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RESEARCH AND COST COMPARISON OF PROPULSOR STEEL OUTFITTING FASTENING METHODS

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TIIVISTELMÄ

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Propulsiolaitteen teräsvarustelun kiinnitysmenetelmien tutkimus ja kustannusvertailu

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Tässä työssä tutkitaan propulsiolaitteen teräsvarustelun kiinnitysmenetelmiä, niiden vaikutusta teräsvarustelun valmistuskustannuksiin sekä vertaillaan kustannukset keskenään. Lähtökohtana käytetään olemassa olevat teräsvarustelun rakenteelliset ratkaisut. Kiinnitysmenetelmien tutkimuksessa käytetään sekä käytössä olevat vaihtoehdot että uudet vaihtoehtoiset menetelmät. Tavoitteena on saada sekä teoriaan pohjautuvat perustelut erilaisten kiinnitysmenetelmien eduista ja haitoista sekä kvantitatiiviset tulokset vertailua, analyysiä ja päätöksen tekoa varten.

Työ suoritetaan tutkimalla tiedossa olevaa dataa, kuten asiakkaan projekteissa käytetyt teräsvarustelun rakenteet ja mallit, sekä keräämällä asiakkaan sisäiset palautteet ja hiljainen tieto. Kirjallisuuden pohjalta tutkitaan erilaisten kiinnitysmenetelmien soveltuvuutta teräsvarustelun sovellukseen ja valitaan kilpailukykyisimmät, myöhempiä laskelmia varten. Kustannuslaskennan menetelmien mukaan valmistuskustannukset jaetaan osa-alueisin ja etsitään mahdollisia säästökohteita. Valmistuskustannukset selvitetään yleisiä hitsauskustannusten laskentamenetelmiä käyttäen.

Valmistuskustannusten laskenta suoritettiin käyttäen kolmea erilaista kiinnitysmenetelmää, jotka valittiin teoreettisen tutkimuksen pohjalta. Saatujen kvantitatiivisten tulosten perusteella käytössä oleva kiinnitysmenetelmä, jonka mukaan teräsvarustelun osat hitsataan suoraan propulsorin runkoon kiinni, on edullisin, kun huomioidaan koko valmistusketju. Tämän lisäksi tulosten vertailussa havaittiin miten kustannukset korreloivat keskenään. Jokaiselle kustannusryhmälle erikseen lasketut kustannusarvot osoittavat mahdolliset säästökohteet ja jatkotutkimuksia vaativia aiheita.

ABSTRACT

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Research and cost comparison of propulsor steel outfitting fastening methods

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72 pages, 16 figures, 9 table and 9 appendices

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Keywords: propulsor, arc stud welding, adhesive bonding, screw connection, manufacturing costs, DFMA, cost analysis, manufacturing method.

In this work, the fastening methods of the propulsion unit steel outfitting are studied, affecting the manufacturing costs of the steel outfitting and comparing the costs. The starting point is the existing structural solutions for steel outfitting. In study of fastening methods, both current methods and alternative methods are used. The purpose is to provide a theoretical basis for the advantages and disadvantages of various fastening methods and quantitative results for comparison, analysis and decision making.

The work is done by examining available data such as structure and models of steel outfitting used in customer projects and collecting internal feedback and silent knowledge. Based on the literature sources, the applicability of various fastening methods to the use of steel equipment is studied, and the most competitive ones are selected for further calculations. According to cost estimation methods, manufacturing costs are divided into groups and investigated for potential savings. Manufacturing costs are determined by common methods of calculating the welding costs.

The manufacturing cost calculation was carried out using three different fastening methods selected based on theoretical research. Quantitative results show that the fastening method where the steel outfitting is gas metal arc welded directly to the propulsor hull, is the most profitable in production when considering the entire production chain. In addition to this, a comparison of the results showed how manufacturing costs correlate with each other. Cost values calculated separately for each cost group identified potential areas for savings and topics for further research.

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ABBREVIATIONS

BOM	Bill of Material
CNC	Computer Numerical Control
DFA	Design for Assembly
DFC	Design for Cost
DFM	Design for Manufacturing
DFMA	Design for Manufacturing and Assembly
FEM	Finite Element Method
HAZ	Heat Affected Zone
MAG	Metal Active Gas welding
MIG	Metal Inert Gas welding
PLM	Product Lifecycle Management
TDS	Technical Data Sheet
WPS	Welding Procedure Specification

1 INTRODUCTION

As a result of many years of experience in propulsion systems, the customer obtained knowledge and feedback on the various production methods and use of propulsion system parts and components, a lot of data is available. The propulsion system is in constant improvement by searching for new manufacturing solutions and improving the existing ones. The results of production methods, based on operating experience and production costs, are analysed and compared. The results obtained make it possible to decide which of the production methods is more optimal for a specific application.

This study will explore the production of propulsor steel outfitting. The main criteria of the study will be a comparison of various methods of fastening and their impact on the cost of manufacturing.

1.1 Propulsor steel outfitting function

For fastening the parts and components of the propulsor equipment to the inner hull surface, so-called steel outfitting is used. The steel outfitting acts as an intermediary between the smooth surface of the hull and the pneumatic, hydraulic, and electrical systems components. In some cases, steel outfitting is a project-specific solution and sometimes a permanent solution for many similar projects. Structurally, it consists of many steel plates of various shapes and small welded assemblies, which must meet special requirements, such as strength and corrosion resistance. Regardless of the project for which steel outfitting is designed, the functions it performs and the overall design idea remain the same.

1.2 Research purpose and questions

The purpose of this research is the lack of quantitative and comparable data on how different fastening methods affect the cost of manufacturing of propulsor hull steel outfitting.

According to research purpose, research questions can be used:

- what are the groups of the manufacturing costs of steel outfitting?

- what are the risks associated with the reliability of the joined parts and the manufacturing cost that may arise when changing the fastening method of steel outfitting?
- how can manufacturing costs be estimated?
- how can manufacturing costs be reduced?

1.3 Research methods

Studying and searching for answers to the research purpose and questions presented above requires theoretical and empirical research. First, a theoretical study is performed, based on which an empirical study will be carried out. One of the purposes of the theoretical approach is to study and compare different fastening methods and their impact on the manufacturing costs of steel outfitting. Another purpose is to check the formation of manufacturing costs, search for the main factors affecting their value and methods to reduce them. The study will draw on reliable sources, such as books, research, and publications in scientific journals in technology and cost calculation. The study of the manufacturing chain of steel outfitting and the selection of equivalent assemblies for the objective research will be carried out by comparing available data and collecting silent knowledge within the customer's organisation.

The result of empirical research will be expressed in quantitative results. Thus, the actual total manufacturing costs will be divided into smaller groups in separate categories for a more thorough analysis of each of the cost groups. Depending on the fastening method, corresponding calculation method will be used. The correlation of the results obtained and the strength of their dependence on changes in the input parameters will be studied using sensitivity analysis. Conclusions will be performed based on the analysis of the results obtained by comparing both separate costs and the total manufacturing costs.

1.4 Research limitation

This research is performed for one customer and a specific product. To maintain a competitive advantage, the customer company does not want to disclose its name and product name. This fact affects the course of the entire study, especially on specific data and numerical results to be encrypted.

The research includes the study of fastening methods for a specific case. This case is the fastening of steel outfitting to the propulsor hull. The purpose is to investigate how the fastening method affects the structure of the steel outfitting and how the construction of the steel outfitting affects the manufacturing costs, both direct and indirect. Indirect costs will not be explored in detail in this study but will be suggested for further research if necessary.

This study aims not to improve any specific steel outfitting structure or to find new design solutions. Therefore, when investigating various fastening methods and calculating the cost of manufacturing, existing design solutions and previously tested materials will be applied with minimal changes.

There are many types of propulsion systems. The study will not focus on any particular type of propulsion system. The operating conditions inside all propulsors are approximately the same, and the function of the steel outfitting remains unchanged, regardless of the type of propulsor system. Accordingly, both the requirements are taken into account in the study, and the results obtained will apply to any propulsion system.

The empirical research will be based on the available actual parameters. It will be necessary to select the appropriate reference projects whose structure and production costs are known and can serve as a starting point for research.

The topic, purpose and questions of this research require a solution that will be quantitative so that the study will be based on quantitative methods. The study includes analysis and comparison of manufacturing costs. Based on the analysis and comparison results, conclusions will be drawn about possible ways to reduce manufacturing costs. In addition to this, proposals will be made for the development of steel outfitting in future research.

2 PROPULSOR STEEL OUTFITTING BACKGROUND

This part provides background information, which is a starting point, and all further research will be based on it. The structure of the steel outfitting and the operating conditions inside the propulsor hull will be studied in detail based on existing solutions. It will also consider the strength requirements of steel outfitting obtained from FEM calculations. Compliance with these requirements has a strong influence on the structure of the steel reinforcement and the choice of the fastening method. At the end of the chapter, a detailed analysis of the structure of currently used steel outfitting options will be given.

2.1 Propulsion system hull

The customer offers many models of propulsion systems on the market. The type and size of the vessel on which the propulsion system will be used determine most of its parameters. In addition to this, the propulsion systems can be divided into two main groups according to where the vessel will operate: the open water propulsion system and the ice-class propulsion system. The type of propulsion system will determine the structure of its hull. The hull structure of an open water propulsion system is not as massive as an ice-class propulsion system. Depending on the required power output, the stator and rotor of the required dimensions are selected to provide the required torque. The dimensions of the stator and rotor and the hydrodynamic requirements determine the external dimensions of the propulsor hull. The internal structure of the hull is determined depending on the loads that the propulsor will experience during operation. Therefore, a more significant number of bulkheads are used in the hull of the ice-class propulsion system. The loads are more evenly distributed over the entire surface area of the propulsor hull. Figure 1 shows the propulsor hull model, where the horizontal dashed line divides it into the torpedo part, which is located under the dashed line and the middle and upper parts above the dashed line. A vertical dashed line separates the hull into a drive end, which is on the right, and the non-drive end, which is on the left.

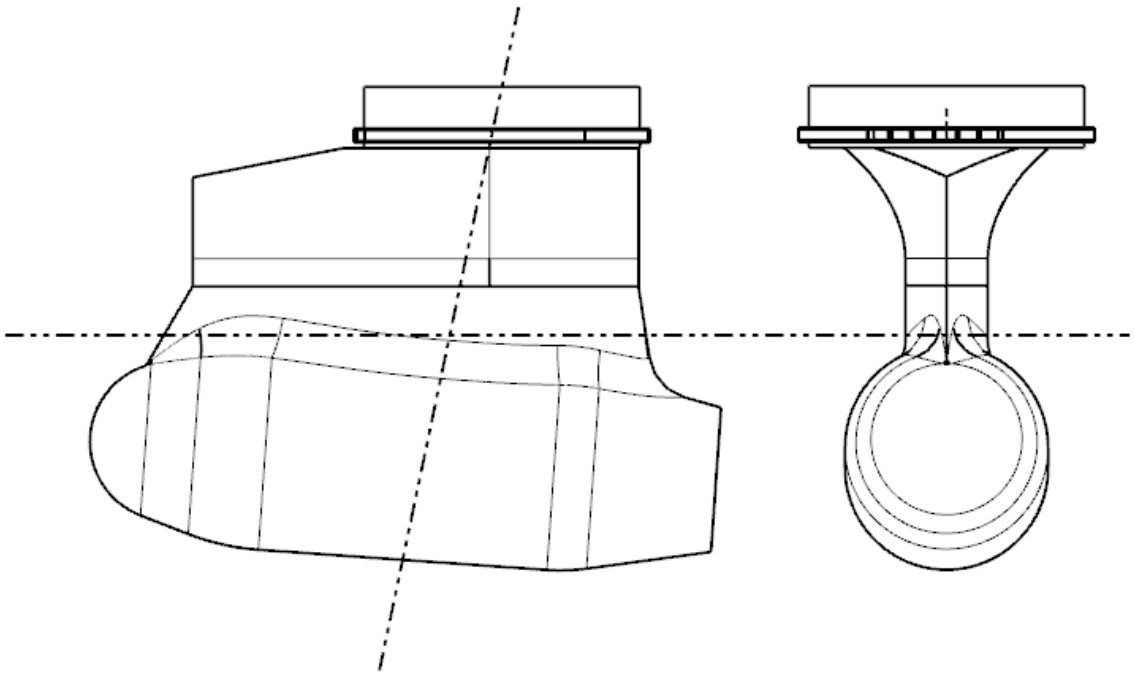

Figure 1. Propulsor hull model.

The open water propulsion system has many standard solutions that do not change from project to project, including hull and steel outfitting. The ice-class propulsion system is constantly being improved, and both the hull and steel outfitting often have project-specific solutions. The structure of the hull and the arrangement of the components determine the design of the steel outfitting. And the choice of the fastening method will be influenced by the following factors: whether the connection will meet all the established requirements, how it will distribute the load and what will be the manufacturing cost. In this study, the difference in hull structures will not be taken into account, and the results obtained can apply to both types of propulsion systems.

2.2 Steel outfitting structure

The structure of the steel outfitting depends on the specific case, which is a propulsion system. The strategy for developing steel outfitting is visible during the study and comparing how its structure and manufacturing requirements have changed with the development and improvement of propulsion systems. Also, the design features and disadvantages are clarified, which must be taken into account in further development.

Steel outfitting structure, depending on the specific propulsion system, is divided into smaller assemblies in different ways; usually, there are three or four. But from a technical point of view, steel outfitting can be divided into two parts, which, due to the structure of the propulsor hull, are fastened to it in different ways. These two parts are the upper part and torpedo part. In the upper part, most of the steel outfitting are attached parallel to the bulkheads of the hull, as shown in the left image in Figure 2. In the torpedo part, the components are fastened perpendicular to the bulkheads, as shown in the right image in Figure 2.

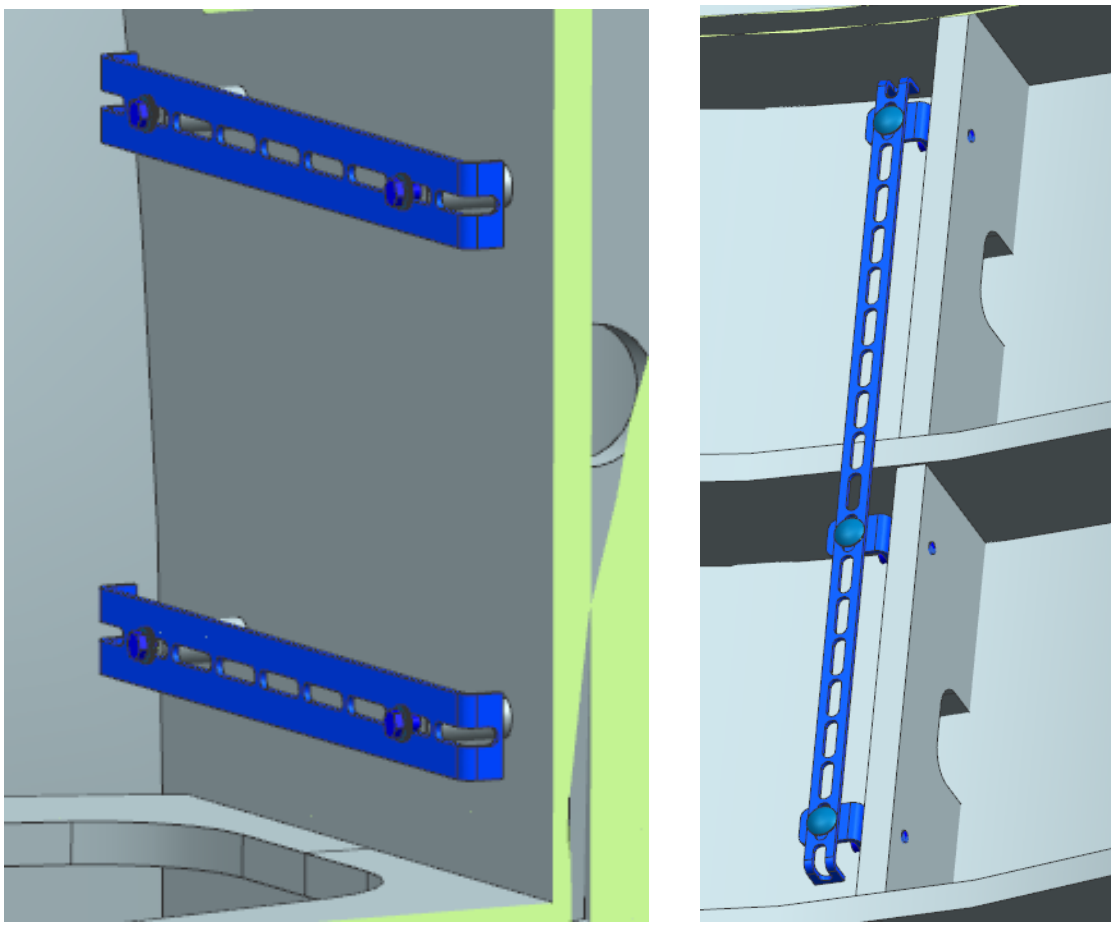

Figure 2. Various ways of fastening steel outfitting parts to bulkheads.

The structure of the steel outfitting and the method of fastening depend on each other. Together, they determine what materials and methods will be used in production and assembly and methods of corrosion protection. In practice, changing one of the parameters involves a change in one or more parameters at once.

Also worth mentioning is the third part of the steel outfitting, which includes additional parts. They are bolted to those parts of the steel outfitting that are already fastened to the propulsor hull. Since the primary loads are borne by the parts attached to the hull, the additional parts do not influence the design and the choice of the method of fastening the parts of steel outfitting to the propulsor hull.

