LUT UNIVERSITY
LUT School of Energy Systems
LUT Mechanical Engineering

Markus-Mikko Kylmälä

DESIGN FOR ASSEMBLY-BASED COMPARISON BETWEEN TWO ASSEMBLY TOOL DESIGNS USED IN ASSEMBLY OF PERMANENT MAGNET ELECTIC MOTORS

Examiner(s): Professor Harri Eskelinen
Lic. Sc. (Tech.) Timo Koljonen

TIIVISTELMÄ

LUT-Yliopisto
LUT School of Energy Systems
LUT Kone

Markus-Mikko Kylmälä

Asennetavuus perusteiseen suunnitteluun pohjautuva vertailu kahden kestomagneetti sähkömoottorien asennukseen käytettävien assennustyökalumallien välillä

Diplomityö

2020

72 sivua, 29 kuvaa, 13 taulukko ja 3 liitettä

Tarkastajat: Professori Harri Eskelinen
TkL Timo Koljonen

Hakusanat: asennus suunta, kokoonpanon uudelleen suuntaaminen, asennusjärjestys, DFA, DFA vertailu

Tämän tutkimuksen tarkoituksena oli tutkia roottorin asennussuunnan vaikutusta asennustyön tuottavuuteen. Samalla tutkittiin, mitkä tekijät vaikuttavat asennustyön tuottavuuteen ja eritoten oltiin kiinnostuneita asennettavien osien kääntöjen vaikutuksesta.

Tutkimus toteutettiin selvittämällä kirjallisuudesta erilaisia DFA-suunnittelu metodeja, asennusjärjestyksen merkitystä ja kääntelyjen vaikutusta muissa tapauksissa. Lisäksi kirjallisuudesta tutkittiin erilaisia DFA-pohjaisia vertailumenetelmiä. Kirjallisuus tutkimuksen perusteella luotiin prototyyppi horisontaalisesta roottorin asennus-menetelmästä. Horisontaalista asennus-menetelmää vertailtiin kohdeyrityksessä käytössä olevaan vertikaaliseen menetelmään kirjallisuustutkimuksen pohjalta luotujen vertailu menetelmien avulla. Luoduilla vertailutyökaluilla voidaan mitata menetelmän osien olennaisuutta, käytettävyyttä, ajan käyttö, virheiden mahdollisuutta ja virheistä aiheutuvia kuluja.

Vertailtaessa horisontaalista ja vertikaalista asennusmenetelmää huomattiin, että horisontaalinen asennusmenetelmä sai paremmat pisteet kaikilla muilla mittareilla paitsi käytettyjen osien olennaisuutta mitattaessa. Tästä päätellen voidaan todeta, että käännösten poistaminen asennustyöstä, luo edun asennustyön tuottavuutta mitattaessa, vaikka se aiheuttaisikin ristiriitoja muita DFA-pohjaisia asennettavuuden helppouteen liittyviä tekijöitä kohtaan.

ABSTRACT

LUT University
LUT School of Energy Systems
LUT Mechanical Engineering

Markus-Mikko Kylmälä

Design for assembly-based comparison between two assembly tool designs used in assembly of permanent magnet electric motors

Master's thesis

2020

72 pages, 29 figures, 13 table and 3 appendices

Examiners: Professor Harri Eskelinen
Lic. Sc. (Tech.) Timo Koljonen

Keywords: assembly direction, assembly reorientation, assembly sequence, DFA, DFA comparison

Aim of this research was to explore effect of rotors assembly direction on assembly works productivity. Additionally, were explored what factors effect on the assembly works productivity and specially how reorientations affect.

Research was implemented by reviewing literature for different DFA design methods, influence of assembly sequence and effect of reorientations in other assembly cases. In addition, different DFA based comparison methods were studied. Based on literature research, prototype for horizontal rotor assembly method was created. Horizontal assembly method was compared to vertical assembly method used by target company with comparison tools created based on literature findings. With created comparison tools, the essentiality of parts, usability, time consumption, risk of error and cost of error can be measured.

While comparing horizontal and vertical assembly methods, it was discovered that horizontal assembly method got better score in every other indicator except for the one that indicates essentiality of the parts. Based on that it can be stated that by removing reorientations from assembly work creates advance while inspecting assembly works productivity event if it is causing conflicts while considering other DFA based factors.

ACKNOWLEDGEMENTS

I would like to thank my supervisors Harri Eskelinen and Timo Koljonen for guiding me through my thesis. Thanks also to my co-workers how have been giving me some tips and some perspective regarding prototype design of this thesis.

I would also like to thank the company where I work. The company have been flexible and supportive during my studies and while I have been working on this thesis. Thanks for all the friends I have got from the university, with you these years have been memorable.

