in divergent perspectives and findings.

Although no company visits took place for firsthand observations of the benchmarks, one of the client's boosters was available for hands-on studying during the research. Not only was this valuable for better understanding the Auramarine boosters and their particularities, it also led to being able better to notice and apprehend the differences and particularities of the benchmark units. Also, the main reason for having several interviewees was retaining the reliability of the research, to avoid misinterpretations and to analyze the research subjects to the fullest. The interviews were recorded and transcribed to avoid missing any details and to allow for better focus on the themes during the interview occurrences. In the team interview, not all the participants agreed on every discussed matter and their opinions did not support each other on everything, but regarding the parameters of this research, there were no actual disagreements amongst the interviewees. Different emphases and opinions of the significance of the parameters were presented, but the truthfulness of the parameters was made reliable. Additionally, the reliability of the research was reinforced with the methodological triangulation used in the research. By having the benchmarking, reverse engineering and thematic interviews to support and complement each other, the results of the research were well-founded. The results of the research also corresponded well with the actual state of the subject of the research. Although the final results did not fully correspond to the presumptions of the researcher, this was due to the incorrect presumptions that were proven mistaken during the research. Learning and gaining new experience therefore also took place during the research.

Gaining accurate information and valid results has been pursued by questioning all the found particularities and reflecting them against the former knowledge of the researcher, especially that gained in the engineering studies. Also, none of the findings of the interviews were taken as absolute truths, and the statements were questioned and verified with other interviewees to maintain the validity of the findings. The group of interviewees selected in the interviews was chosen to represent professions as widely as possible and having people with long experience and wide expertise was considered important. However, interviewees from outside the client company could have brought additional perspectives and more critical remarks to the research. It would be beneficial to consult an external authority, such as an engineering agency, in future researches using the methodology derived in this research.

5.3 Key findings

The findings of this research comprised of identified differences between the boosters of the client company and products of the benchmark companies, potential areas of development identified from the silent information that affect the manufacturability of the booster units of the client company and suggestions of the designs that would improve the manufacturability of the booster units of the client company. The identified differences between the booster units of the client company and products studied with benchmarking were:

- Whether or not there is an upper frame
- The way the electrical enclosures are implemented
- The installation location of the electrical enclosures
- The type of used heat insulation
- Whether the heater components are aligned vertically or horizontally in the unit

- The way the pipe connections are positioned
- The implementation of the feeder pump installation
- Proportions of the booster's frame

These were the concluded differences because these could be perceived when benchmarking the Auramarine boosters against the available benchmark materials. The potential areas of development that could improve the manufacturability of the booster units of the client company identified from the silent information were:

- The width of the booster's frame
- The way modularization is applied in the design of the boosters
- The product categories to which the boosters are included
- The limitations and objectives used in the pipeline design
- Whether instrument modules and instrumentation pipes are designed and to what extent
- The structure of the frame and the method the materials are used in the frame

These are the particularities that emerged during the interviews that were concluded to affect the manufacturability of the booster units. The conclusions made based on the silent information were also verified with further interviews and in the group interview. Of the designs and principles identified in this research, these were the ones that can be used to improve the manufacturability of booster units of the client company:

- No longer using the dual-sided design for the connections of the pipes and allowing the connections to be located at any height on the front or back of the unit. In the future, allowing the connections to be located all around the unit, even in the outlet of the last component of a function, would improve the manufacturability even further.
- Using a larger dimension for the width of the smallest units. Exact maximum dimension is difficult to suggest without prototyping and conceptualization.
- Designing the instrument modules, repetitive instrumentation pipes and trace heated instrumentation pipes in the mechanical design. In the future, all instrumentation pipes should also be designed.
- Designing the boosters to all product categories, even the standard product category.

- Applying modularization to the boosters in conjunction with the product categories, using standard products as a basis for semi-standard products. Also, standalone modules based on the used extra modules could be produced for special orders.
- Aiming in the use of standard pipes and curve dimensions, mainly 90° and 45°, even at the expense of having to increase the frame width. Irregular curve dimensions should only be used in special orders.

These solutions were concluded to lead to the possibility of using simpler pipes with more repetitiveness in the parts of the client's boosters. It was found that the pipes and the frame are the parts of the booster designed by the client company, as most of the other components are mainly purchased from outside the company. Since it was found that there is most trouble at the pipe production and the manufacturing costs of the pipes were found to have the most multiplier effects, affecting their manufacturability was concluded to have the greatest impact on the manufacturability of the boosters.

In addition, ideas of new designs of the components designed by the client company, such as the heaters or the mixing tank, sprouted up during the research. These designs could lead to new possibilities with the booster arrangement and layout, further improving the manufacturability of the units. Also, some development projects that have gotten decelerated were mentioned during the interviews, and it was concluded that investing in these projects as well as being generally more aggressive in developing the boosters is recommended. These ideas could be carried out and conceptualized along larger development projects that require tearing down the used designs in any case.