2.3 The operating conditions

In the design of steel outfitting, operating conditions play an important role. Throughout the life of the propulsion system, the steel outfitting parts and their connection with the hull will be subjected to specific conditions inside the propulsor hull.

The main operating conditions and limitations:

- the hull is made of structural steel, the thickness of the bulkheads about 25-40 mm
- parts are subject to corrosion due to an aggressive environment
- presence of hydraulic oil and other chemicals
- strong vibrations
- the propulsor hull is slightly deformed during operation
- the temperature inside the hull can rice up to 70° C.

2.4 Strength calculation results

The strength of the fastening of steel outfitting and all its parts is critical in every aspect. In the event of failure of any part of the steel outfitting, the operation of the entire propulsion system may be disrupted. The FEM analysis method is used to calculate the strength of joints and the whole structure at the design stage. At the moment, the strength calculation results of the steel outfitting connection to the hull have been performed for two different design options, as shown in Figure 3, but using the same fastening method - gas metal arc welding.

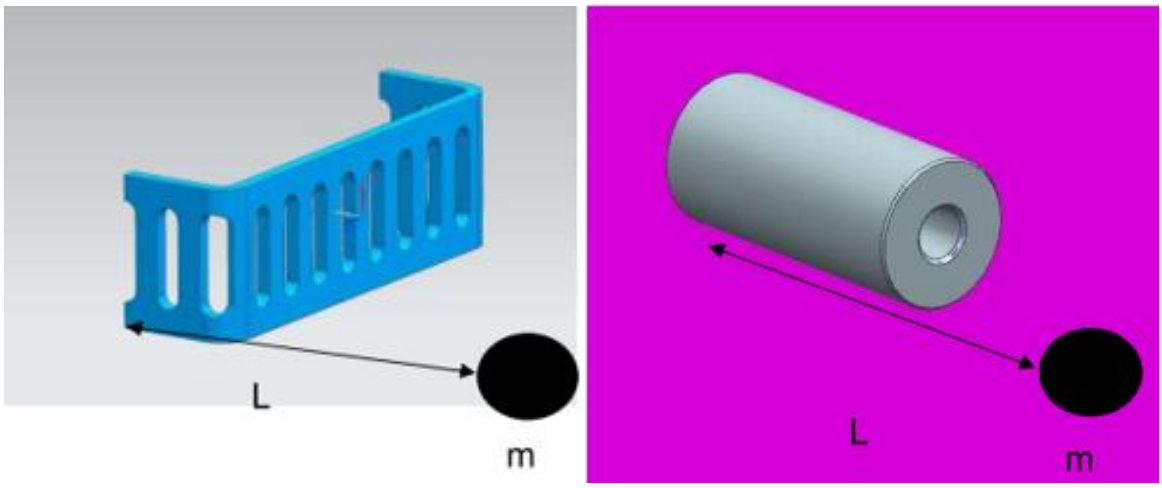

Figure 3. Strength calculation for two different steel outfitting option (Kock 2020).

The following factors were considered in the strength calculations:

- static loads
- dynamic loads with the safety factor
- loads caused by deformation of the propulsor hull

Based on these factors, the load that the various steel outfitting options can withstand have been calculated. The calculation results showed that the steel plate welded by the a3-weld to the propulsion hull has sufficient strength. It can withstand a load of 120 kg at a distance of L = 160 mm from the welded joint, as shown in the left image in Figure 3. The threaded stud must be welded with an a5-weld to obtain corresponding results under similar conditions. Then the strength of one 30 mm diameter stud can withstand a load of 65 kg at a distance of L = 160 mm from the welded joint, as shown in the right image in Figure 3. (Kock 2020.)

2.5 Steel outfitting options in use

Currently, the customer has experience in the production, installation and use of three different options of steel outfitting. Since all three options differ from each other, the structure of their manufacturing costs also differs. Steel outfitting design varies depending on the fastening method. Still, the basic design idea remains the same, and any steel outfitting option includes many different steel plates and small welded assemblies.

Below are examples for these three options of steel outfitting in which steel plates of approximately the same shape and dimensions were selected for better understanding and

simplification of comparison. These examples demonstrate how different fastening methods affect the assembly design and how manufacturing costs are generated, which will help achieve good reliability and validity.

In the first option of the steel outfitting, the steel plates are gas metal arc welded directly to the propulsor hull, as shown in Figure 4. The structure of manufacturing costs is divided into the following groups:

- manufacturing of steel plates
- gas metal arc welding of steel plates to the propulsor hull
- painting (also with a brush).

The costs of the painting of steel outfitting parts cannot be calculated without considering the painting costs the hull's inner surface. When the steel outfitting parts are welded to the hull, they become one piece. The contractor can only calculate the price for painting the entire structure. But by using the same propulsor hull size with different steel outfitting options, it is possible to calculate and compare how different steel outfitting options affect the overall cost of painting.

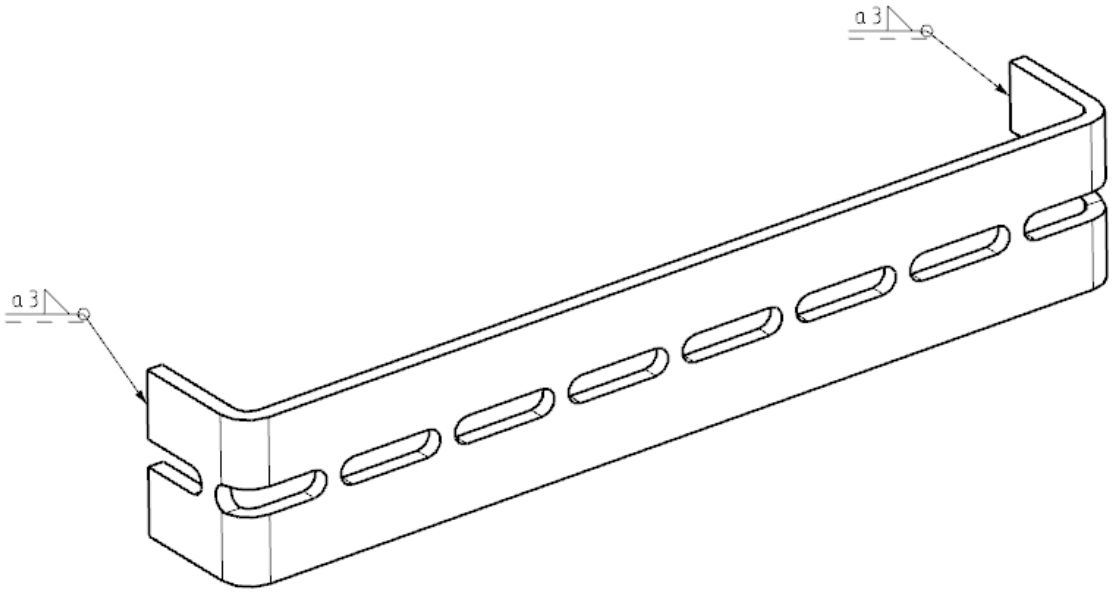

Figure 4. Example of the first option of steel outfitting.

In the second option of the steel outfitting, threaded studs are used, which are gas metal arc welded to the propulsor hull, as shown in Figure 5. The assembly consists of five parts:

1. Steel plates (stainless steel)
2. Threaded stud
3. Hex socket countersunk screw
4. Special washer
5. Threadlocker.

The hex socket countersunk screw and threadlocker are standard components. The steel plates, threaded studs and special washer are project-specific components manufactured according to individual drawings or standards. A special washer is used because many electrical cables are fixed to the steel outfitting, which can be damaged by the sharp edge of a standard washer. Therefore, special washers are used on many joints, which are smooth in shape and edges.

Apart from component costs, there are other manufacturing costs such as:

- gas metal arc welding of threaded studs to the propulsor hull
- painting including protection of the threaded holes
- final assembly of steel plates using screws and special washer.

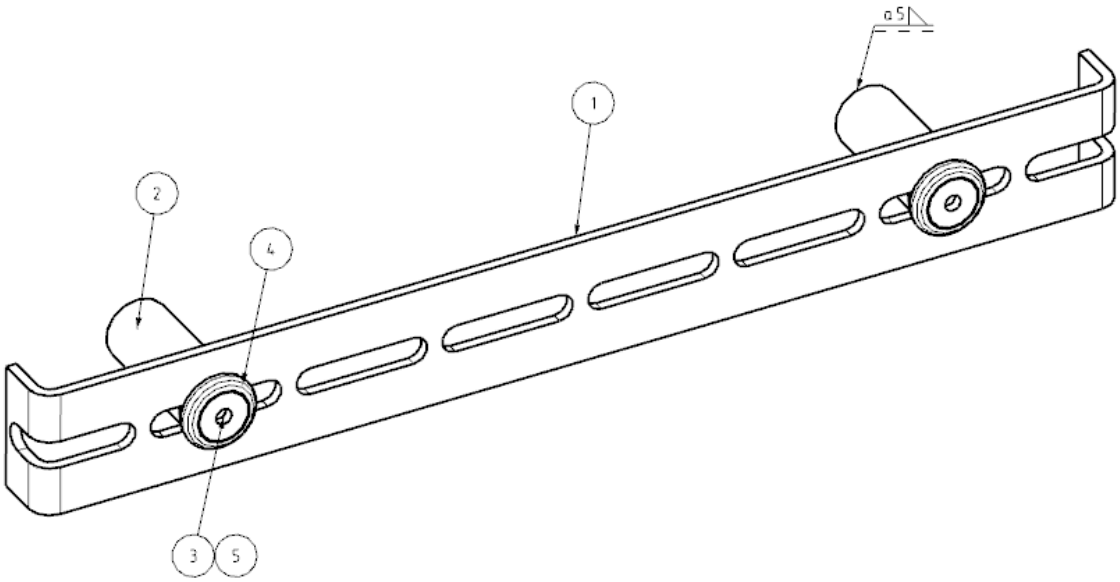

Figure 5. Example of the second option of steel outfitting.

In the third option of the steel outfitting, the steel plates are joined using screws and threaded holes made in the bulkheads of the propulsor hull, as shown in Figure 6. The assembly consists of six parts:

1. Steel plates (stainless steel)
2. L-brackets (stainless steel)
3. Cup head square neck
4. Hexagon socket head screw
5. Nord-lock washer
6. Hexagon regular nut

Parts number 3-6 are standard components. The steel plates and L-brackets are project-specific components and are manufactured according to individual drawings or standards.

Apart from component costs, there are other manufacturing costs such as:

- manufacturing of threaded holes in the bulkheads
- protection of the threaded holes before painting
- final assembly of steel plates and L-brackets using screws, washers, and nuts.

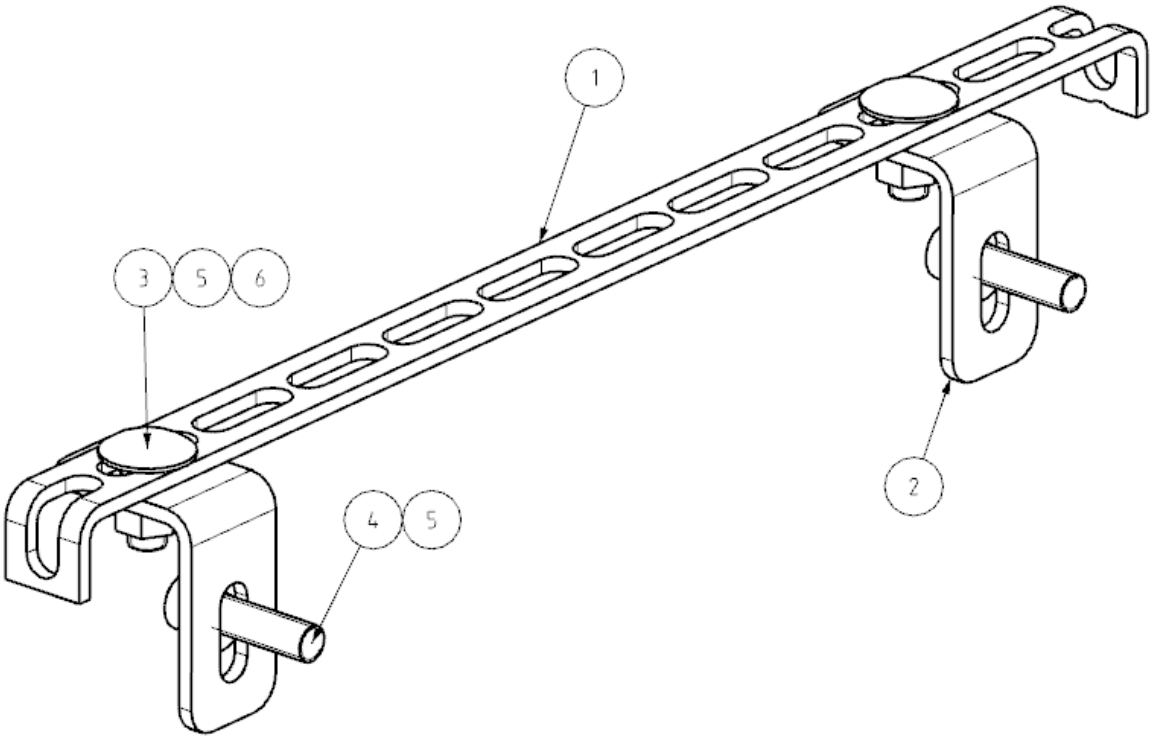

Figure 6. Example of the third option of steel outfitting.

The above options for steel outfitting, the first is the standard option for steel outfitting in propulsion system case and has been tested in all parts (upper, middle and torpedo parts) of the propulsor hull. The second option with threaded studs is used only in the upper and middle parts of the hull. The third option, which requires threaded holes in the bulkheads, is used only in the torpedo part of the hull.

3 FASTENING METHODS

An ideal connection of structural parts should effectively distribute forces between the connected components and throughout the assembly. In contrast, the connection should meet all specified requirements, and its cost should be possible the lowest. The choice of a suitable type of fastening is primarily influenced by the technical requirements that apply to the connection. In particular, this is the effect of mechanical stresses throughout the entire service life. Many different connection options are often suitable for connecting the same parts. The most significant difficulty is determining which one is the most optimal in terms of serviceability and cost. These factors are often confused with each other. The choice of the optimal connection option can depend on the number of parts connected, equipment costs, joint location, final weight and desired product characteristics, worker experience and technical production capabilities. (Campbell 2011, pp. 1, 19.)

Parts joined together to form a single assembly that performs one or more functions. Functions are divided into three main groups: structural, mechanical, and electrical. Structural assembly implies use in applications with static or dynamic loads. The main types of joining parts into an assembly are divided into three types: mechanical joining, adhesive bonding and welding. The mechanical connection is beneficial when creating temporary connections, but adhesive bonding and welding are mainly used to create a strong permanent connection. (Messler 2004, pp. 4, 22.)

3.1 Used and alternative fastening methods

There are many fastening methods, some of which are the most suitable for the studied case. Campbell (2011, p. 4) divided the most used fastening methods for the following primary classes: welding, brazing, soldering, adhesive bonding, mechanical fastening. Each of these may be made in many ways, which should be chosen depending on the specific situation. Some fastening methods are already used in steel outfitting application; they are:

1. Gas metal arc welding
2. Screw connection using a threaded hole.

Along with the fastening methods already in use, the following alternative fastening methods will be studied, which may compete with those already in use:

3. Adhesive bonding
4. Brazing
5. Bolt connection using a through-hole
6. Arc stud welding.

The previous section 2.5 discussed how the chosen fastening method and the steel outfitting structure interact. Based on this knowledge, it is possible to determine how alternative fastening methods will influence steel outfitting and the entire manufacturing process.

The structure of the steel outfitting when using the permanent fastening method has two options - it is either a steel plate or a threaded stud. The priority is the threaded stud option due to its small size and a simpler and faster connection. The size, shape and location of the steel plates vary. For this reason, their connection to the hull creates many problems in the fitting stage, which takes a significant amount of time. Therefore, when studying alternative fastening methods such as adhesive bonding and brazing, the focus will be on the threaded stud option.

The structure of the steel outfitting using alternative fastening method bolt connection using a through-hole is comparable to the structure of the steel outfitting when using method screw connection using a threaded hole. Arc stud welding is a method by which only parts identical in shape to the stud can be welded.

Based on the above, to visualise the fastening method interaction with the structure of the steel outfitting, Table 1 is compiled. The table contains all six methods, that is, both already used and alternative methods.

Table 1. Fastening methods and their influence on the steel outfitting structure.

Number	1		2	3	4	5	6
Fastening method	Gas metal arc welding		Adhesive bonding	Brazing	Screw connection using a threaded hole	Bolt connection using a through-hole	Arc stud welding
	steel plate	threaded stud					
Steel plate	x						
Steel plate SS		x	x	x	x	x	x
Threaded stud		x	x	x			
Special stud							x
Arc stud welding equipment							x
Screw		x	x	x	x	x	x
Special washer		x	x	x			x
Nord-lock washer					x	x	
Nut						x	
Thread-locking		x	x	x			x
Painting	x	x	x	x			x

As shown in the table, options number 1 and 4 are already in use and the 2, 3 and 6 options viewed as threaded studs used, as shown in Figure 5. And option number 5 is comparable to option number 4, as shown in Figure 6.

3.2 Welding

The welding method has a long history. During the last century, there are opened and taken to use a lot of different welding methods. They all can be divide into two groups: pressure welding and fusion welding. During pressure welding, the joined surfaces are weld by sufficient outer force. As a result of this is the applied plastic deformation of both facing surfaces. The facing surfaces are usually heated, but it is typically unnecessary, and usually, no filler material is needed. Fusion welding does not require outer forces. Welding is made

by melt facing surfaces and adding a filler material, but it is unnecessary. (Weman, 2012. p. 9.)