Markus-Mikko Kylmälä
Riihimäki 15.6.2020

TABLE OF CONTENTS

LIST OF SYMBOLS

AEM	*Assembly Evaluation Method*
ASF	*Assembly Sequence Flowchart*
ASP	*Assembly sequence planning*
CAD	*Computer aided design*
DFA	*Design for assembly*
D-end	*Drive end*
N-end	*Neutral end*
PLM	*Product Lifecycle Management*
VDI 2221	*Systematical design process by Germany engineering covenant*

1 INTRODUCTION

The purpose of this work is to compare differences between horizontally and vertically working assembly tools used for rotor stator assembly to permanent magnet electric motor. Comparison of the solutions will be made DFA (design for assembly) based to measure productivity of the operations. Currently, the rotor stator assembly of the target company is executed in vertical position.

1.1 Background and motivation

The assembly work is being done vertically because it is a neutral way to insert a rotor down inside to a stator. In the vertical assembly method, there is no need for massive support elements executing an assembly. The drawback in the vertical assembly is that the package, which consists a frame and a stator, must be turned from a horizontal to a vertical position by a special tool and an overhead crane. A rotor must be also turned to same position after its previous production phase, before insertion to a stator. After the assembly the whole package must be once again turned back to horizontal position with the special turning tool. The special turning tool is attached to a frame during whole assembly sequence.

In the current assembly method, a rotor is lowered to a stator with a hook attached to an overhead crane. There is a shaft guide to insert into the shaft through the bearing in a correct position in the N-end (neutral end) of the rotor. Good things in a simple guided entry is that a rotor is easy to insert through a bearing for the assembly and an overhead crane has not to be located precise because adjusting can be easily guided by a hand to get a rotor into a stator. Downside in method described is that there is not horizontal support and magnetic forces of permanent magnet rotor can cause a rotor to contact to the inner edge of the stator. The contact can be harmful to the balance of the rotor and to the surface of the rotor or the stator in general.

1.2 Research problem

The problem is that a target company has no knowledge about a profitable way of assembling a rotor to an electric motor. More time-consuming method might reveal to an unprofitable total solution even if the assembly time of the alternatives has no big difference and an initial investment might be more expensive. When annual production volume rises, even a small saving time can show as great savings and positive impact to capacity annually.

The bare assembly time is not the only significant issue to be considered. Also, time saving of moving parts from last work phase to next one must be considered, as well as, waiting times of special tooling, machines and cranes and times used to turn heavy components to different positions.

There are a lot of things that need to be taken into account when considering which assembly method is going to be more profitable and effective. A comparison tool must be created to see which way of assembly method gives the best result.

1.3 Objective

The objective of this work is to find solutions to the problems described above. the prototype of the assembly tool for a horizontal assembly method is designed and the comparison between the current vertical assembly method and a new horizontal one is made to figure out if the horizontal method is more profitable than the vertical method or not.

1.4 Research questions

This research is going to answer following research questions:

1. Is it more profitable to assemble the rotor of the permanent magnet electric motor to the stator horizontally or vertically? How does reorientations affect on profitability of the assembly work?
2. What different factors affect on profitability of the assembly work?
3. How manufacturing volume affects on profitability of both assembly method?

1.5 Scope

This thesis is scoped to concern only the motor sizes that are currently manufactured vertically in the factory of the target company. This thesis work is limited to consist research of effects of assembly directions, material reorientations during assembly, design of the prototype for the assembly method of the horizontal rotor insertion and comparison between the vertical and the horizontal assembly method in terms of profitability. For the prototype, only design will be done within the framework of this research.

1.6 Contribution

Contribution of the thesis work is the knowledge for the target company about the different solutions to assembly a rotor into stator. Especially when manufacturing volume increases there might be need for a change of the production layout and then the information about the most profitable assembly method of the rotor can be taken into account. Also, the target company benefits if the new assembly method is discovered to be clearly more profitable than the current assembly method. In that case the company can make actions to develop a horizontal assembly tool based on the prototype when designing an actual assembly tool for assembly of the rotor.

2 RESEARCH METHODS FOR DESIGN OF PROTOTYPE AND FOR COMPARING

In this chapter there are presented different research methods that are implemented in this thesis. The methods are selected in the way that they support logical working and support each other making the thesis whole. There are three main chapters in this thesis, literature search, prototype design and comparison between the current assembly method and the prototype design assembly method. The chapters will be linked to each other as presented in in Figure 1. Literature search is being done to support reasoning for making of new prototype design for assembly tool and for creating working comparison tool. With prototype design productivity comparison between current and new assembly methods can be done. After comparison is done the results can be reviewed based on literature search findings.