5.4 Significance of the results

The significance of the results for the scientific community is mostly trivial. The new information produced and important findings of the research were heavily associated with the products of the client company. As the results were different design options and suggestions of their use for improving the manufacturability of the Auramarine boosters, the relevance of the results for the scientific community is controversial. This research can, however, be used for reflecting future researches of similar nature and same methodology used.

On the other hand, for the client company internally, the results are of notable significance. By implementing the resultant suggestions be to a degree, positive impacts on the manufacturability of the boosters can be achieved. The outcomes following the improved manufacturability are decreased production costs and lead times, better suitability of the parts for subcontracting, better serviceability, less claims and easier estimation of the total costs of the products. However, it must be noted that obtaining the benefits is not the only significance this research bears to the client. To achieve the mentioned outcomes, customer consultation, redesign, prototyping and discourse with subcontractors must first be made. In other words, investments and effort is required before the profits can be expected.

5.5 Usability and generalizability of the results

Globally, the generalizability of the results is limited. Like what was defined in the research problem, the results focused on identifying means for improving the manufacturability of the client’s boosters locally, considering the particular products and current situation of the company. However, across comparable products facing similar needs for manufacturability improvement, the results are also partially generalizable, as the resultant suggestions consisted of altered principles and objectives for the product design. The results can additionally be generalized with other subjects of similar nature, as for example standardization and modularization can be used to improve the manufacturability of other products as well.

Since the results were principled suggestions for design changes and objectives, the magnitude of their effects is difficult to measure in advance. Should the suggestions be implemented, however, the effects could be measured using typical DFMA evaluation criteria. The following variables can be used for monitoring the success, and smaller value is better:

- Throughput time of a unit in design
- Throughput time of a unit in production
- Amount of manufacturing operations applied to a component
- Number of joints in a component
- Amount of installations in an assembly
- Total number of parts in a unit
- Amount of different parts used across all units

- Amount of newly designer parts in a new product

Additionally, as some of the results were already either thought of or even partially utilized in Auramarine, the results of this research can also be used to verify the relevance of those ideas. Not all the found parameters and solutions were considered useful in this research, and new or previously disregarded solutions were contemplated profoundly. Therefore, the results of this research can also be used to reassess the past decisions regarding those design changes.

5.6 Suggestions for further research

Because benchmarking is a tool for continuous improvement, proceeding with the development is recommended even after implementing the results of this research. The used methodology can be utilized for future development researches with new benchmarks available, for example when the competing companies release products with new designs, or if products in new areas are planned at the client company with competitors already in the market. In addition to that, the parameters excluded in the morphological analysis should also be subjected to comprehensive research complete with prototypes and concept products. These parameters were:

- The electrical enclosure
- Heater orientation and redesign of the heaters
- Insulation types
- Feeder pump installation
- The structure of the frame and the method materials are used in it

Additionally, the layout, arrangement and order of the used components in the boosters could be examined critically and out of the box. This would require extensive familiarization with the boosters, their processes, electrical design and mechanical embodiments. The questions the research seeks answers for could be about the process flow, functions, flow arrangement and dimensions of the units and integration of separate components, processes and functions within the units. Being a suggestion for creative thinking, precise constraints and starting configuration are hard to set. The motivating idea could be that if NASA was given a contract to design a new booster unit from a clean slate, what would the outcome be like.

6 SUMMARY

This research consisted of identifying means for improving the manufacturability of the marine feeder-booster fuel supply units produced by Auramarine Ltd. The research was performed on the client's initiative due to their desire to improve the manufacturability of their products. The objective of finding means for improving the manufacturability was contemplated from a design for manufacturing and assembly point of view. The research mostly focused on changes of the piping, frame and their design, because those were found to be the sections of the boosters the manufacturability of which could be affected. The piping of the boosters has also proven the most important manufacturability-wise in the client's situation, so the research emphasized its manufacturability the most. The research only considered the booster products, although the results were partially applicable to other product families of the client company as well.

The research was executed using benchmarking, reverse engineering and thematic interviews. Competing products were studied using benchmarking for finding the differences and various designs used in the products when compared to the client's boosters, and reverse engineering was used for analyzing and assessing the effects of the findings on the manufacturability of the boosters. Thematic interview was used throughout the research for complementing the benchmarking and reverse engineering as well as expanding the perspective for the observations. Silent information was also made audible with thematic interview, and the results were lastly verified with a group interview amongst professionals from different departments. All the interviewees were Auramarine's employees.

The outcomes of the research were then analyzed using morphological analysis and morphological matrix. The key results of the research were suggestions for changing the pipe connections, frame width, extent of instrument and instrumentation line design, usage of product categories as well as modularization and rethinking of the pipe design constraints and objectives. These suggestions were estimated to lead to simpler pipes with improved manufacturability, more spacious booster frames for better assemblability and serviceability, better predictability of the production costs of the boosters and more standardized production.

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