Many types of welding are often suitable for welding the same application. But Campbell (2011, p. Viii) notes that up to 90% of all industrial welding is arc welding, which refers to fusion welding. The remaining 10% of industrial welding is usually specific tasks like unique materials, constructions, or welding in extreme conditions. Sometimes welded parts are designed to be used with a particular welding method, for example, for financial reasons. Figure 7 shows that arc welding can be made by using shielded gas and without it.

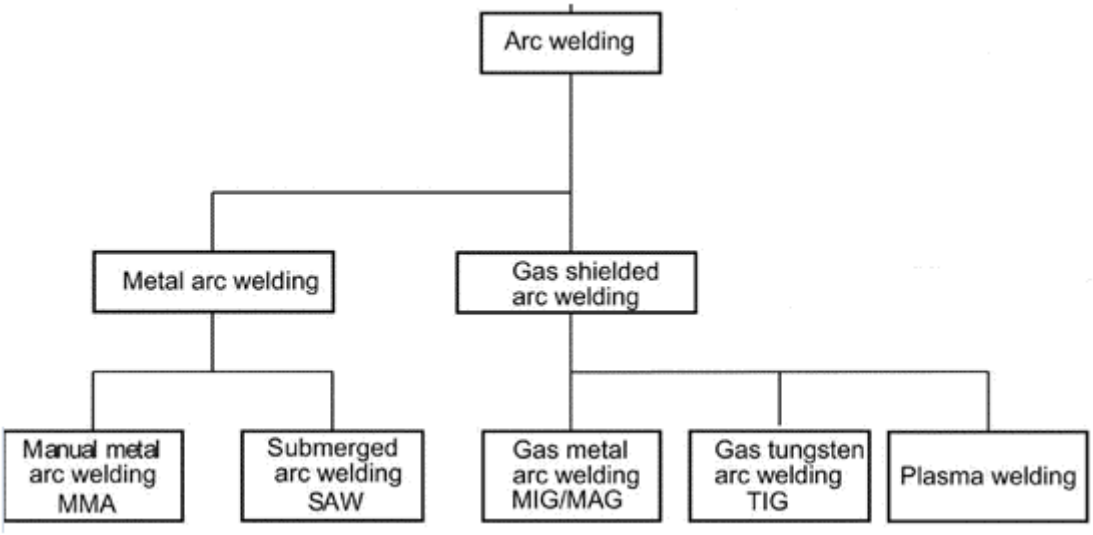

Figure 7. Arc welding types. (Weman 2012, p. 8, modified)

According to Lukkari (2011, pp. 2-3), the welding costs are consisting of the following parts:

- labour costs (welders)
- material costs (additives, shielding gases and welding powders)
- equipment costs (welding machines and their maintenance)
- electricity costs (electrical energy consumed by the welding machine)

If these costs are known, then adding them up will find out the total price of welding. Before starting the calculation, it is needed to determine which unit should be used in the calculation. The cost of welding can be calculated per meter or kilogram of the weld or for the entire part. For welding costs accurate calculating, there are specific formulas that can be used. For

example, Lukkari (2006 p. 8) or Hobart Institute of Welding Technology (2012 p. 39) suggest their formulas and calculating MIG/MAG welding methods.

The costs of other stages of welding-related work, such as preparatory work, inspection and possible subsequent repairs, are usually not directly included in the cost of welding. Of course, they are also counted separately in the cost of the final product. The most significant cost item in industrial production is labour costs. For manual welding of unalloyed steel, these costs vary in the region of 75-90%, the rest of the costs are divided into additives, shielding gases, equipment and energy. (Lukkari 2006, pp. 8-11.)

3.2.1 Gas metal arc welding

Manufacturers typically use gas metal arc welding like MIG/MAG method to weld large constructions made of structural steel. Since this method is prevalent, many manufacturers have the equipment and knowledge of this welding method. The following are the advantages and disadvantages of the method.

Advantages:

- can be used to weld most commercial metals and alloys, ferrous and non-ferrous
- compared to shielded metal arc welding and gas tungsten arc welding, the gas metal arc welding has good travel speeds and deposition rates
- good welding accuracy and, accordingly, high welding quality
- can be used in all positions.

Disadvantages:

- gas shielded arc welding equipment is more complex, costly, and less portable than metal arc welding equipment
- air flows can blow the stream of shielding gas away from the arc
- the gas shielded arc welding gun is large compared to the related equipment, but for metal arc welding. (Hobart Institute of Welding Technology 2012, p. 2.)

As shown in Table 1, gas metal arc welding (method number 1) connects two different steel outfitting options - threaded studs and steel plates. In both cases, structural steel is used, making it possible to use the common MIG/MAG welding method.

Strength calculations using FEM analysis, discussed in more detail in section 2.4, showed that a steel plate and threaded stud made of structural steel are welded to the hull according to the welds shown in Figure 4, and Figure 5 can withstand the required loads.

The painting of the internal surfaces of the propulsor hull following the project-specific surface treatment specification document implies that welded parts of steel outfitting will be painted too. Since the welded parts of steel outfitting and the hull are now one-piece, they must be painted simultaneously. Painting is carried out with a spray gun, and the surfaces are pre-treated by sandblasting. Welded steel plates can be sandblasted and painted without any restrictions. In some cases, little space is left between the steel plates and the hull surfaces, making it difficult to spray paint. In this case, it is necessary to use a brush and paint by hand. In the case of a threaded stud, it is required to protect the threads during sandblasting and painting. For protection, plugs are used, the installation and removal of which significantly increases the painting time.

3.2.2 Arc stud welding

Arc stud welding is a widely used method of joining parts like studs, threaded rods, and ties bolts to a metal workpiece. The possible diameter range in the welding area is 2-25 mm (SFS-EN ISO 14555 2017, p. 36), but the length can be up to a few tens of centimetres. Arc welding of studs provides an excellent alternative to other welding processes and replaces other fastening procedures such as drilling and tapping, screwing, and bolting. The arc stud welding process is similar to other arc welding methods. The power source can be a transformer/rectifier or motor generator, like that used for MIG/MAG welding, but with the higher power. (Campbell 2011, pp. 83-84.)

Drawn-arc stud welding can be performed both mechanically and automatically. A particular welding gun or welding heads are required for welding. The stud is inserted into the welding gun (can be used with the ceramic ring if necessary) is applied to the workpiece. First, the stud is lifted by the welding gun mechanism, after which the welding arc is struck between

the end of the stud and the workpiece. As a result, the face of the stud and the base material melt, then the stud is immersed with a small force (less than 100N) into the molten bath, and the power source is turned off. Then the ceramic ring is removed. Figure 8 shows the welding sequence using a ceramic ring, where:

L - lift

P - protrusion

X - time

Y - current

Z - stud movement

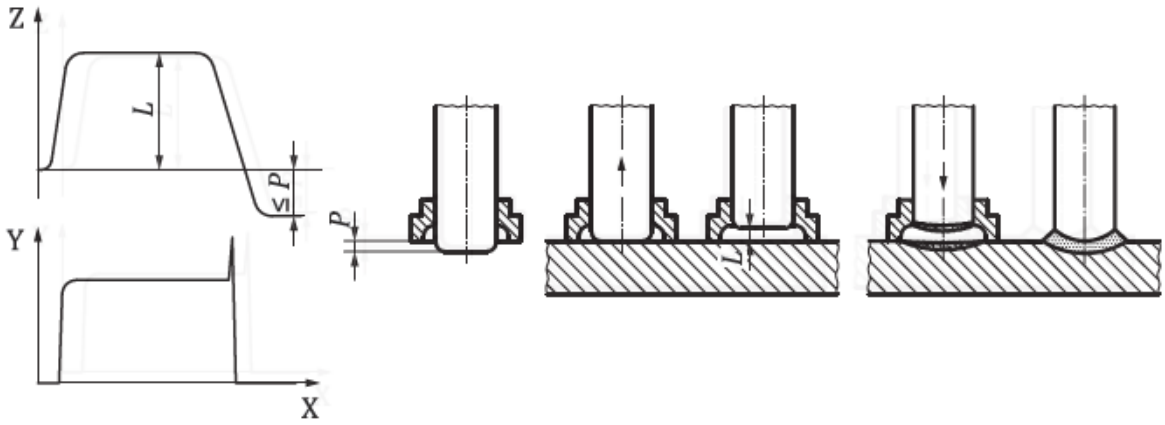

Figure 8. Drawn-arc stud welding. (SFS-EN ISO 14555 2017, p. 102.)

Following the standard SFS-EN ISO 14555 (2017, p. 47), the welding time for a stud with a diameter greater than 12 mm for a flat position (PA) can be calculated using the formula:

$$tw = 0{,}04 * d \qquad (1)$$

In formula 1 the *tw* is welding time (s), and *d* is the diameter of the welded stud (mm). Using this formula can be calculated that for a stud with the largest allowable diameter of 25 mm, the arc time of welding will equal 1 second. Short arc time of welding is the main advantages of arc stud welding (Retco 2020).

The main disadvantage of the arc stud welding method is the relatively small maximum allowable stud diameter. Due to the high welding current (up to 4000A), the molten metal

begins to flow during the arc time. Therefore, the diameter of the studs is limited, depending on the welding position, as follows:

- 25 mm for PA-flat position
- 20 mm for PE-overhead position
- 16 mm for PC-horizontal position. (SFS-EN ISO 14555 2017, p. 34.)

For this type of welding, a FEM analysis was performed (Kock 2020) in the same way described in section 2.4. The calculations were carried out for threaded stud with a diameter of ø25 mm. The calculations showed promising results comparable to gas metal arc welding of the threaded stud option results, as shown in Figure 9:

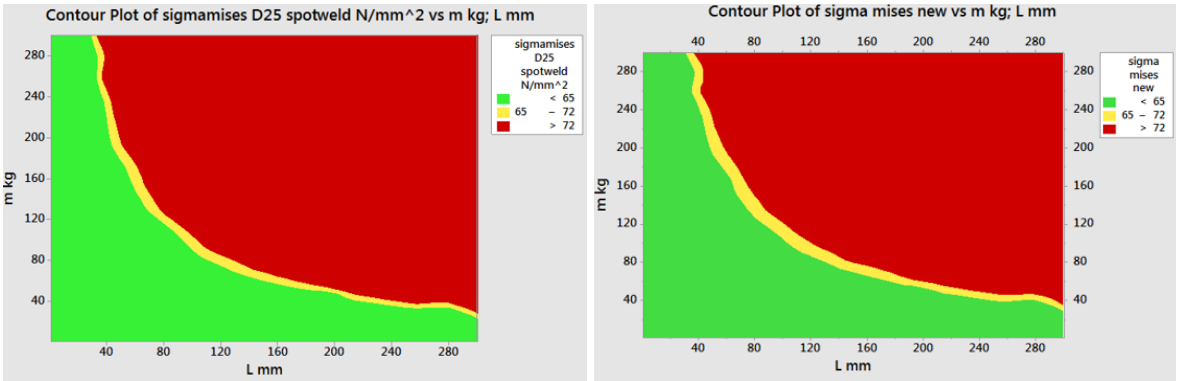

Figure 9. FEM-analysis results.

The left diagram shows the results of arc stud welding, and the right diagram shows the results of gas metal arc welding of threaded stud. In the diagrams, the vertical scale "kg m" indicates the weight and the horizontal scale the distance from the connection "L mm", as shown in Figure 3. The area of non-hazardous loads on the graph is indicated in green and yellow, but the yellow area should be avoided if possible. Dangerous and, therefore, unacceptable regions are marked in red. Thus, the strength of the connection is determined by the location of the load point and its magnitude.

Studs with a diameter of less than ø 25 mm were not considered since the welded surface area will be small, and the strength of the connection may decrease to unacceptable limits. If it is necessary to use smaller diameter studs, further study of the connection strength will be required.

The equipment for arc stud welding is not as common as equipment for gas metal arc welding. But equipment for arc stud welding is freely available and can be purchased or rented. When performing the cost calculations in the following chapters, the cost of equipment for arc stud welding should be considered.

3.3 Brazing

If the filler material melts below 450 ° C, this process is called soldering, and if the melting point is higher than 450 ° C, then it is brazing. But brazing differs from welding in that the base material does not melt (Campbell 2011, pp. 165). During brazing, the area to be joined are heated to the working temperature of the filler metal. Removal of oxides from the surfaces to be united and prevent new oxide layers from forming during heating is typically used flux. As a result of thermodynamic processes, the molten filler metal spreads between the surfaces to be joined and diffuses into the base material. Brazing is an excellent alternative to welding. The main advantage over welding is the lower process temperature at which the base material does not melt (Engineerlive 2013). That allows joining different ferrous metals with non-ferrous metals, regardless of their melting points. Brazing speed can be up to two times faster than welding, and after brazing, the seam does not require stripping or slag removal, which saves working time. (Weman 2012, p. 168.)

The strength of a brazed joint is influenced by many factors, including the area of the joint. The larger the area of the joint, the more forces the joint can withstand. Only an overlap width of at least three times the thickness of the thinner part can provide sufficient joint strength. The example of a joint is shown in Figure 10. (Weman 2012, p. 172.)

In addition to the above strengths of brazing, Campbell (2011, pp. 165-167) highlights the following disadvantages of the brazing method:

- surface cleanliness plays a significant role in creating a strong connection
- some methods of brazing needs before the surfaces to be joined are heated, which is difficult and expensive for large parts
- tight mating of components is required, which often requires costly machining
- the worker must have exceptional skills in manual brazing

The main brazing methods are divided into the following types:

- Braze welding
- Arc brazing (including MIG, TIG and Plasma arc brazing)
- Laser beam brazing

Braze welding is capillary brazing, the strength of which depends on the brazed area and the quality of the capillary force between the surfaces. Arc brazing is less dependent on the capillary force and more on the strength of the metal filler used to fill the joint. Laser beam brazing is an excellent alternative to Arc brazing, but for thin steel plates. Figure 10 shows the fundamental difference between Braze welding, Arc brazing and Gas metal arc welding:

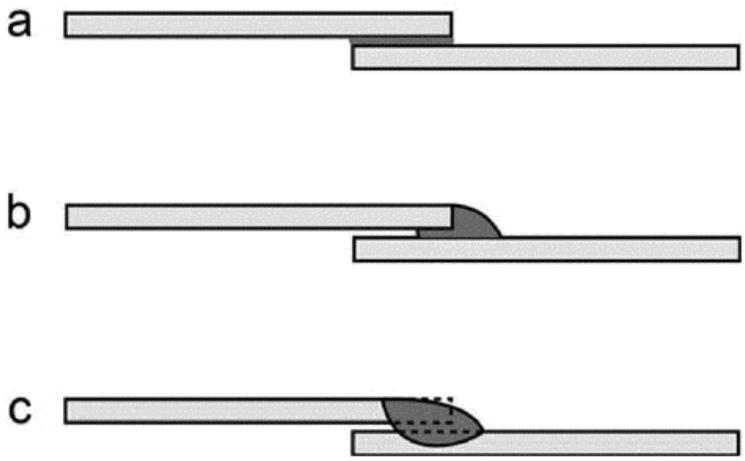

Figure 10. The difference between brazed and welded joints, where: “a” is capillary brazing, “b” is arc brazing, and “c” is welding. (Weman 2012, p. 173.)

Raekorppi (2006 p. 18) writes that modern manufacturers produce filler wire for arc brazing, the tensile strength of which reaches 1000 N/mm^2. The use of such a wire achieves the fatigue resistance of the arc brazed seam equal to the specific fatigue resistance of the base material. Studies confirm the joint strength by Lepistö (2004) and Gericke et al. (2019).

Lepistö (2004) conducted a study in which arc brazed thin-walled unalloyed steel plates with CuSi3 filler wire. Based on fracture tests, Lepistö claims that arc brazing fatigue resistance is as stable or even slightly higher than MAG welding.

Gericke et al. (2019) conducted a study, the theme of which was similar to the one that is studied in this work. The studies are the same in materials, joining technique and parts shape.

They looked at static loaded studs in the cyclically stressed tower for wind energy plants and reasons for notch effect on weld detail, which were MIG welded and arc brazed using two different composition filler wires CuSi3 and CuSi3Mn. The study results showed that the notch effect decreases when the MIG welding process is replaced by arc brazing with CuSi3Mn filler material. In contrast, the fatigue class of the arc brazed seam is higher than that of the welded, regardless of the metal thickness. The bearing capacity of the arc brazed studs turned out to be comparable to the base material. FEM calculations confirmed the results obtained practically. In the future, it is planned to continue research for a deeper study of the arc brazing process in the steel construction industry using various filler wires and brazing parameters. (Gericke et al. 2019.)

Arc brazing method is most widespread in the automotive industry. The heat input during arc brazing is significantly lower than when using a metal electrode in gas metal arc welding, which makes arc brazing especially suitable for joining zinc-coated steel sheets. Due to the low heat input, the steel sheet does not warp, and the zinc coating is not damaged (Kemppi 2021).

Based on the above results of many studies, it can be said that arc brazing is an excellent alternative method for joining steel outfitting parts to the hull. But the use of this type of fastening in practice is not advisable since the method requires the correct design of the joints, specific quality of the surfaces to be joined and their cleanliness. The main advantages of this method are not necessary for steel outfitting application. In heavy structural parts, this type of joint is not well studied to be used with a high degree of confidence in important application such as steel outfitting of the propulsor hull.

3.4 Mechanical fastening

Mechanical fasteners are used in various applications to provide strengths, in some cases the desired appearance and reusability. Reusability is a significant feature of mechanical fasteners, as many assemblies require the ability to be disassembled for service or repair. Mechanical fasteners provide a good level of assembly strength due to their holding force. Selecting the correct mechanical fastener requires a clear understanding of all possible operational loads, both static and dynamic, and requirements for reusability, appearance and cost-effectiveness. (Speck 2015, p. 1-12.)