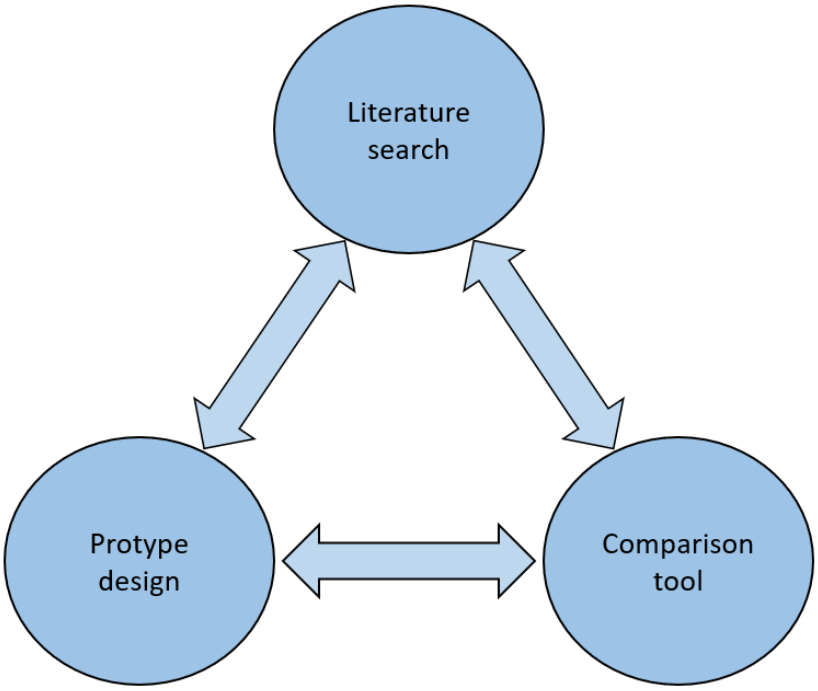


Figure 1. Figure of connection between different research methods.

2.1 Literature search for reviewing different assembly methods that have an effect on productivity in the assembly

Purpose of the literature research is to give support for the actual design work and comparison. Idea is to find out how different factors affect on productivity on the assembly and how these factors can be taken into consideration on design work for a new assembly tool. Main focus is to determine main characteristics that have an effect on productivity of the assembly and to focus on those, while developing a new tool and tools to evaluate different solutions. The questions that are to be answered with literature research are:

1. What are the main factors that affect on productivity in the assembly?
2. How assembly sequence planning and assembly reorientations affect on time consumption and productivity of assembly?
3. How differences are measured between the assembly designs?

Literature search is done by using books from LUT academic library and databases of LUT Finna and Knovel. Keywords used in databases were assembly direction, assembly reorientation, DFA, assembly sequence planning, LEAN, assembly comparison and DFA comparison.

2.2 Systematic design process

In design phase, idea is to follow guidelines of systematical design process by Germany engineering covenant called as VDI 2221. Idea in the VDI 2221 is to define problem and then divide it to pieces. Then different solutions are invented to fix the pieces of the problem. Different combinations of the solutions invented for the pieces of the problem are created and compared with each other. Best solution is selected and design of that can be done. In the Figure 2 the process is shown. (Mital et al. 2008. p.55.)

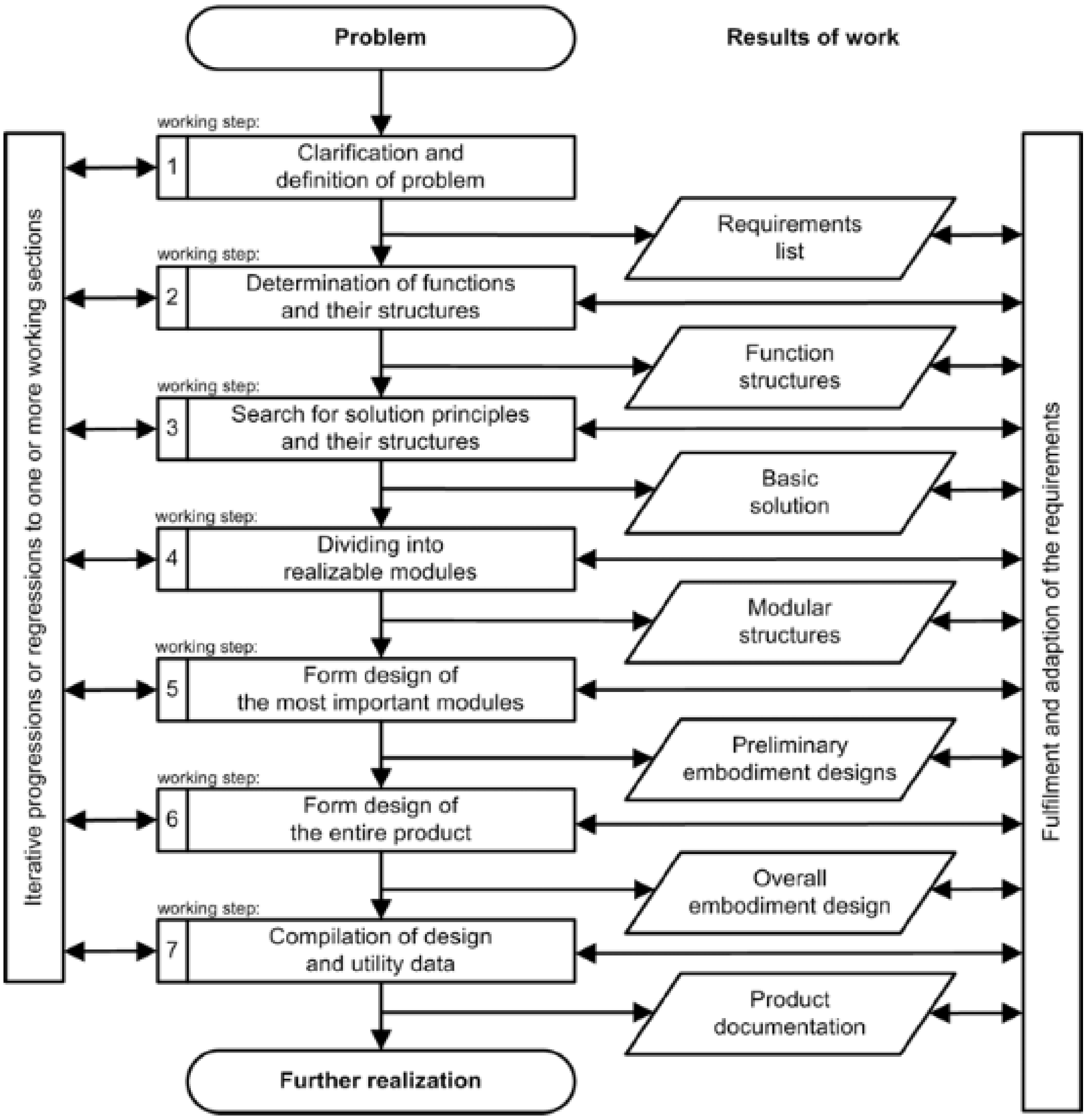


Figure 2. VDI 2221 design process (VDI 2221, 1993).

As shown in Figure 2, the phases of the design are quite straight forward. Clarifying and defining the task is done in this case with the target company and based on that list of requirements will be created. Based on the list of requirements the function structure is going to be created and different part functions will be figured out. Principal solutions will be crated based on part functions and of the best combination will be selected with morphological analysis.

In morphological analysis designed object is divided to functions. For each function there should be invented as many as possible ways to implement the function. After that, different functions and all the solutions for implementing those functions are being arranged to matrix. From the matrix different overall solutions can be found by picking up one solution for each function. Amount of possibilities for different overall solutions grows easily very high. For example, if there are five different functions and for all those there are six different solutions the amount of overall solutions grows to 6^5=7776 different solutions. Problem with morphological analysis is to find reasonable overall solutions from all the options. Usually some of the solutions for the functions are not compatible with other solutions for different functions and that narrows down the possibilities. Principle of morphological analysis and selection procedure is shown in Figure 3. In Figure 3 there are four functions F1-F4 and four solutions for all functions S11-S44. In the table, there are two overall solutions created OS1 and OS2. (Tooley. 2010. p. 468.)

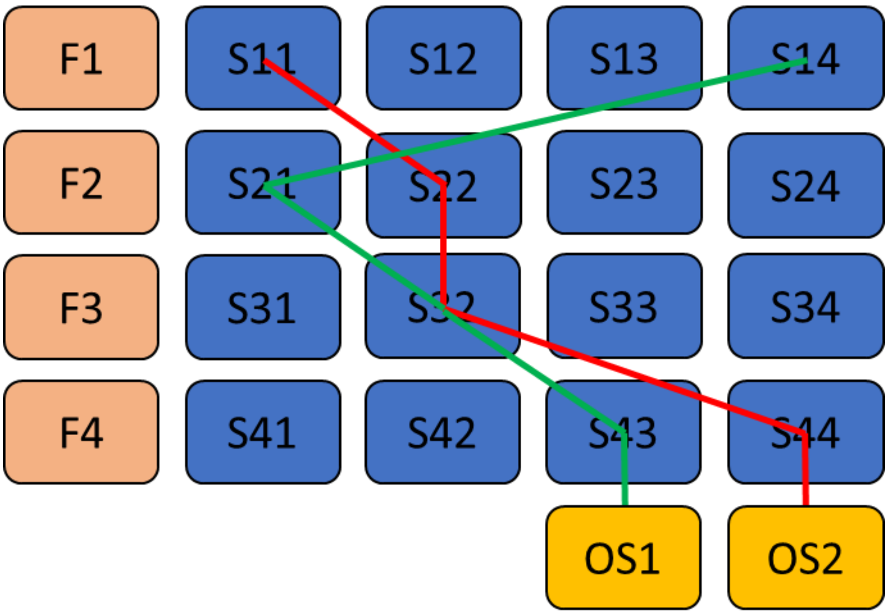


Figure 3. Principle picture of morphological analysis.