The advantages of mechanical fastening include:

- no high requirements for the qualifications of workers
- no strict surface preparation required
- usually do not require non-destructive testing
- allow disassembly
- easy to repair.

The disadvantages of mechanical fastening include:

- the presence of holes causes a concentration of stresses around them. As a result of which the fatigue properties of the material/part are reduced
- it can be problematic to obtain and ensure that the correct preload (tightening torque) on the installed fasteners is preserved during the entire service life
- some special fasteners can be expensive compared to alternative fastening methods
- during assembly, the correct preparation of the holes and the surfaces around them plays an important role. The incorrect installation of the washers can cause residual stresses during assembly
- abrasion, and corrosion of joints during operation can lead to their failure. (Campbell 2011, p. 207-209.)

3.4.1 Threaded hole

The thickness of the bulkheads of the hull allows making a threaded through a hole in them of sufficient size to withstand the required loads. The customer has experience in producing and using threaded holes in the torpedo part of the hull. A perpendicular arrangement of steel plates to the bulkheads, as shown in Figure 2, makes using this method preferably to using welding method.

The structure of the hull in the middle and upper part is very different from the torpedo part. In the middle and upper part, steel plates have a parallel arrangement to the partitions, as shown in Figure 2. Sufficient space must be left between the steel plate and the hull bulkhead to fasten the equipment with bolts further. Compliance with this requirement requires a steel outfitting design change or additional parts, which will complicate the design and make it more expensive.

The manufacturing of the threaded hole is simple and cheap in comparison to the welding method. Each location for a threaded hole must be considered individually, taking into account all constraints. The experience knows the customer that in this application, the threaded hole method has a hided cost. Firstly, it is the threads protection during sandblasting and painting. Secondly, the threads need to be opened and checked before steel outfitting steel plates installation. Because otherwise, the chips come off during the assembly, when the stator of propulsor is already fixed on the place. The chips can cause operation problems when they get into the stator air gaps. The work task of checking the threads and the subsequent installation of the steel plates increases the number of working hours, which must be considered. Of course, if the fastening of many steel plates by welding method can be replaced with several screwed joints, it is a good alternative. But using a threaded hole method for fastening all parts of steel outfitting may be economically disadvantageous compared to welding.

3.4.2 Through-hole

Fastening steel outfitting with a bolt and nut using a through-hole is similar to the method of fastening with a threaded hole described in the previous section 3.4.1. But in terms of the production process, it is simpler and cheaper because it is produced by an automatic laser cutting machine without manual labour for threading.

The inner surface of the hole refers to the inner surface of the hull. Accordingly, it must be protected against corrosion by painting together with the hull following the surface treatment specification. Small-diameter holes of about 14 mm in a bulkhead up to 40 mm thick are easily filled with paint, as a result of which it either significantly reduced in diameter or wholly clogged.

The painting problem can be solved, for example, by increasing the diameter of the holes, but this will weaken the structure of the hull and cause a chain reaction, which lead to an increase in the size of the bolt and other parts, that is unacceptable. Another limiting factor is the need to use a second worker to tighten the nut on the rear side of the large area bulkhead. When assembling in a workshop, this is not a problem. Still, already on a commissioned propulsion system, it can be problematic to provide two certified workers inside the propulsion system at the same time. The service team usually consists of two

workers, while only one of them is inside the propulsion system, and the second must be outside and monitor the safety of the first.

3.5 Securing bolted joints

Looseness problems often occur in threaded connections. Issues of this type can be caused by temperature changes, vibrations or incorrect tightening torque. As a result of mechanical loosening, gaps are formed in the threaded connection, which leads to complete loosening of the bolted connections. (Henkel 2020)

For additional fixing and increasing the reliability of the connection, depending on the design of the threaded connection, one or more of the following methods are often used:

- thread-locking
- nord-lock washer
- thread-sealing
- wire lock.

Depending on the connection, different types of securing fastening methods are used during assembly. The choice of a particular method is influenced by the size of the joint, its mechanical properties, whether a specific torque is used to tighten it, whether the connection is permanent or is meant to be opened, for example, for maintenance work.

Costs of the additional securing methods are low, especially if taken into account how many qualities of the bolted joint is increasing. If the joint needs a nord-lock washer or wire lock securing, it needs to be considered when designing the parts and assembly.

3.6 Adhesive bonding

Adhesive bonding is the process of joining parts together using glue, epoxy resins or various plastic substances which bind by evaporation of the solvent or cure by heat, pressure or time (Campbell 2011, p. 243). In a joint created with adhesive bonding, the stresses are distributed more evenly than in most mechanical methods and welds. Uniform stress distribution is achieved by eliminating stress concentration points such as bolt holes. When used correctly, the adhesive fills the entire joint. It creates adhesion forces over the whole joint area, not at individual attachment points, which minimises the initially low strength indicators compared

to mechanical attachment methods. (Messler 2004, p. 182-184.) Many different types of materials can be bonded with glue, but the beneficial properties of the glue appear best when bonding thin materials (Campbell 2011, p. ix). When glueing large surfaces, the adhesives evenly distribute the load over the entire surface area, thereby removing load peaks and making the connection stronger and leading to better fatigue life (Messler 2004, p. 4, 22).

The advantages of adhesive bonding include:

- bonded joints are not visible from the outside of the joined parts, creating smooth external surfaces
- working as a damper well resists bending and vibration loads
- prevents galvanic corrosion when joining materials with different potentials
- adhesives easily bond uneven surfaces
- has an excellent strength to weight ratio
- practically do not change the size or geometry of parts. (Messler 2004, p. 186.)

The main disadvantages of adhesive bonding are the following:

- bonded joints by characteristics are permanent joints. Its repairing or disassembly is not an easy task. Repairs often result in damaged surfaces and the surrounding structure of the parts
- compared to mechanical bonding, adhesive bonding is susceptible to surface preparation. Good process conditions are necessary to guarantee a good adhesion result: a clean workspace, temperature, and humidity control
- the presence of voids and unbonds in the adhesively bonded joints can be checked by NDE testing, but destructive methods are required to verify the strength of the bonded joint. In such a case, the test pieces must be manufactured under the same conditions and using the same adhesive and joining method as the actual structure
- the storage conditions of the adhesive bonding materials specified by the manufacturer must be strictly observed
- an aggressive environment or working conditions can hurt adhesives. The properties and durability of most adhesives can be reduced by elevated temperatures or chemical impact. (Campbell 2011, p. 245.)

Five most widely used chemically reactive structural adhesives:

- Epoxy
- Polyurethane
- Modified acrylic
- Cyanoacrylate
- Anaerobic. (Campbell 2011, p. 252.)

The epoxy adhesive has the highest tensile strength, up to 50 MPa. (Campbell 2011, p. 254.) The strength calculations for steel plate and threaded stud welding are used at the tensile level of 72-94 N/mm^2 (Kock 2017). It means that adhesively bonded joint cannot withstand the same loads as-welded joint accordingly to nowadays design of steel outfitting parts. Coupled with strict surface quality requirements, needed pressure during curing, and long cure time, this method noticeably loses to other fastening methods.

3.7 Summary of fastening methods

In this chapter 3, the following fastening methods were considered:

- Gas metal arc welding
- Arc stud welding
- Arc brazing
- Threaded hole
- Through-hole
- Adhesive bonding.

According to the knowledge of different fastening methods which are discussed in the previous chapters, these fastening methods can be divided into the three groups: recommended, recommended with restrictions, not recommended, as shown in *Table 2*:

Table 2. Summary of fastening methods.

Gas metal arc welding	Recommended
Arc stud welding	Recommended with restrictions
Threaded mounting hole	Recommended with restrictions
Through-hole mounting	Not recommended
Arc brazing	Not recommended

Adhesive bonding	Not recommended

Gas metal arc welding or MIG/MAG welding is a well-studied and common welding method. It allows welding in any position, for example, PA-flat position, PE-overhead position or PC-horizontal position. Most manufacturers have welding equipment and experience in welding works. The costing is easy to calculate using known calculation methods. The results of FEM analysis have shown that the strength achieved with the gas metal arc welding method is sufficient for applications with steel outfitting.

The arc stud welding method is intended only for welding studs and similar parts. It cannot be used for welding steel plates. The technique of metal melting during welding does not allow welding the threaded studs currently used due to their large diameter. However, FEM analysis indicated that a 25 mm stud would be sufficient, but this is the maximum stud size for the arc stud welding method and requires a vertical weld position. The use of studs with a smaller diameter is possible only when the structure of the steel outfitting is changed, or the number of studs is increased. Considering all the listed restrictions, arc stud welding method can be used in this application.

A threaded mounting hole is a good compromise for the welding method. Bolted joints are temporary. The most significant advantage of this method is the ability to adjust the position of the assembly parts and, if necessary, dismantle them. The disadvantages of this method include the impossibility of positioning the threaded hole close to the bulkhead edge or welding seam for reasons of strength theory. There should also be enough space around the threaded hole to attach and adjust the steel plates. Also, difficulties are associated with ensuring the quality of threads at all stages of production. When calculating production costs, it is essential to consider the time required to inspect and clean the threads and final assembly of the steel sheets. Using the threaded holes as a fastening method for all parts of steel outfitting involves designing the hull structure together with threaded holes. Otherwise, this method can be used in conjunction with other fastening methods, for example, if several threaded holes can replace a large volume of welding or if temporary fastening is necessary.

Through-hole mounting has similar advantages and disadvantages as the threaded mounting hole option. Compared to other fastening methods, this method is the easiest to manufacture

and probably the cheapest. But painting the inner surfaces of small holes is very difficult, and it will be impossible to guarantee a good result on hundreds of holes. In addition, a second worker on the other side of the bulkheads will be required to install a bolt and nut to the through-hole in a large bulkhead, which can create difficulties during maintenance work. Due to these limitations, this method is not recommended for use.

Adhesive bonding and arc brazing methods have advantages that other fastening methods do not, but they are not required when attaching steel outfitting parts. Both methods are very demanding on the preparation and cleanliness of the surfaces to be joined, which is difficult to ensure in this case. In addition, Adhesive bonding and arc brazing work best when the parts to be joined thin and have a large area, which also does not match the structure of the steel outfitting. In the existing design of steel outfitting, the adhesive bonding cannot provide the required strength, and the arc brazing requires more in-depth research for application in heavy structural parts. Adhesive bonding and arc brazing methods are not recommended for use in this application when alternative, reliable, and well-studied methods such as welding and mechanical fastening are available.

4 COST ESTIMATION METHODS

Estimating the cost of manufacturing a product is one of the most complex and essential tasks for an engineer during developing or improving a product. In the case of a product redesign, with minor changes, it is possible to make an early estimate of the costs quite accurately based on the current costs that are already known. Calculating the final cost of manufacturing a product will require the designer's collaboration with purchasing and cost estimation departments. Their joint work will help make the final estimate of production costs, sharing responsibility for the data provided. There are many concepts to consider and cost estimates to find the best option. (Ullman 2010, p. 315-316.)

There may be many intermediaries, such as manufacturing or logistics, who may have their requirements for the product in the gap between the end-user and the engineer. In any case, the research and development of a product primarily consider the needs and wishes of the end-user who will purchase and use the product. Well-known design and manufacturing methods will help achieve an excellent result according to the established requirements and standards.

The cost estimating of a product, usually, is part of the cost estimation team's work tasks. The purpose of cost estimation can be different. It is essential to understand why the cost estimation is required because it will directly affect the estimation methods and data used. Cost estimation methods are presented below, which will be used to estimate, analyse and consider possible ways to reduce manufacturing costs for steel outfitting.

4.1 Selection of materials and processes

When designing or developing product manufacturing, the choice of materials and processes is an essential and necessary design step. Typically, the combination of materials and processes is selected early in the design phase and then assessed as the project progresses and, if necessary, corrected. The task for which the product is created and its design determine the material and processes, and since the choice is made at an early stage, then most of the subsequent manufacturing costs will depend on it. (Boothroyd et al. 2011, pp. 29, 31-32.)

When studying steel outfitting, it is essential to know the cost of materials and labour to understand how these parameters affect the total cost of production. It is also necessary to know the cost of materials and labour when comparing the cost of different production methods and to find options for reducing the cost. Only after the manufacturing material and process will be known it is possible to find out the price of a kilogram of material and a labour or machine cost.

The relationship between the various levels of product development is well illustrated in Figure 11:

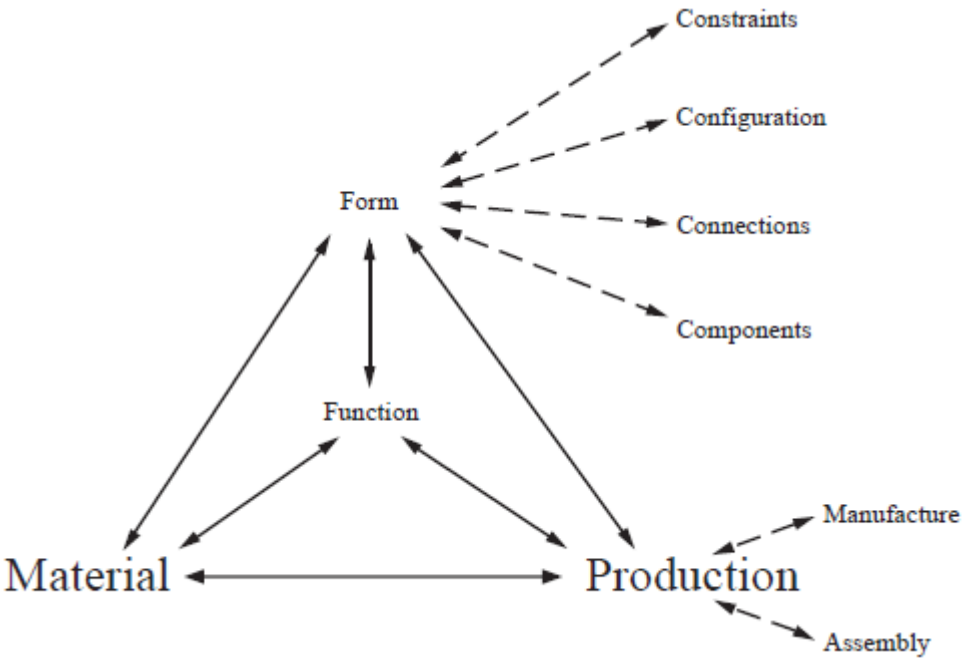

Figure 11. Relationship between the various levels of product development. (Ullman 2010, p. 264.)

Most of the assembly parts of a product are produced using several sequential manufacturing processes. Depending on how difficult the detail is to manufacture, a compromise is often required when choosing a material. For example, some materials are better suited for welding and others for turning.

Most materials are divided into groups according to various criteria, such as physical or chemical properties, to simplify the selection process. The decisive parameters when selecting material are usually machinability and cost.

Another widely well-known methods are benchmarking and comparison with similar products. In terms of concept, material selection and manufacturing process, this technique can help for the following reasons:

1. The batch size of a product or the number of parts significantly produced influences the manufacturing processes used.
2. The choice of material and process is greatly influenced by previous experience gained from the production of parts similar in concept and structure.
3. The presence or absence of knowledge and experience in materials science and production technology greatly influences the final choice. (Ullman 2010, pp. 264-266.)

4.2 Design for Cost

When cost is a top priority in product development, Ullman (2010) suggests using the DFC (Design For Cost) method for product development and improvement. For the most efficient calculation of the total cost of a product to the customer, or in other words - the list price, the DFC method suggests taking into account the entire production chain of a specific product, from design to its sale, as shown in Figure 12:

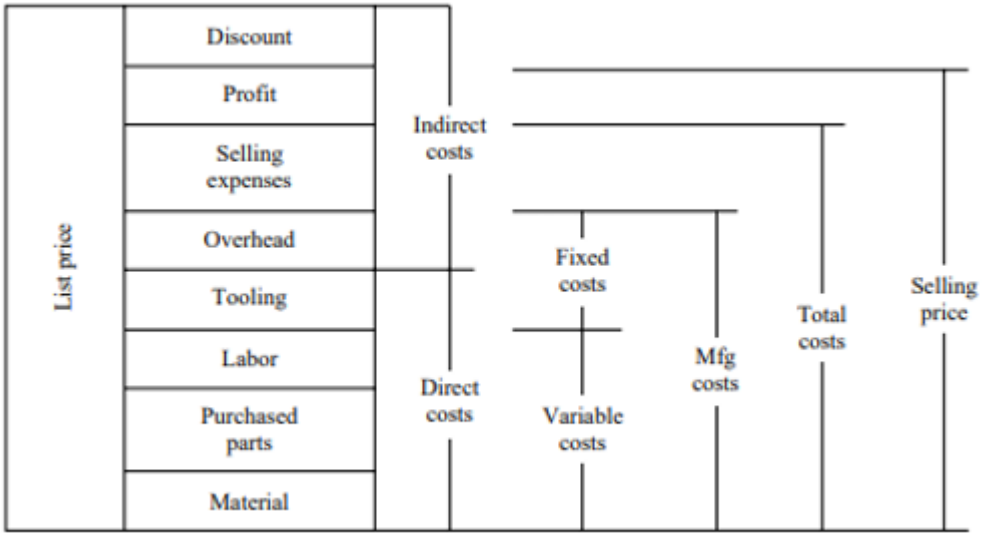

Figure 12. The structure of the list price of a product. (Ullman 2010, p. 316.)