Based on morphological analysis, three best choices will be evaluated by their functions and properties and then most suitable overall solution will be selected with the target company for further development.

2.3 Comparison of solutions based on DFA methodology

Comparison between the current vertical assembly method and the new horizontal one that is being created during this work. Comparison is to figure out which solution is better when considering productivity aspect of the solutions.

Comparison is done with a customized comparison tool. The comparison tool is created based on findings in literature search. While creating the comparison tool, different factors that can be seen to have effect on productivity must be taken into consideration. The comparison tool must be fitted the requirements of target company and to compare assembly tools. All effecting factors need to be weighted in the way that they reflect their real value in the assembly process.

3 FACTORS THAT AFFECTS ON PRODUCTIVITY OF ASSEMBLY WORK

Principles of DFA have remained same for decades. Even Henry Ford were looking solutions for simple and modular solutions in design. (Moultrie & Maier 2014). The basic goal in DFA is to ease assembly and to reduce costs of the assembly work by changing design. There are multiple ways to do so. (Boothroyd et al. 2002, p.1).

Base for reducing assembly costs comes from design. When the final products costs are calculated only 5% comes from design, 50% from materials, 15% from labor and 30% are other costs. But it is stated that for real, approximately 70% of the final products costs are fixed on design. Difference that the materials can do is 20%. Labor and other factors can affect on total 10% of the costs, 5% each. Based on that, it is important to consider the DFA in early stage of the designing. Often design is made by only considering final products usability and functionality. In those cases, the DFA is not utilized in the early stage of the design and the costs can become unnecessary high. Designers should co-operate with the manufacturing engineers and develop a product together instead of using so called “over-the-wall approach” where both sides concentrate only to their own fields without communication with each other. (Boothroyd et al. 2002, p.5-7.)

Basic way to increase productivity in assembly work is to speed up the process. Usually the speeding up is being done by reducing the parts of the assembly by redesign or easing some assembly steps by improving the details in the product design. (Boothroyd et al. 2002, p.9-11, 85-143.) Also reducing extra handling like reorientations and unnecessary moving of the components by considering the assembly sequence again can have an effect on total assembly time (Pan & Smith 2006, p. 4583-4584). As well as implementing Lean tools in the assembly, to reduce wastes in material and in assembly time (Vuorinen 2013, p.72).

3.1 DFA

While reconsidering design with DFA, number of parts, ease of handling and insertion are the elements to be considered. When reducing parts form the assembly there is need to consider next three thing on each component:

1. While final product is operating, is the component having relative motion against the other components that already assembled?
2. Is it necessary that the component is made of different material than the other components that are already assembled? Or is it necessary to be isolated from the other components already assembled?
3. Is it necessary that the component is separate from the other components to make assembling and disassembling other components of the assembly possible?

After these questions are answered to the all parts the reduction can begin. If there are some parts that had negative answer to all questions above, the essentiality of them needs to be reconsidered and justified to be included in the product. (Boothroyd et al. 2002, p.9.)

Reducing of the parts is usually made by combining two or more simple parts to one little more complicated one or by reducing external fasteners by changing the design so that need for fasteners is reduced or by replacing them with mechanical joints. In some cases, if ideal improvement can be executed by minimum number of parts, simple combining and reduce of the fasteners can reduce part count by 60% and shorten the assembly time by 70%. (Boothroyd et al. 2002, p.9-13.)

On handling and insertion point of view designs assembly efficiency can be considered by thinking component characteristics like if material is slippery, flexible or abrasive. Size matters as well as ease of assembly factors such as need for gripping or holding before attachment is secured, ease of alignment, need for vertical assembly and what type of fastener is needed. (Alfadhlani et al. 2018.) There is a lot of different guidelines for designing products to ease of assembly. For example, Boothroyd et al. (2002) have introduced general design guidelines for manual assembly. These guidelines include geometrical solutions for avoiding jamming, easing insertion and avoiding need for holding part on its place while attaching it. Those guidelines also have tips for designing parts, so they are easier to handle. Those tips advice for example to use symmetrical parts when it is possible and when it is not the asymmetrically in parts should show clearly. There is also advised to consider material properties like flexibility and slippery of the material. (Boothroyd et al. 2002, p.86-92.)

3.2 Assembly sequence planning

ASP (assembly sequence planning) can have an effect on productivity of assembly work. Assembly costs can be reduced with properly done ASP. That is because it can ease the assembly process and reduce assembly time and needed quantity of tools. ASP is usually done by computer program that takes into consideration all feasible possibilities and chooses the optimal or near optimal solution within limitations defined by the user. (Lai & Huang 2004, p.752-753.)

In ASP number of possible assembly sequences rise exponentially as number of parts rises. That why it is important to define limitations for the assembly to rule out some assembly sequences. Multiple limitations can be set, and importance of each limitation can be prioritized to find best possible assembly sequence. As Hamrol & Kujawinska & Barraz (2019, 46) have listed typical limitations may be one or several of the following: “assembly time, movement complexity of assembly units, degree of difficulty in achieving the next process state, number of changes in assembly orientation, number of tool changes, required number of changes of necessary reorientations of the base unit, technological production capacity, economy and correctness of the course of assembly, or, for example, indicators of the characteristics of the process of combining parts proposed in work.” Based on chosen limitations all feasible assembly sequences will be created and chosen algorithm will give out best possible assembly sequence. Simplified, algorithm can for example work in four steps:

1. It finds all the feasible assembly sequences.
2. It gives weights to the selected limitations.
3. It evaluates the different assembly sequences.
4. It defines which assembly sequence is the most suitable for the case

These steps can be implemented manually, but often they are done by a computer because large part count creates a big matrix out of the algorithm. (Hamrol et al. 2019, p. 45-54.)

3.3 Assembly directions and reorientations

While looking for an optimal assembly sequence, consideration of assembly directions is important if goal is to reduce assembly time. If assembly work can be only from one side, preferably from top to get help of the gravity to the work, the reorientation of the product should not be necessary. All unnecessary moving and reorientations takes time, especially if the product is large and heavy, but also with the smaller products. Extra handling and reorientations can be reduced by ASP. (Pan & Smith 2006, p.4569-4570.)

Pan & Smith (2006, p. 4569-4585) have done research about impact of reorientations on assembly times. Research studied 6 phased assembly work with changing groups of people and with robot. The product was relatively small and easy to handle. Robot testing was done by assembly sequences where there was one reorientation, two reorientations and three reorientations. Assembly sequences were generated with automatic assembly sequence planner while restrictions were adjusted to be one, two or three reorientations. Automatic assembly sequence planner is generating optimal or nearly optimal assembly sequences that are feasible based on CAD (computer aided design) model and on given restrictions. Average assembly times and times taken for reorientation can be seen in Table 1. From the Table 1 it can be noticed that with each added reorientation in the assembly the percentage of the time used for reorientations from whole assembly work raised by little over ten percentage points. It can also be noticed from the Table 1, that the assembly time without reorientations is almost the same with all assembly sequences. It can be stated that at least in this case the reorientations just raised the assembly time without any additional value to the work. (Pan & Smith 2006, p. 4573-4575.)

Table 1 Average times of the robotic assembly with different amount of reorientations in the assembly work (Pan & Smith 2006, p. 4575).

Number reorientations	Total assembly time (s)	Time taken to reorientations (s)	Time used to reorientations from whole assembly time	Assembly time without reorientation time (s)
One reorientation	189	39	20,60 %	150
Two reorientations	221	68	30,70 %	153
Three reorientations	257	107	41,60 %	150

With human operators in Pan & Smith research (2006, p. 4575-4581) the deviation of the results was bigger than with a robot. The order of assembly sequences was randomized so the effect of learning the product structure was minimized. First group of human operators assembled all three predetermined assembly sequences in randomized order once, but after that researchers decided to get a new group and they did the same thing, but they did it twice. After these two tests, third group was summoned and they did assembly work twice with each one, two and three orientations. Difference with third group was that this time reorientations were not specified. In Table 2 there is average times for all these assembly works and from it can be noticed that the relative change between one and two orientations are noticeably bigger in every group than it was with the robot, over twice as big in groups one and two. But changes between assembly times of two and three reorientations with human operators are in the both sides of the change with the robots assembly times. Also noticeable is that with human operators the relative changes between one and two reorientations are from almost twice as big to almost three times as big as the relative changes between two and three reorientations. (Pan & Smith 2006, p. 4575-4581.)

Table 2. Average assembly times of three assembly groups of human operators (Pan & Smith 2006, p. 4575-4581).

Group	Number of reorientations	Total assembly time (s)
	One reorientation	28,25
	Two reorientations	41,63
1	Three reorientations	47,00
	One reorientation	24,44
	Two reorientations	35,88
2	Three reorientations	43,75
	One reorientation	13,70
	Two reorientations	17,13
3	Three reorientations	19,75

The study of Pan & Smith shows that by reducing reorientations there is possibility to shorten total assembly time, but they emphasize that this is only one case. They also mention that variance in two and three orientations with human operator was so big that results are not reliable. For more reliable results there should be bigger sample size and different kind of assemblies. (Pan & Smith 2006 p. 4583-4584.)