According to Figure 12, the manufacturing costs are divided into two broad groups: fixed and variable. Variable costs include the costs of materials, labour and purchased parts as they are directly related to the number of units produced. Other manufacturing costs are fixed, such as the cost of the tool. The number of parts made does not affect costs in any way. (Ullman 2010, pp. 317-318.)

4.3 Product calculus

Pellinen (2019) suggests using product calculus to calculate the cost of the product. Product calculus is an organisation-specific calculation formula that targets production costs to products and how unit cost calculation is based. According to the calculations of the product calculus, it is possible to determine how much it costs to produce one product or any quantity of a product. Main parameters of product calculators:

- minimum calculus
- average calculus
- normal calculus.

Each calculus has its calculation formula, presented below (formulas No. 2, 3 and 4). Before choosing a calculation method, it is necessary to objectively assess the impact of all parameters on the cost of production. Depending on this, a suitable calculation method should be chosen, which will give an objective estimate of the cost.

$$\text{minimum calculus} = \frac{\text{variable costs for the accounting period}}{\text{actual production volume}} \quad (2)$$

$$\text{average calculus} = \frac{\text{manufacturing costs for the accounting period}}{\text{actual production volume}} \quad (3)$$

$$\text{normal calculus} = \frac{\text{variable costs}}{\text{actual production volume}} + \frac{\text{fixed manufacturing costs}}{\text{normal production volume}} \quad (4)$$

Calculus helps determine how to calculate the unit cost of a product. The cost of the product, defined as a result of the calculation, is called either the production cost or the cost price. When calculating the manufacturing value, only the manufacturing costs of the product are considered. When calculating the cost value, a share of all the company's costs, such as

marketing and administrative costs, is assumed. Since the steel outfitting is only part of the propulsion system, the value of the costs is calculated for the entire propulsion system and will not be considered in this work. The manufacturing value is divided into three parts which correspond to the calculus as follows:

- minimum manufacturing value – minimum calculus
- manufacturing value – average calculus
- normal production value – normal calculus.

In the next chapter, the calculations will be based on minimum manufacturing value and manufacturing value. (Pellinen 2019, pp. 74-76.)

4.4 Design for Manufacturing and Assembly

Boothroyd et al. (2011, p. 1) divide in the book the production process of a product into two stages. The first stage is manufacturing, which involves manufacturing the constituent parts of a product or subassembly. The second stage is assembly, during which a single product is assembled from several separate parts. These product creation methods are described as DFM (Design For Manufacturing) and DFA (Design For Assembly), and the combination of both manufacturing methods is called DFMA (Design For Manufacturing and Assembly). DFMA is used to study and solve the following tasks:

- to guide product development in the interest of reducing manufacturing and assembly costs by simplifying product structure and quantifying improvements
- as a tool for comparing and studying competitors' products and carrying out a quantitative assessment of difficulties during manufacturing and assembly
- as a tool for calculating the mandatory costs of production and assembly of a product, which can maintain overall control of product costs and simplify the conclusion of contracts with suppliers and contractors.

According to the DFM method principle, the cost of manufacturing is a critical factor in the economic success of a product, and an economically successful design ensures high product quality with minimal manufacturing costs. The main idea of the DFM method includes the following steps:

- estimation of production costs
- reduction in component costs

- reduction in assembly costs
- reduction in supporting production costs
- consider the impact of DFM decisions on other factors. (Ulrich & Eppinger 2011, pp. 255-256.)

According to the DFM method, the manufacturing cost can be divided into three parts, as shown in Figure 13:

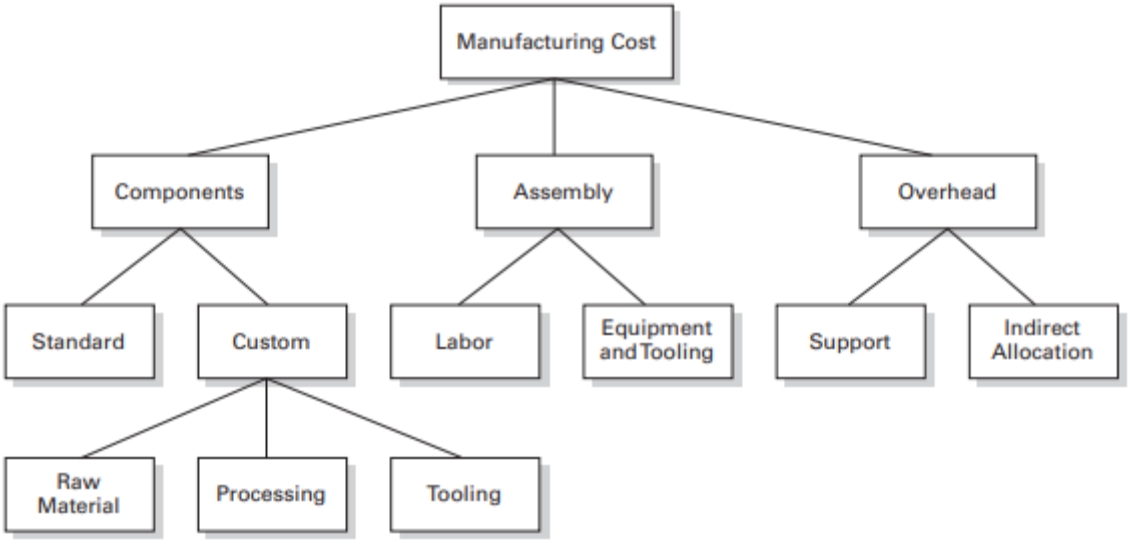

Figure 13. Manufacturing cost. (Ulrich & Eppinger 2011, p. 258.)

The DFMA method is somewhat similar to the DFC method, but it considers different production costs in more detail, as shown in Figure 13, and not on the price list as the DFC method by Figure 12.

4.4.1 Components cost

Product components include standard parts and custom parts. Standard parts are purchased from suppliers who usually have ready-made catalogues for quick and easy part selection. Custom parts are typically made according to individual drawings and customer requirements.

The cost of a standard component can be found in two ways. In the first case, the component must be compared with an already existing similar component that the company already

produces or purchases in comparable quantities. In the second case, it is necessary to ask for prices from reliable suppliers. The cost of non-essential components, such as fastening components, is usually determined based on the customer's experience with similar components. In contrast, the cost of significant components is generally determined based on the supplier's proposals. When requesting prices from suppliers, it is essential to indicate the estimated production volumes.

Custom components differ from standard components in that they are manufactured for a specific assembly or task. Manufacturing methods for custom components rarely differ from standard ones. Typically, manufacturing methods such as machining, laser cutting, bending, punching, and others are sufficient to make these components. However, in terms of application, custom components are usually only suitable for a specific case in a particular product and to a specific manufacturer. An estimate of the cost of a custom component can be made by calculating the amount of material, manufacturing time, material and labour costs, and considering the cost of the tool. (Ulrich & Eppinger 2011, pp. 261-262.)

4.4.2 Assembly cost

Assembly costs include labour costs calculated according to the time spent on assembly and the costs of tools and equipment required during assembly.

Products that consist of more than two parts require assembly. If the products are not produced in an extensive series or if it is impossible to automate the assembly for some reason, manual labour is used for assembly. Manual assembly costs can be estimated by summing the estimated time for each assembly operation and multiplying by the wage rate. On average, one assembly operation takes less than a minute, and in the case of a large-volume assembly, it is divided into parts. The process is performed by several people either simultaneously or sequentially. Often unique fixtures and tools are used to simplify the assembly process. (Ulrich & Eppinger 2011, pp. 262-263.)

As noted in section 4.4 above, there is a specific method to improve the assembly process, such as the DFA method, to calculate and reduce the assembly costs. Campbell (2011) assumed that the main idea of the DFA method is to simplify the assembly of the product as much as possible by developing easily assembled structures. The goal of the DFA method is

to reduce assembly costs by streamlining the product. Campbell (2011) also noted that the application of the DFA method often leads to an increase in the quality and reliability of the product while reducing the number of spare parts and required equipment. Achieving these improvements is often more valuable than the initially stated goal of reducing assembly costs. The basic principles of the DFA method include the following:

- combining parts responsible for several functions into separate units
- modular design
- assembly in an open area
- structural design for easy orientation of parts during assembly
- parts standardization
- using symmetrical parts
- downward direction assembly execution. (Campbell 2011. p. 3.)

4.4.3 Overhead cost

Overhead costs include all other costs such as support costs and other indirect allocation. Support costs include direct costs such as handling or logistics costs of a manufactured product. Other indirect allocations are the costs of maintaining equipment and tools or cleaning the workshop, independent of the amount of product produced. Estimating overhead costs is very difficult for both an existing product and a new product. It isn't easy to track and separate overhead costs between different production lines. One way to calculate overhead costs is to link them to drivers of the direct costs proportionally. The main drivers of direct costs are the cost of purchased materials, installation work, and the number of hours of equipment operation spent manufacturing the product. Another approach to defining overhead costs is to allocate all overhead costs among as many different cost drivers as possible. Moreover, the more cost drivers are used, the higher the results of the overhead cost estimate will be. (Ulrich and Eppinger, 2011, p. 264.)

4.4.4 BOM-material specification

Efficiently organized and correctly stored information simplifies the estimation of production costs. For this, a unique BOM (Bill of Material) material specification is used. Each product has its list of components: a BOM, which contains information about each component. (Ulrich and Eppinger, 2011, p. 260.)

5 CALCULATION OF MANUFACTURING COSTS

This chapter talks about how the manufacturing cost calculations of steel outfitting were performed. Two fastening methods were selected for further calculations based on the theoretical study described above. It is possible to manufacture three options of steel outfitting using the selected fastening methods. Since it is difficult to find a suitable value to compare the welding costs for fastening methods such as arc stud welding and gas metal arc welding, then the welding costs of comparable parts in pieces will be used as a comparison value. So, for calculations will be used reference assemblies made according to fastening methods and steel outfitting structures. In the future, they will be called as:

- Reference Assembly №1, in which the steel plate is joined by Metal gas arc welding, as shown in Figure 4.
- Reference Assembly №2, in which the threaded stud is joined by Metal gas arc welding, as shown in Figure 5.
- Reference Assembly №3, in which the special stud is joined by Arc stud welding, the assembly is similar to that shown in Figure 5.

To calculate the painting and assembly costs will be used data from the known reference projects. The known data refers to the cost of working with the entire steel outfitting. It is assumed that the painting is performed on the whole inner surface of the hull, including welded steel outfitting parts, and the known assembly time refers to all assembled parts of the steel outfitting. Trying to apply this data to reference assemblies will significantly reduce the reliability of the results. Therefore, the comparison will take into account data that includes the manufacturing costs of entire steel outfitting. Two ready-made projects were selected for which the necessary data are known. Reference projects have the same hull size, and their only difference is in the options of the steel outfitting. For one of them, there corresponds an option similar to Reference Assembly №1, and for the other Reference Assembly №2, in the future, they will be called as:

- Reference Project Y, where the fastening method of steel outfitting is similar to the Reference Assembly №1.
- Reference Project P, where the fastening method of steel outfitting is similar to the Reference Assembly №2.

When calculating the manufacturing costs, we need to know the hourly labour costs. This data was obtained from the customer and is shown below:

- Welder, who works in the production of the contractor – 70 €/h
- Assembler, who works in the production of the customer – 155 €/h
- Assembler, who works in the production of the contractor – 60 €/h

The unit for calculating manufacturing costs when using the gas metal arc welding method will be one meter of the weld, and when using the arc stud welding method, one stud. All used prices for consumables and offers from contractors for the separate steel parts manufacturing have been confirmed. Calculations of labour and additive costs will be carried out using the calculation method and formulas of Lukkari (2006). Since the purpose of the calculations is to find out how different fastening methods affect the cost of manufacturing steel outfitting, the calculations will focus on getting comparable results rather than finding exact manufacturing costs. Therefore, if necessary, the methods and formulas for calculating proposed by Lukkari (2006) will be adjusted.

5.1 The manufacturing costs structure of the steel outfitting

According to the DFC cost calculation method, the manufacturing costs should be divided into variable or fixed cost types. Depending on the cost type, it will be taken into account in the cost calculations in different ways. It should be stated that in future research, “manufacturing costs” will mean the costs of welding, painting, and assembly of steel outfitting. And “welding cost” implies labour, additive, and part costs of the steel outfitting. Then the welding costs of steel outfitting are allocated as follows:

Variable costs include:

- Labour costs: welders, assemblers
- Component costs: steel plates, screws, washers and other
- Additive costs: welding wire, shielding gas and energy cost.

Fixed costs include:

- Tooling costs: welding equipment.

In this case, the painting costs are calculated for the entire inner surface of the propulsor hull. The time used for assembly work is calculated for all separate parts of the steel outfitting. Painting and assembly costs should be considered fixed for a single propulsor unit to maintain a good level of reliability for cost calculation results.

Most of the welding costs are related to variable costs. It was agreed with the customer that the cost of purchasing welding equipment for arc stud welding would be considered separately. Usually, contractors have gas metal arc welding equipment, and its cost is included in the offer. If the customer wishes to use the arc stud welding method, the contractor will have to purchase the equipment separately.

Other costs, such as overheads, are not included in the calculations. They are included in the overhead costs of the entire propulsor system because the steel outfitting is part of it.

Campbell (2011, pp. 83-84) states that the power source for metal gas arc welding and arc stud welding is similar. The difference is only in power characteristics. Welding equipment for metal gas arc welding and arc stud welding has different maintenance costs. Still, it is in the range of 200 e/year, which Lukkari (2006, p. 9 and 2011, p. 4) uses in calculating the cost of welding using the metal gas arc welding method. When calculating welding costs in the following sections, the maintenance costs of the welding equipment will not be considered because it is minimal and will not affect the accuracy of the calculations in this study.

5.2 Materials and processes selection

The choice of material for the manufacture of steel outfitting parts is primarily influenced by the base material of the propulsor hull, with which they will be joined. In this case, the choice of material for the steel outfitting parts is based on previous experience and strength calculations.

S355 structural steel is used to manufacture steel plates, and S235 structural steel is used to manufacture threaded studs following standard EN 10025. The separate steel outfitting plates, which are connected by bolting, are more accessible and more economical to

manufacture from stainless steel 1.4404 according to the EN 10088 standard. The separate plates do not need to be protected with paint.

The processes (fastening methods) are described in section 3.7. According to *Table 2*, the calculations use the fastening methods as gas metal arc welding and arc stud welding.

5.3 Calculations

During preliminary calculations using standard formulas for calculating the welding costs, it became clear that when using a duty time, which usually ranges from 10% to 80% (Lukkari 2011, p. 4), the results will differ several times from the actual cost. The results of the preliminary calculation are shown in Appendix III. The calculation used the input data from Appendix II, excluding the duty cycle and labour costs. Therefore, it was decided to calculate in the reverse order, using known actual welding costs. Suitable steel outfitting, whose actual welding costs are known, were selected from Reference Project P. The next step is to divide the welding costs into groups and determine the cost of each of them. The steel outfitting structure of Reference Project P corresponds to Reference Assembly №2, the cost structure shown in *Table 3*.

Table 3. Breakdown of costs by groups.

Cost groups	Size	Price €/pcs	Reference Assembly №1	Reference Assembly №2	Reference Assembly №3
Welding costs					
Labour			x	x	x
Additives			x	x	
Energy			x	x	x
Component costs					
Perforated plate steel	450x30x30 mm	7	x		
Perforated plate SS	450x30x30 mm	10		x	x
Threaded stud	See appendix VIII	2		x	
Special stud	⌀25x75 mm	4			x

Bolt	M12x30 mm	0.34		x	x
Special washer	See appendix IX	3.98		x	x
Thread-locking		24.48		x	x
Equipment costs					
Arc stud welding equipment		15000			x
Other costs					
Painting			x	x	x
Assembly work			x	x	x

The calculation of the manufacturing cost will be done in three stages:

1. At first, will be calculated welded costs for Reference Assembly №2.
2. Based on the results calculated in the first stage, it is possible to calculate the welding costs for other reference assemblies.
3. At the third stage will be found how different steel outfitting options affect painting and assembly costs.

After completing all the above steps, the following chapters will present and analyse the calculation results and draw conclusions about the effect of the fastening method on the manufacturing costs of steel outfitting.

5.3.1 Gas metal arc welding of threaded stud

The steel outfitting of Project P is used as a reference, the actual manufacturing cost of which was 23340 euros. Its manufacture includes the following costs: threaded studs, steel plates, additives, and labour costs, as shown in *Table 4* below:

Table 4. Cost calculation.

	Quantity (pcs)	Weight (kg)	Weld (m)	Cost (€)
Total		89	24.6	23340
Threaded studs	210	76	19.8	420
Steel plates		13	4.8	98
Additives				18

Labour				22804

The referenced assembly consists of similar 210 threaded studs and several steel plates of different sizes. The diameter of the threaded stud is 30 mm, which allows calculating the length of the weld. The length of the welded seams of the steel plates was roughly calculated by hand using a 3D model. With the help of the purchasing department, the cost of the threaded studs and steel plates was found out. The purchasing department requested an offer from the manufacturer for a batch of 210 threaded studs and 105 steel plates. The cost of steel plates is calculated approximately using the estimated weight of the assembly steel plates (13 kg) and the weight of the reference steel plate (0.92 kg), the price of which is known.

Additives costs include welding wire, shielding gas and energy costs. Welding wire and shielding gas costs are calculated based on the proposals of the contractors. The average electricity price for 2020 is used following Statistics (2020) to calculate energy costs. Utilising the additive costs, the size of the weld and welding parameters showed in Appendix II, and the length of welds shown in *Table 4*, the additive costs can be calculated per meter of weld or for a reference assembly.