3.4 Lean manufacturing

Lean manufacturing is based on just-in-time manufacturing that has been developed by Japanese car manufacturer Toyota at late 1940s. Toyotas lead production engineer got task of rising production capacity of the company. His idea was to combine great productivity of Fords assembly line production and American supermarkets ability to deliver what and when customer needed. (Vuorinen 2013, p.71.)

Basic idea in Lean is to eliminate from production everything that does not create any value to the customer. Adding customer value is done by reducing wastes and errors. Seven original wastes in Lean manufacturing were overproduction, waiting, unnecessary transportation, unnecessary handling, extra inventory, unnecessary motion and errors. Afterwards unused employee potential in creativity has been added as eight waste. By removing these wastes, production can be done in more effective way. (Vuorinen 2013, p.72.)

Implementation of the Lean manufacturing can be done in five steps.

1. Considering what adds value to customer. It must be known what customer wants, because in the end customer is the one who is paying.
2. Identifying value stream. Value stream must be defined for products whole production cycle, from design and raw material manufacturing to delivery. All waste must be removed and that is possible only when whole value stream is defined properly.
3. Creating flow to the production. Production cycle must be planned in the way that there is no extra waiting, moving or handling. Maintenance and quality of production lines equipment needs to be considered with high importance. That way can be created production cycle with good flow, what is continuous and short.
4. Creating pull. All production should start only after customer have placed order. That way there is not any unnecessary work done and there will not be any extra inventory.
5. Aiming for perfection. Getting Lean manufacturing to work in workplace takes input from all employees. Everybody have to work with good quality and efficiently, as well as think possible wastes that there is still in production cycle and make development proposals to remove those.

With these steps of Lean manufacturing it is possible to create flexible and fast production that is not aiming for massive quantities rather than great quality. That way there can be savings in production costs. All that is done is done for customer and nothing goes to waste. In quantity-based production unit cost for single product might be cheaper than in Lean manufacturing but there are also extra costs from unnecessary work and errors and that why quantity-based manufacturing gets more expensive than Lean manufacturing. Good productivity of Lean manufacturing is based on good quality, short manufacturing time caused by removing waiting times and need for less inventory space because there is no need for inventory to sub-assemblies. (Vuorinen 2013, p.72-73.)

4 EVALUATION OF DIFFERENT ASSEMBLY SOLUTIONS

There have been created many ways to evaluate DFA properties of products designs. In this chapter three different evaluation methods are reviewed. These methods are Hitachi assembly method, Lucas DFA method and Boothroyd Dewhurst DFA method. These methods differ from each other. Hitachi method looks up weaknesses in design with an assembly evaluation and an assembly cost ratio. Lucas method has three steps to analyze design, it has functional analysis, feeding analysis and fitting analysis. Boothroyd Dewhurst method aims to reduction on part count with evaluating consumed time in handling and in manual insertion. (Mital et al. 2018, p. 140-149.)

4.1 The Hitachi assembly evaluation method

The Hitachi assembly evaluation method have been developed in 1976 and is often referred as AEM (Assembly Evaluation Method). With Hitachi method five different indicators can be achieved. Those indicators are assembly time, assemblability, assembly cost ratio, design efficiency based on parts and simplicity factor. To get these indicators following steps need to be followed.

1. List parts and their quantity of the assembly in the assembly sequence.
2. Form a figure of the assembly sequence
3. Calculate assembly time
4. Calculate assemblability.
5. Calculate design efficacy. Before calculating design efficacy, it is mandatory to determinate number of parts that could be eliminated.
6. Calculate simplicity factor.
7. Calculate assembly cost ratio.

For assemblability, simplicity factor and assembly cost ratio there is recommended limit values. If values of those ratios do not keep inside limit values the redesign should be considered. (Ezpeleta et al. 2019, p. 674.)

Hitachi method is based onto idea where points are taken of as a penalty if the optimal assembly method is not used. For the optimal part design, the penalty score is zero and then AEM score for that design is 100. To get AEM score for whole product the average of all parts AEM score needs to be calculated. With products AEM score and number of parts used, the assembly time and the assembly costs can be estimated. (Ohashi et al. 2002, p.568.)

4.2 The Lucas DFA method

The Lucas DFA method has been developed for Lucas Corporation in 1980s. In this method there is scale point that can be used to relatively measure assembly difficulty. The method analyzes design on three ways. It has functional analysis, feeding analysis and fitting analysis. The method works on ASF (assembly sequence flowchart) shown in Figure 4. Lucas method works with penalty system like Hitachi. Difference is that Lucas is divided to three categories. Functional analysis gets as a results design efficiency, feeding analysis gets feeding ratio and fitting analysis gets fitting ratio. From these feeding ratio and fitting ratio is based on penalty system and design efficiency calculates ratio between essential parts and all parts. (Leaney & Wittenberg. 1992.)