After calculating the labour cost (22804 €) and the total length of the weld seam (24.6 m), the labour cost of one welded meter (928 €) can be calculated. For 210 threaded studs, the total weld length is 19.8 m. The total labour cost for 210 threaded studs can be calculated (18351 €) using the labour cost of one welded meter (928 €). Based on the hourly labour cost of the welder (70 €/h), the total time required to welding 210 threaded studs (262.2 h) can be calculated.

Calculations are used welding parameters from Kemppi (2017) WPS for a throat thickness of a5-weld, according to which the travel speed is 40 cm/min. For a weld length of 19.8 m, the arc time is approximately 50 min. or 0.82 h. With a total working time of 262.2 h and an arc time of 0.82 h, the duty cycle can be calculated equal to 0.31%.

The welding costs of the Reference Assembly №2 can be calculated using the labour and additive costs of welding two threaded studs and the component costs, following *Table 3*. The welding costs of the Reference Assembly №2 equal to 198 euros.

5.3.2 Gas metal arc welding of steel plate

To calculate the welding costs of gas metal arc welding of steel plate, Reference Assembly №1 is used. The calculations consider the necessary costs such as labour, additives and energy, and component costs following *Table 3*.

In terms of functionality, gas metal arc welding of one steel plate corresponds to the welding of two threaded studs. The contractor estimated that using gas metal arc welded threaded studs in middle and upper struts and welded steel plates in the torpedo strut as a fastening method could reduce welding costs by about 25% compared to gas metal arc welded steel plates. In its assessment, the contractor relies on many years of experience in producing propulsor hulls of various types and with different options of steel outfitting.

Calculations are based on the welding costs of the Reference Assembly №2 (198 €), which is 25% less expensive than Reference Assembly №1. The welding costs of Reference Assembly №1 can be calculated and equal to 264 €, and without component costs, it is 257 €. When the weld length of one steel plate is 0.26 m, the cost of one welded meter (988.6 €) can be calculated, and labour cost without additive costs (0.5€) for the one welded meter is 988.1 €. For 105 steel plates, the total weld length is 27.3 m. Based on the labour cost for the one welded meter (988.1 €), can be calculated the labour costs for 105 steel plates welding (26976 €). The total time required for welding 105 steel plates (385.4 h) can be calculated based on the hourly labour cost of the welder (70 €/h).

Calculations are used welding parameters from Kemppi (2017) WPS for a throat thickness of a3-weld, according to which the travel speed is 26 cm/min. For a weld length of 27.3 m, the arc time is approximately 105 min. or 1.75 h. With a total working time of 385.4 h and an arc time of 1.75 h, the duty cycle can be calculated equal to 0.45%.

5.3.3 Arc stud welding of special stud

The Reference Assembly №3, welded by arc stud welding method, has a similar structure to the Reference Assembly №2, welded by gas metal arc welding method. The difference in component costs is shown in *Table 3*. This welding method requires the use of a special stud and a ceramic ring to protect the weld. Welding equipment suppliers offer special studs in standard sizes with a ceramic ring.

The calculations take into account the cost of equipment for arc stud welding. Amortization of welding equipment is calculated based on the following properties: 5 years, 10 % per year and 10500 studs per year, which means only 0.36 euros per stud.

The steel outfitting option using arc stud welded special studs is entirely identical to the steel outfitting option using gas metal arc welded threaded studs. For example, the number of studs, their location on the hull and size are approximately the same. The difference is only in the arc time of the total working time.

The arc time when welding one special stud, using the arc stud welding method, is calculated in subsection 3.2.2 and is 1 second. Accordingly, the arc time for welding 210 special studs will be 3.5 minutes. The total working time can be calculated using the results obtained in section 5.3.1, and it is 262.2 h for total working time and 50 min for arc time. The total working time calculation needs to arc stud welding of 210 special studs, the arc time (50 min) in the total working time (262.2 h) should be replaced by the arc time of the arc stud welding (3.5 min), and obtain a result of 261.4 h. With a total working time of 261.4 h and an arc time of 3.5 min, the duty cycle can be calculated equal to 0.02%.

The welding costs of the Reference Assembly №3 can be calculated using the labour and energy costs of welding two special stud and the component costs, following *Table 3*. The welding costs of the Reference Assembly №3 equal to 202 euros.

5.3.4 Assembly and painting costs

Regardless of the steel outfitting fastening method, each steel tooling includes parts that are fastened with bolts. Accordingly, after connecting some parts of the steel outfitting with the hull and painting them, it will be necessary to assemble the remaining parts.

The production of a propulsion system is not mass production using a conveyor line, where every movement of the assembler can be taken into account. Due to the large size and the complex structure of the hull, it takes different time to attach the same part to other locations on the hull. The assembly is carried out in one step, and therefore the calculation will use the total assembly time of steel outfitting. The same applies to painting, as the contractor paints the entire hull's entire inner surface at the same time, including the parts of the steel outfitting welded to the hull.

It is necessary to compare the same type and size of the hull to understand how different types of steel equipment affect the cost of painting a hull. The only significant difference between the hulls of Reference Projects Y and P is the different types of steel outfitting in terms of painting. To calculate the assembly costs of Reference Projects Y and P, we need to know the assembly time and the hourly labour cost. The production department reported how long it took to assemble the separate parts of the steel outfitting of the reference project, which are shown in *Table 5*.

Table 5. Assembly time of reference projects.

	Reference Project Y	Reference Project P
Assembly time (outfitting)	16 h	128 h
Assembly overtime		48 h

The actual known costs of Reference Projects Y and P are used to study how the fastening method and steel outfitting option affects assembly and painting costs. Project Y uses gas metal arc welding to fastening steel plates and corresponds to the Reference Assembly №1. Project P uses gas metal arc welding to fastening threaded studs and corresponds to the Reference Assembly №2. Reference Assembly №3 has a similar structure as Reference Assembly №2. Therefore, to estimate the painting and assembly costs of the Reference Assembly №3, the results obtained in Project P can be used.

6 RESULTS

This chapter presents the calculation results. The primary purpose of the calculations was to obtain quantitative and comparable data on how different fastening methods affect the cost of manufacturing the steel outfitting of the propulsor hull. Quantitative results also help answer the research questions in section 1.2. The results are presented in the sections below and include manufacturing costs, assembly and painting costs, and the sensitivity analysis.

6.1 Reference assemblies welding costs

As a result of calculations of reference assemblies welding costs, quantitative results were obtained. *Table 6* shows the results for three reference assemblies.

Table 6. Welding costs.

Costs	Reference Assembly №1		Reference Assembly №2		Reference Assembly №3	
	€	%	€	%	€	%
Additive	0.11	0.04	0.14	0.07	0.72	0.36
Labour	256.91	97.31	174.77	88.26	174.26	86.23
Part	7.00	2.65	23.11	11.67	27.11	13.41
Total	264		198		202	

The results are divided into three main groups: additive, labour and part costs, making up the total cost. For a better understanding and comparison of the significance of each cost, the results are also presented in percentages.

6.2 Reference projects assembly and painting costs

Calculation of assembly and painting costs was carried out for two reference projects, as shown in *Table 7*.

Table 7. Assembly and painting costs.

	Project Y	Project P

			1h=				1h=	
	h	€	155€	60€	h	€	155€	60€
Assembly time	16		2480	960	128		19840	7680
Assembly overtime					48		7440	2880
Painting costs		15550				18700		

The assembly costs were calculated separately for scheduled assembly time and assembly overtime. Results are calculated using two different hourly labour cost. Painting costs were obtained directly from the contractor and are fixed for each referencing project, so they do not need to be calculated.

6.3 Summary of calculations

The calculation results are summarized in *Table 8*.

Table 8. Summary of calculation results.

	Welding costs		Painting costs		Assembly costs	
Ref. Assembly №1	264€	0				
Ref. Assembly №2	198€	-25%				
Ref. Assembly №3	202€	-23.5%				
Ref. Project Y			15550€	0	2480€	0
Ref. Project P			18700€	+20.3%	27280€	+1100%

In *Table 8*, costs are compared with each other as a percentage, in addition to the previous results. The welding cost of the Reference Assembly №2 compared to the Reference Assembly №1 is 25% cheaper. The welding cost of the Reference Assembly №3 compared to the Reference Assembly №1 is 23.5% more affordable.

The calculated painting and assembly costs are actual for Reference Projects Y and P. The painting costs of Reference Project P are more expensive, up to 20.3 %, than Reference Project Y. Also, assembly costs of Reference Project P are more expensive, up to 1100 % in comparison to Reference Project Y. Figure 14 shows what percentage of the actual total manufacturing costs in Reference Projects Y and P is the painting and assembly costs.

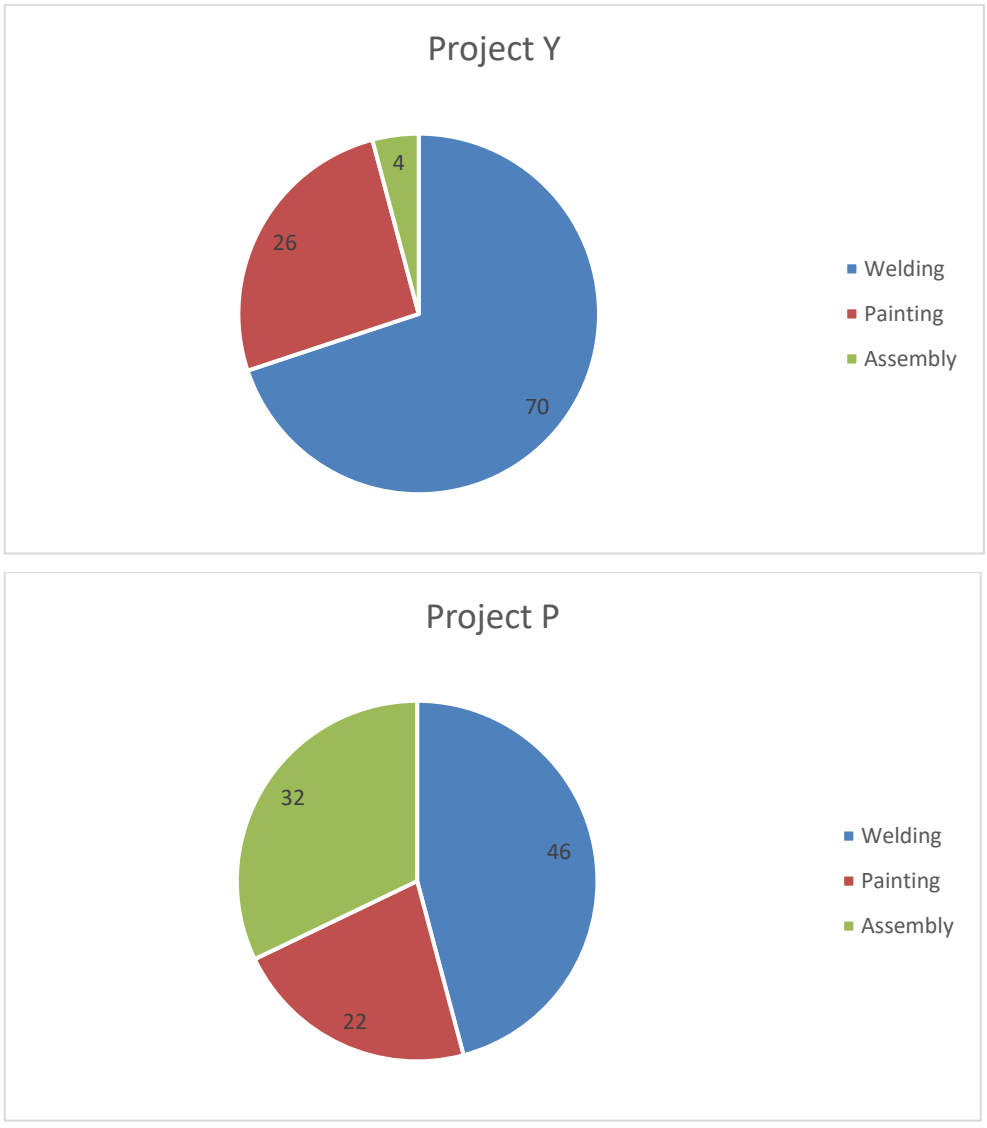

Figure 14. The manufacturing costs percentage of the reference projects.

As shown in Figure 14 the percentage of the actual painting and assembly costs for Reference Project Y will be used for analysis paired with welding costs of the Reference Assembly №1. The percentage of Reference Project P will be used for analysis paired with welding costs of the Reference Assemblies №2 and №3.

6.4 Sensitivity analysis

According to Eskelinen & Karsikas (2014, p. 133), the sensitivity analysis consists of three parts: sensitivity of input data, the sensitivity of calculation model and sensitivity of decision making.

The manufacturing costs are divided into three groups: additive, labour and part costs. The additive costs are including welding wire, shielding gas and energy costs. Labour costs refer to welding costs only, excluding assembly or painting costs. The part costs include the purchase prices of the components that make up the assembly. A more detailed listing of the components is presented in *Table 3*.

Table 9 shows how three times the cost of additives and parts will affect the total manufacturing costs.

Table 9. Impact on welding costs three times increase in the cost of additives and parts.

Costs	Reference Assembly №1		Reference Assembly №2		Reference Assembly №3	
	€	%	€	%	€	%
Additive	0.33	0.12	0.42	0.17	2.15	0.84
Labour	256.91	92.34	174.77	71.48	174.26	67.61
Part	21.00	7.55	69.32	28.35	81.32	31.55
Total	278		245		258	

The additive costs represent a minimal part of the welding costs for all reference assemblies. The total welding cost would be minimal even if the additive costs increased by three times. The most significant changes occur in Reference Assembly №3, which considers the amortization cost of the welding equipment. Even in Reference Assembly №3, the additive costs grow only up to 0.84% of the total welding cost. In Reference Assemblies №1 and №2, the effect of additive costs is lower.

The manufacturer or supplier determines the cost of parts. The cost depends on the size of the part, manufacturing complexity, material, and other parameters. According to actual offers for Reference Project P, the average cost of 1 kg of separate steel plates of steel outfitting is 35 euros, and for Reference Project K is 37 euros (see Appendix V). It is about three times higher compared to the part costs used in the reference assemblies. *Table 9* shows that raising part costs three times increases the influence of the part costs on the total welding costs. When compare reference assemblies to each other, the most impact is obtained in

Reference Assemblies №2 and №3, where the percentage increased to about 30%. The most negligible impact in Reference Assembly №1, where the percentage remained at 8%.

Labour cost depends on the manufacturing time of the reference assembly and hourly labour cost. In steel outfitting, many factors affect the manufacturing time, such as the size and shape of the steel plates, the adjustment time of the steel plates, the welding location and position, the size of the weld, and other factors. Figure 15 shows how the change in the hourly labour cost affects the welding costs of reference assemblies and how they correlate with each other.

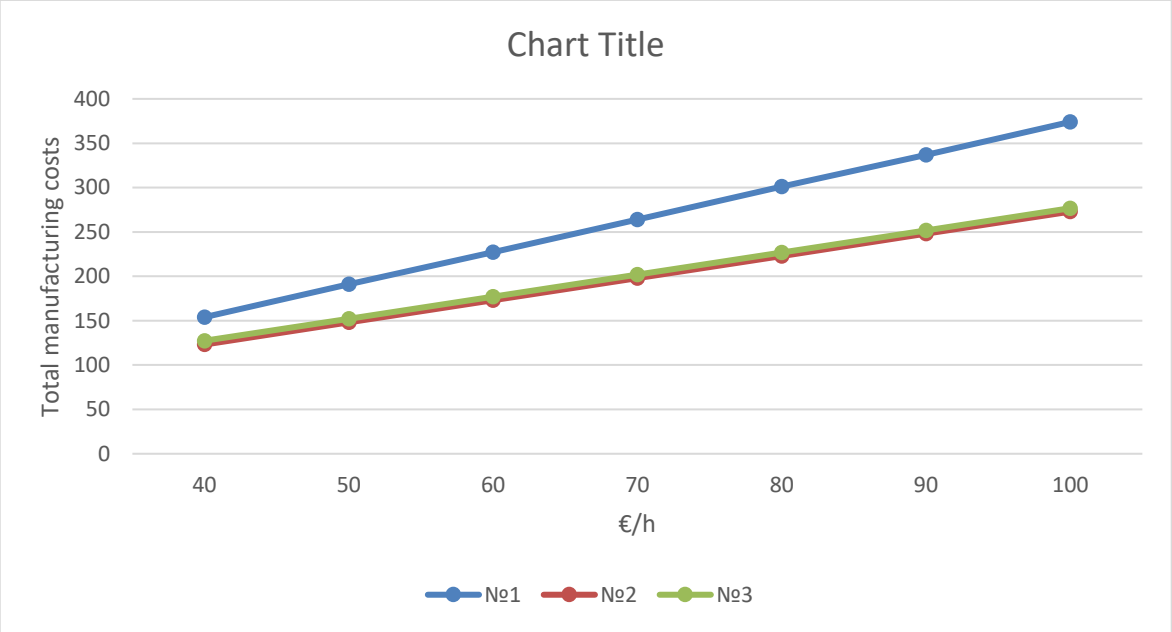

Figure 15. The effect of hourly labour costs on the welding costs of reference assemblies.

On the graph, the horizontal scale shows hourly labour costs between 40 €/h and 100 €/h, and the vertical scale shows the welding costs of reference assemblies. The Reference Assemblies №2 and №3 have a parallel growth, and the difference of 4 euros is unchanged for any hourly labour costs. The welding costs of Reference Assembly №1 grows faster than Reference Assemblies №2 and №3 as the hourly labour costs increases. The difference at the beginning between Reference Assembly №1 and Reference Assembly №2 is 31 euros at an hourly labour cost of 40 euros and gradually increases to 101 euros at an hourly labour cost of 100 euros.

The following graph in Figure 16 shows a situation similar to the previous one shown in Figure 15 for the hourly labour cost in the range of 40 to 100 euros. The only difference is that the welding costs of the reference assemblies take into account the three times increase in the additive and part costs.

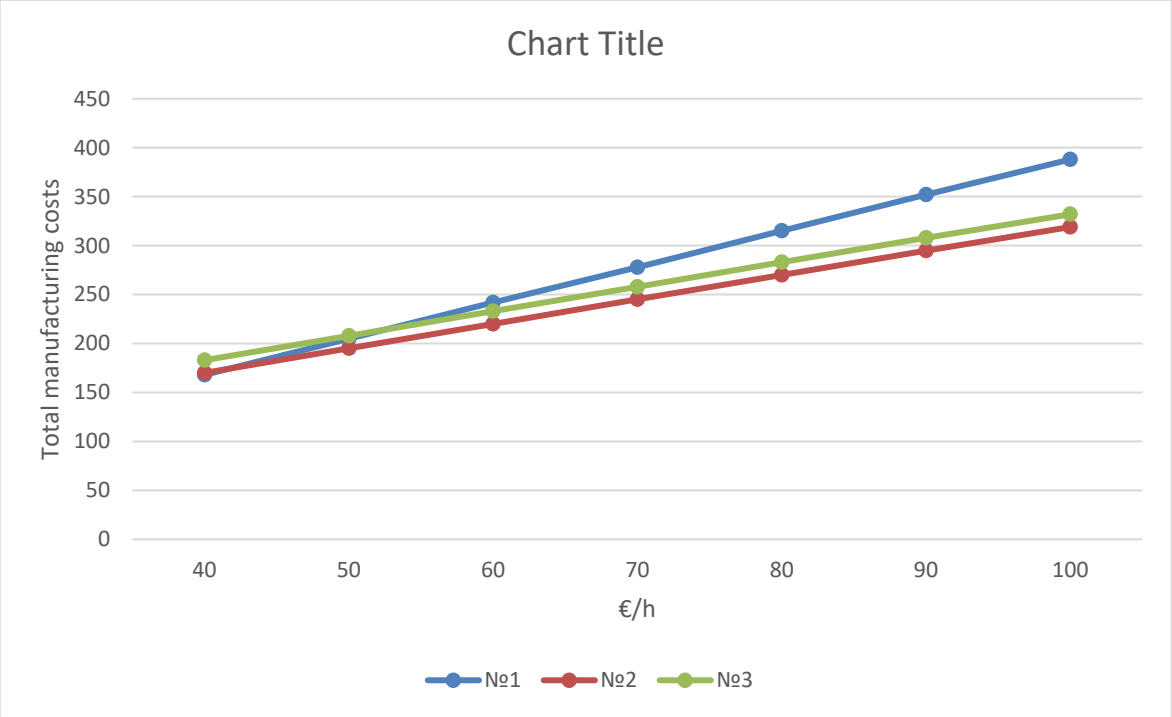

Figure 16. The effect of hourly labour costs on the welding costs of reference assemblies, when the additive and part costs are increased by three times.

The situation with Reference Assemblies №2 and №3 has remained the same. They grow in parallel, and the difference of about 13 euros does not change for any hourly labour costs. The welding costs of Reference Assembly №1 varies differently than in the previous graph shown in Figure 15. At an hourly labour cost of 40 euros, the welding costs of Reference Assembly №1 is 2 euros cheaper than the Reference Assembly №2. At an hourly labour cost of 100 euros, it becomes 69 euros more expensive.

7 ANALYSIS

This chapter will analyse the results obtained in empirical research. Separately, the results of the welding costs will be analysed using the example of reference assemblies. Then, based on reference projects, the effect of the fastening method on both welding, painting and assembly costs will be analysed. Empirical studies show that the fastening method significantly impacts the total manufacturing costs and each separate cost group.

According to the welding cost results, the reference assemblies can be arranged in ascending order:

1. Reference Assembly №2
2. Reference Assembly №3
3. Reference Assembly №1

The difference in welding costs between Reference Assemblies №2 and №3 is meagre, but Reference Assembly №1 is more expensive than Reference Assemblies №2 and №3, as shown in *Table 6*. In all three reference assembly options, labour costs represent the most significant percentage of welding costs.

The additive costs are meagre in all three reference assembly options. Even in Reference Assembly №3, which considers the costs of welding equipment, the additive costs do not significantly affect the welding costs. Sensitivity analysis, when the additive costs increase up to 3 times, as shown in *Table 9*, also did not show a significant increase in the impact on welding costs.

The part costs have a different effect on welding costs, depending on the reference assembly option. *Table 6* show that the part costs percentage from the welding costs in the Reference Assembly №1 is lower than in the Reference Assemblies №2 and №3. The sensitivity analysis (see *Table 9*) showed that in the Reference Assembly №1, even with an increase in the part costs by three times, the component cost percentage of the welding costs remains below 10%. The reason for the low impact on part costs is the structure of the reference

assembly. It consists of only one steel plate made of structural steel, which is cheaper than stainless steel.

The part costs for Reference Assemblies №2 and №3 are approximately identical since their structure is similar. The only difference between the Reference Assemblies №2 and №3 is that they have different threaded studs, as shown in *Table 3*. For Reference Assembly №3, the threaded stud is slightly more expensive because it is a special stud for the arc stud welding method. The calculation results in *Table 6* showed that the part costs significantly impact welding costs compared to additive costs. The sensitivity analysis results in *Table 9* showed that when the part costs was increased by three times, then in Reference Assemblies №2 and №3, the percentage of part costs from the welding costs increased to about 30%. It is quite possible to increase the part costs to this level since many parts of the actual steel outfitting are already welded or are challenging to manufacture. It will significantly increase their cost, compared to the simple to manufacture steel plates used in the reference assemblies. Average cost calculations showed that in the Reference Project P, the cost of one kilogram of separate steel plates of steel outfitting is approximately three times higher than the cost used in the calculations (see Appendix V). In addition, in Reference Assemblies №2 and №3, the steel plates are made from stainless steel, which is slightly more expensive than the structural steel used for manufacture steel plates in Reference Assembly №1.

Labour costs are the main costs in all three reference assemblies that significantly impact the welding costs. In Reference Assembly №1, labour costs reach 97% of welding costs (see *Table 6*), and even if the additive and part costs grow three times, labour costs will remain at about 92% of total manufacturing costs (see *Table 9*). In Reference Assemblies №2 and №3, labour costs are about to 86-88% of welding costs, as shown in *Table 6*. As mentioned earlier, the costing structure of these assemblies is very close to each other. They are more sensitive to changes in the additive and part costs than Reference Assembly №1. With an increase in the additive and part costs by three times, the share of labour costs in Reference Assemblies №2 and №3 decreases to about 68-72% from welding costs (see *Table 9*). Such high impact of labour costs on the welding costs associated with many working hours spent on production. Sensitivity analysis (see Figure 15) has shown that reducing the hourly labour cost significantly reduces welding costs between reference assemblies. Another sensitivity analysis (see Figure 16) showed that with a three times increase in the additive and part costs,

the welding costs of Reference Assembly №1 becomes cheaper than manufacturing Reference Assembly №3 with hourly labour costs of less than 50 euros. When the hourly labour costs decrease below 40 euros, Reference Assembly №1 becomes cheaper than manufacturing Reference Assemblies №2 and №3.

Analysis of the painting and assembly costs using reference projects and then analysing the total manufacturing costs formation showed that the welding costs do not determine the total manufacturing costs. The painting and assembly costs have a crucial role in determining the most profitable fastening method regarding manufacturing costs. The share of welding costs in manufacturing costs in Reference Projects Y is 70%, and in Reference Projects P, only 46%, as shown in Figure 14. It is worth mentioning that the welding cost structures of Reference Project Y correspond to Reference Assembly №1, and Reference Project P corresponds to Reference Assemblies №2 and №3. Accordingly, changes in the welding costs will only affect the manufacturing costs percentage shown in Figure 14. The calculation (see Appendix VI) showed that the manufacturing costs for Reference Project P are 42% higher than for Reference Project Y.

A sensitivity analysis (see Appendix VII) showed that manufacturing costs could be reduced to 12 % using approximately 2.6 times lower hourly labour costs, which is 60€, for assembly work and eliminating overtime assembly work. Still, the production costs of Reference Project P will remain more expensive.

8 DISCUSSION AND CONCLUSIONS

Subjectively selected reference assemblies used to compare welding costs and reference projects chosen for the analysis of painting and assembly costs cannot provide accurate results on the cost of manufacturing steel outfitting. Calculations and analyses were based on specific cases and manufacturer-specific offers. Calculations were performed based on known data and partly in reverse order. A large number of parameters used in the empirical part of the research increased the tolerance of the results. However, apart from the subjectively selected reference assemblies and projects, all inputs were obtained from reliable sources. If necessary, the validity and reliability of the input data can be confirmed. The purpose of this research is to compare the impact of the fastening method on manufacturing costs. The results obtained in the study made it possible to objectively analyse the costs that make up the total manufacturing cost of steel outfitting. It also became known how the costs of welding, painting and assembly correlate with each other depending on the chosen fastening method.

The performed theoretical analysis and empirical comparison of the steel outfitting fastening methods gave precise quantitative results. As stated earlier, the parameters used for the calculations are specific to this case research. And the welding time was calculated based on known parameters, which is the total welding cost and hourly labour cost, but the actual welding time is unknown. The analysis of the obtained results showed that, in addition to the welding costs, it is necessary to consider the costs of painting and assembly, which significantly affect the total manufacturing costs. Calculated arc time showed that the fastening method does not have a significant effect on the welding costs. It follows that replacing the fastening method with a faster one will not significantly affect the welding costs. Accordingly, if the arc time is so short compared to the total welding time, then the rest of the welding time is spent on preparatory work. It means that it is first necessary to consider the structure during improving and developing the steel outfitting. Structure refers to the number of parts, the shape and size of the parts, their location on the hull, dimensional tolerances, and other manufacturing requirements. When improving steel outfitting, it is necessary to consider the entire manufacturing cost chain and predict how each of the manufacturing steps taken will affect the cost of the next manufacturing step.

A typical manufacturing model shows that only 20% of welding costs are related to material and additive costs, and 80% is related to labour and overhead costs. Accordingly, while saving 10% on material and additive costs, the welding cost will decrease by only 2%. And if you save 10% on labour and overhead costs, the welding cost can be reduced by 8%. This information is relevant for manual and semi-automatic welding of mild steel. (Rosenthal 2003, p. 46.)

Lukkari (2011, p. 8.) offers many methods with examples of concrete results to improve the duty time of welding: this is a change in the shape of the groove and the deposition rate, the effect of throat thickness of a-weld, the impact of steel strength on the amount of deposited metal, the use of welding jigs and others.

Analysis of the fastening method influence on the Reference Assemblies №2 and №3 showed that the reduction of the arc time due to the replacement of the gas metal arc welding method by the arc stud welding method does not lead to a noticeable change in the total welding time. Also, the technical limitations associated with the arc stud welding method will strongly limit the development process and reduce the number of technological solutions that a design engineer could use in his work. It turns out that in steel outfitting application, arc stud welding loses to gas metal arc welding, both in technical terms and in terms of manufacturing costs.

As stated earlier, Reference Assembly №2 is the cheapest to manufacture, but the impact of painting and assembly costs makes the total manufacturing cost less cost-effective than Reference Assembly №1. Reducing the welding costs should be carried out by simplifying the structure of steel outfitting and the number of parts in it, which will help to reduce the part and labour costs. The assembly costs can be affected by lowering the hourly labour cost, for example, by outsourcing this step to a contractor and eliminating overtime required to inspect and clean the threaded holes. The research also showed that depending on steel outfitting welded to the hull, the painting costs could vary significantly. The search for an opportunity to reduce the cost of painting should begin with finding out what factors influence the formation of painting cost. In Reference Project P, sandblasting and paint penetration protection of the threaded holes contributed to the increase in costs. In Reference Project Y, it wasn't easy to paint the welded steel plates from the inside, which had to be

painted with a brush, contributing to the cost increase. Accordingly, it is necessary to determine why the difference in the cost of painting the reference projects differs by 20.3%.

In factories, the possibility of partial or complete robotization of the production process is often studied. The robotization of production helps to significantly reduce the cost of manual labour, increase production speed, and achieve consistency of quality by eliminating the human factor from the production process. The robotization is an unprofitable and even impossible task in the steel outfitting case. The reason is the complex structure, the large size of the parts, the variety of propulsion systems, production requirements, frequent updates of modifications and the relatively small production volume.

To further study the influence of fastening methods on the manufacturing costs of steel outfitting, it should be remembered that with the current design, the time spent on the fastening process itself (the arc time of welding) is negligible compared to the total welding time. Based on this, it turns out that finding an alternative fastening method will not help reduce the overall fastening time. Further research should have a complex approach to the proposal, and improvement should affect all manufacturing stages related to steel outfitting.

Of the alternative fastening methods studied, the most competitive are threaded mounting hole and through-hole mounting. The reasons why these fastening methods have not been considered do not diminish their potential. The development of steel outfitting simultaneously with propulsor hull may provide an opportunity to use alternative fastening methods. Using the experience and knowledge of contractors to investigate and find solutions to the problems associated with alternative fastening methods can yield positive results.

The following suggestions for further research can help develop the structure of steel outfitting and reduce the associated production costs:

1. Detailed analysis of welding time (short arc time vs long total welding time)
2. Painting costs (reasons for the 20.3% difference in cost between Reference Projects Y and P)
3. Assembly overtime of the Reference Project P (reason, solutions)
4. Construction of steel outfitting parts (can it be simplified).

Below are brief answers to the research questions on which the entire work was structured:

- What are the groups of the manufacturing costs of steel outfitting?

The manufacturing costs are divided into two broad groups: fixed and variable. Variable costs include the costs of materials, labour and purchased parts as they are directly related to the number of units produced. Other manufacturing costs are fixed, such as the cost of the tool.

- What are the risks associated with the reliability of the joined parts and the manufacturing cost that may arise when changing the fastening method of steel outfitting?

If the reliability of the joined parts and the joint cannot be confirmed throughout the entire service life, then there is a risk of part breakage, which as a result, can damage the propulsion system. Risks in calculating manufacturing costs are associated with possible hidden costs and maintenance costs in the future.

- How can manufacturing costs be estimated?

To estimate manufacturing costs, they must first be divided into groups according to their structure and determine the materials and production processes. After that, using the designer's collaboration with the purchasing department, the cost of each separate group can be calculated. In calculations can be used the DFC method and calculus formulas.

- How can manufacturing costs be reduced?

According to the DFMA method, the reduction of manufacturing costs has many stages. The main thing is to understand the drivers of manufacturing costs in a specific case. Then the costs of components, assembly and other manufacturing stages are reduced by standardizing components, using optimal manufacturing processes and search for the best offers from contractors.

9 SUMMARY

The purpose of this thesis was to provide the customer with objective data on how different fastening methods affect the cost of manufacturing propulsor hull steel outfitting through a case study. It was necessary to study the production process of various propulsion systems to answer the research questions. The structure of steel outfitting was analysed using the example of those solutions that are already in use. It is allowed to divide the production process into stages and helped to understand how the manufacturing costs are formed. The applicability of different fastening methods to steel outfitting was studied through literature analysis, and two welding methods were selected for further study.

Empirical analysis of welding cost was performed for three functionally comparable reference assemblies. In contrast, painting and assembly costs and a rough comparison of total manufacturing costs were performed on two reference projects. Cost calculation method such as DFC and manufacturing process developing method such as DFMA have been used to research and analyse the formation of manufacturing costs. Welding costs for reference assemblies such as labour and additives were calculated using welding cost formulas, and the purchasing department provided data on the part costs. The painting costs of the propulsor hulls became known from the contractor. The actual assembly time documented in the production workshop was used to calculate the assembly cost. The customer also reported the actual hourly labour costs of the welder and assembler.

In addition to the answers to the research questions that were presented during the work, the scientific value of the research and meaningful data obtained regarding steel equipment, which the customer can apply in practice, is:

- percentage difference in the welding costs depending on the fastening method of steel outfitting
- percentage difference in the painting costs depending on the fastening method of steel outfitting
- percentage difference in the assembly costs depending on the fastening method of steel outfitting.

Well-established production of the product ensures hassle-free production and maintains product quality and costs at the desired level. Due to the constantly increasing demand for the product, the client needs to know which production options will meet all technical requirements with minimal production costs. In this case, the customer will have to find a compromise between a cheaper method of manufacturing steel outfitting, which creates a permanent joint, and a more expensive but temporary joint that is more practical to use. For the further development of the steel outfitting, specific proposals were proposed. The case research showed which of the possible alternative fastening methods should be avoided. The sensitivity analysis showed how different costs correlate with each other and which parameters can be changed up or down during further product development.

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Työkustannukset (K_T)

$$K_T = \frac{M}{T} \times \frac{1}{e} \times H_T \ (€/m)$$

M = hitsiainemäärä (kg/m)
T = hitsiaineentuotto (kg/h)
e = paloaikasuhde (-)
H_T = työtunnin hinta (€/h)

Hitsauslisäainekustannukset (K_L)

$$K_L = M \times \frac{H_L}{N} \ (€/m)$$

M = hitsiainemäärä (kg/m)
H_L = lisäaineen ostohinta (€/kg)
N = hyötyluku/riittoisuus (-)

Suojakaasukustannukset (K_S)

$$K_S = \frac{M}{T} \times V \times H_S \times 0{,}12 \ (€/m)$$

M = hitsiainemäärä (kg/m)
T = hitsiaineentuotto (kg/h)
V = kaasun virtaus (l/min)
H_S = suojakaasun ostohinta (€/m³)

Jauhekustannukset (K_J)

$$K_J = M \times J \times H_J \ (€/m)$$

M = hitsiainemäärä (kg/m)
J = jauheen kulutus (kg/hitsiainekilo)
H_J = jauheen ostohinta (€/kg)

tai

$$K_S = M \times S \times H_S \ (€/m)$$

M = hitsiainemäärä (kg/m)
S = kaasun kulutus (m³/hitsiainekilo)
H_S = suojakaasun ostohinta (€/m³)

Energiakustannukset (K_E)

$$K_E = M \times E \times H_E \ (€/m)$$

M = hitsiainemäärä (kg/m)
E = energian kulutus (kWh/hitsiainekilo)
H_E = energian hinta (€/kWh)

Konekustannukset (K_K)

$$K_K = \frac{M}{T} \times \frac{1}{e} \times H_{KT} \ (€/m)$$

M = hitsiainemäärä (kg/m)
T = hitsiaineentuotto (kg/h)
e = paloaikasuhde (-)
H_{KT} = koneen tuntihinta (€/h)

Koneen tuntihinta (H_{KT})

$$H_{KT} = \left(H_H \times \left(\frac{1}{T_p} + \frac{p}{2 \times 100}\right) + Y\right) \times \frac{1}{T_K} \ (€/m)$$

H_H = koneen ostohinta (€)
T_p = koneen poistoaika (v)
p = pääoman korkoprosentti (%)
Y = vuosittaiset kunnossapito-kustannukset (€)
T_K = koneen vuosittainen käyttöaika (h)

APPENDIX II

Input data for calculations.

	Reference assembly №1		Reference assembly №2		Reference assembly №3	
Weld:	3	PB position	5	PB position	⌀25 stud: PA position	
Welding method:	1,2	mm. MAG-steel wire	1,2	mm. MAG-steel wire	arc stud welding	
Amount of weld metal:	0,072	kg/m	0,2	kg/m	-	
Wire feed:	6,5	m/min	10	m/min	-	
Welding current:	210	A	300	A	2250	A
Arc voltage:	24	V	32,5	V	40	V
Deposition rate:	3,78	kg/h	5,4	kg/h	-	
Travel speed:	26	cm/min	40	cm/min	1	sec/stud
Duty cycle	0,5	%	0,31	%	0,02	%
Labour cost:	70	€/h	70	€/h	70	€/h
Filler metal price:	3	€/kg	3	€/kg	-	
Efficiency:	95	%	95	%	-	
Gas flow:	20	l/min	20	l/min	-	
Price of the gas:	4	€/m3	4	€/m3	-	
Gas consumption:	0,28	m3/wire kg	0,1	m3/wire kg	-	
Energy consumption:	1,3	kWh/kg	1,8	kWh/kg	90/ 0,025	kWh/ kWh/stud
Energy price:	0,07	€/kWh	0,07	€/kWh	0,07	€/kWh
Welding equipment price:					15000	€
Amortization of equipment:	-		-		5v/ 1v =	10 %/ 10500 studs

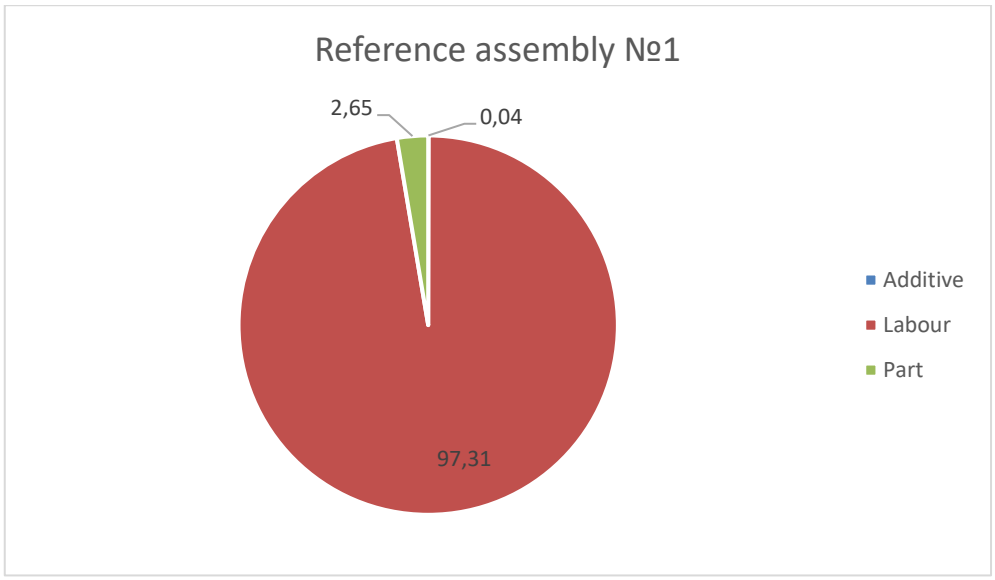
APPENDIX III

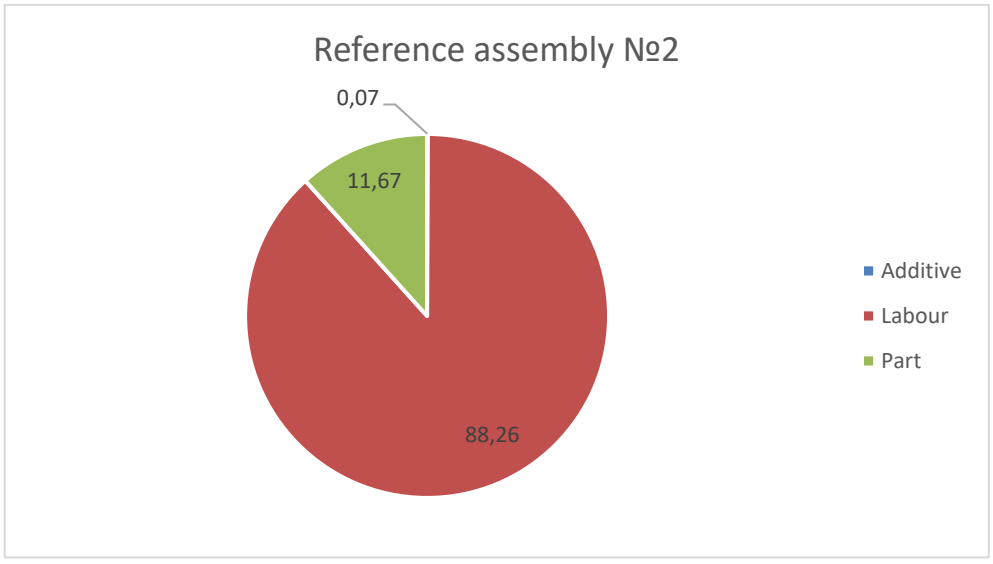
Preliminary calculation results.

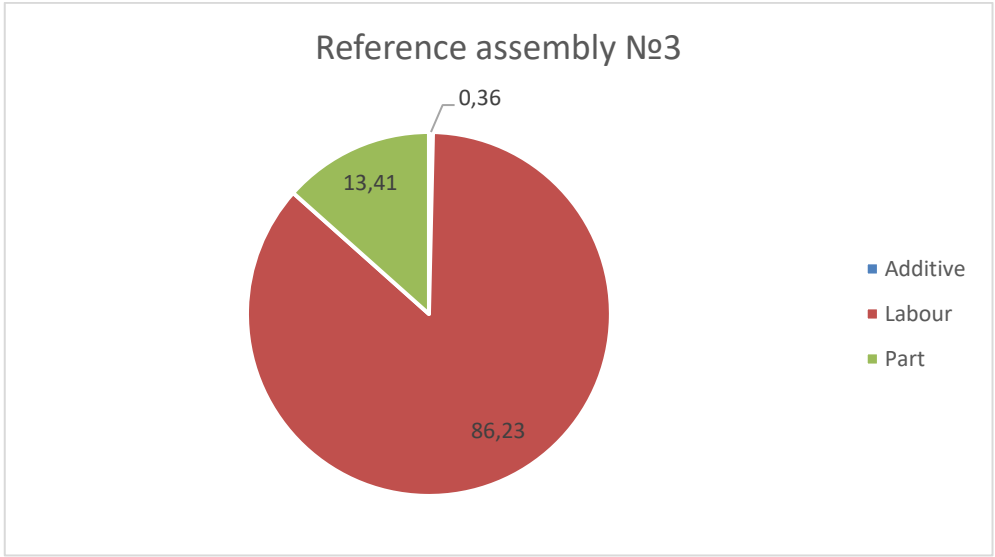
Costs	Reference Assembly №1		Reference Assembly №2		Reference Assembly №3	
	€	%	€	%	€	%
Duty cycle	20	%	45	%	3	%
Labour cost:	40	€/h	40	€/h	40	€/h
Additive	0,11	1,36	0,14	0,59	0,72	2,52
Labour	0,99	12,22	0,62	2,60	0,70	2,45
Part	7	86,42	23,11	96,82	27,11	95,02
Total	8,1		23,9		28,5	

APPENDIX IV

Total manufacturing costs of reference assemblies.







APPENDIX V

Average cost calculation of 1 kg separate steel parts of steel outfitting.

	Reference Project P		Reference Project K	
Separate steel outfitting	€	kg	€	kg
NS	3900	126	3500	111
NT	2500	60	2500	58
DS	2900	116	2500	98
DT	6300	142	6000	127
Total	15600	444	14500	394
1kg=	35		37	

APPENDIX VI

Total manufacturing costs calculation of the reference projects.

	Reference Project Y		Reference Project P	
	€	%	€	%
Welding	41886	70	38940	46
Painting	15550	26	18700	22
Assembly	2480	4	27280	32
Total	59916		84920	
			+42 %	

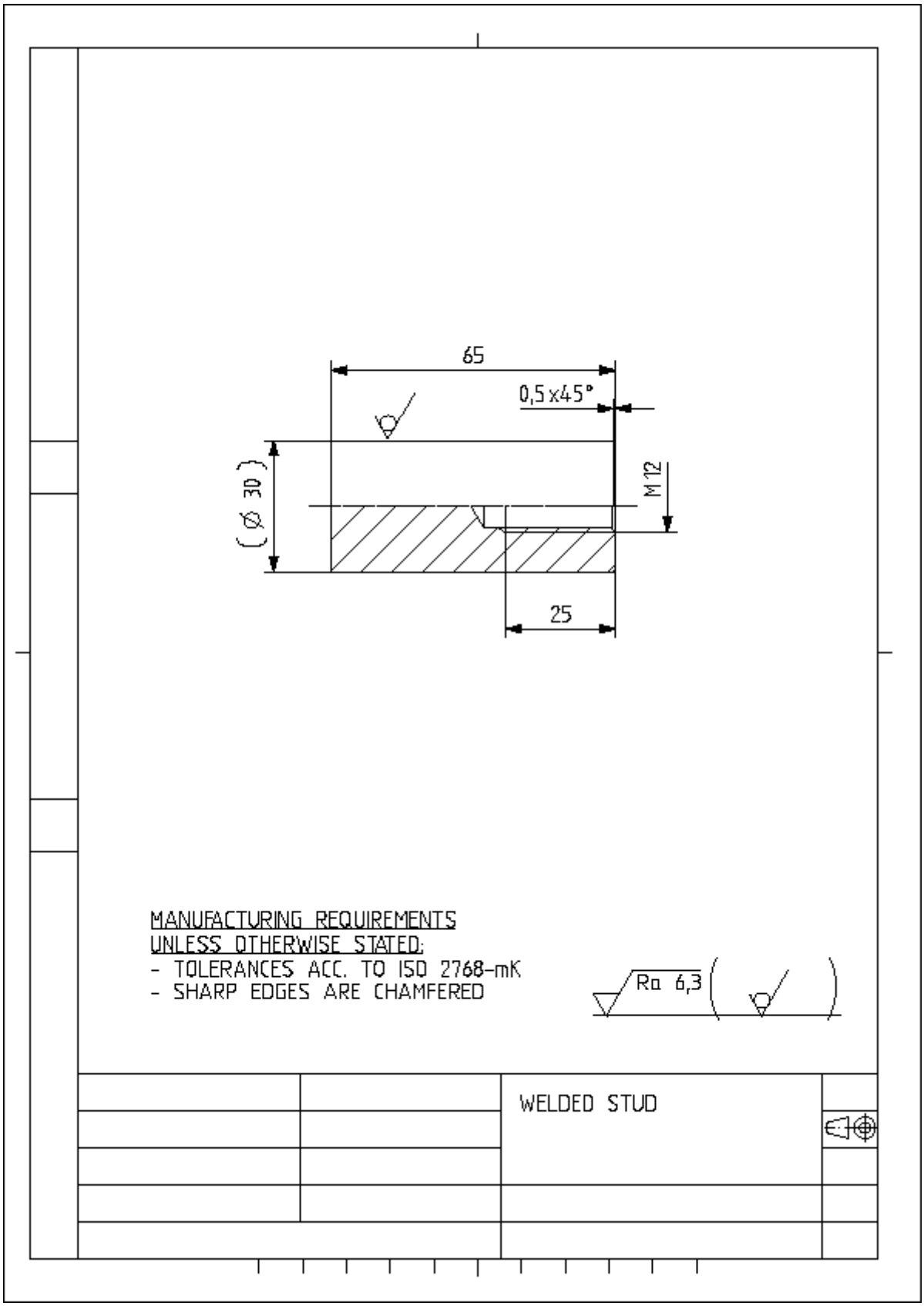
APPENDIX VII

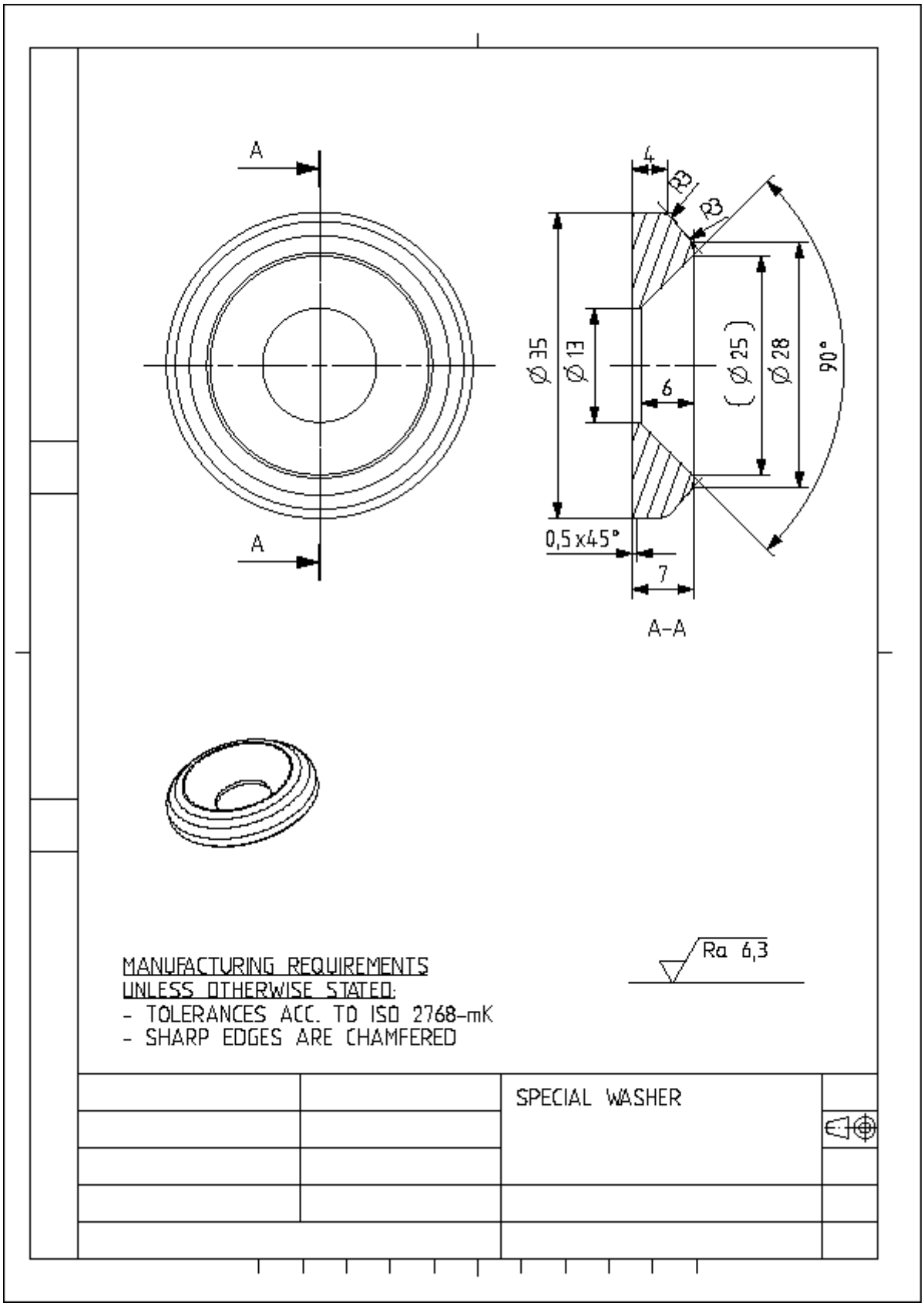
Sensitivity analysis for total manufacturing costs calculation of the reference projects using lower hourly labour cost (60€) for assembly works.

	Reference Project Y		Reference Project P	
	€	%	€	%
Welding	41886	72	38940	60
Painting	15550	27	18700	29
Assembly	960	2	7680	12
Total	58396		65320	
			+12%	

APPENDIX VIII

Welded stud.



APPENDIX IX

Special washer.