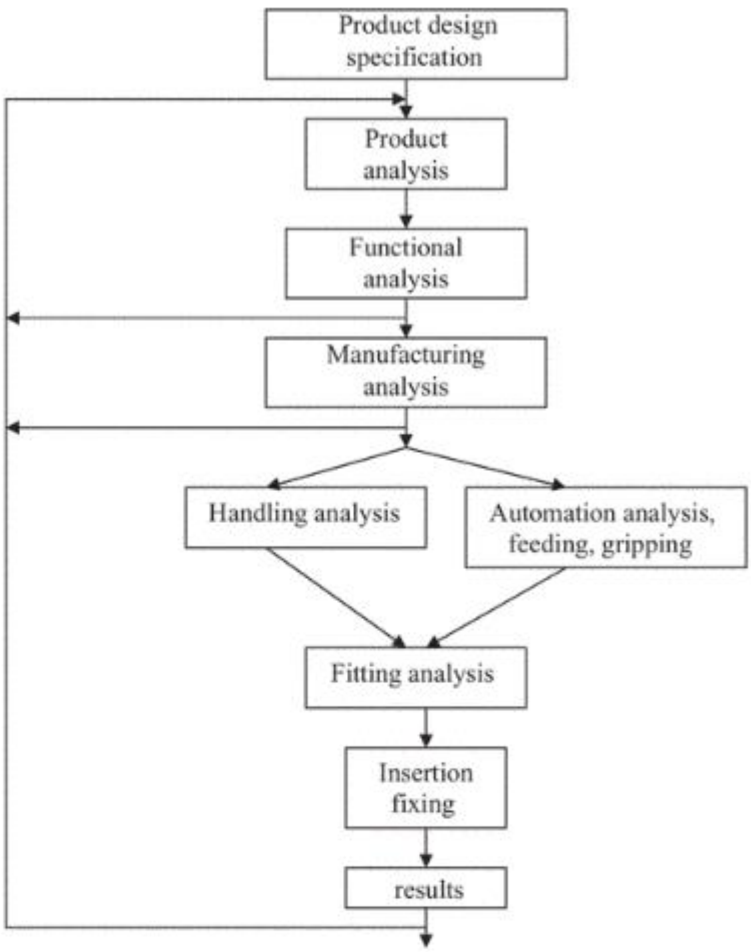


Figure 4. ASF used in Lucas DFA method (Mital et al. 2008, p. 142).

For functional analysis parts used in assembly need to categorize to groups A and B. Group A is for essential parts and group B is for non-essential parts. Designs efficiency is calculated by dividing amount of essential parts with amount of all parts. Target is to get at least 60% efficiency. If efficiency percent is lower than that redesign should be considered. (Mital et al. 2008, p. 143.)

For feeding analysis feeding ration must be calculated. Feeding ratio is being calculated by dividing feeding index by amount of essential parts. The value to be pursued is 2.5. To get feeding index parts handling values from groups A to D shown in Figure 5 must be summed. (Mital et al. 2008, p. 143.)

	Score
A. Size and weight of part	
Very small, requires tools	1.5
Convenient, hands only	1
Large and/or heavy, requires more than one hand	1.5
Large and/or heavy, requires hoist or two people	3
B. Handling difficulties	
Delicate	0.4
Flexible	0.6
Sticky	0.5
Tangible	0.8
Severely nesting	0.7
Sharp or abrasive	0.3
Untouchable	0.5
Gripping problem, slippery	0.2
No handling difficulties	0
C. Orientation of part	
Symmetrical, no orientation required	0
End to end, easy to see	0.1
End to end, not visible	0.5
D. Rotational orientation of part	
Rotational symmetry	0
Rotational orientation, easy to see	0.2
Rotational orientation, hard to see	0.4

Figure 5. Handling values for calculation fitting ratio with Lucas DFA method (Mital et al. 2008, 144).

Fitting analyze is quite similar to the feeding analyze. In fitting analyze the fitting ratio is calculated by dividing fitting index by essential parts and fitting index can be caught by summing values got from groups A to F shown in Figure 6. Pursued value in fitting ratio is also 2.5. Compared to feeding ratio, fitting ratio gets often more variance because it has more possible penalty features than feeding ratio. (Mital et al. 2008, p. 143.)

	Score
A. Part placing and fastening	
Self-holding orientation	1.0
Requires holding	2.0
Plus one of the following:	
Self-securing (i.e., snaps)	1.3
Screwing	4.0
Riveting	4.0
B. Process direction	
Straight line from above	0
Straight line not from above	0.1
Not a straight line	1.6
Bending	4.0
C. Insertion	
Single insertion	0
Multiple insertions	0.7
Simultaneous multiple insertions	1.2
D. Access and/or vision	
Direct	0
E. Alignment	
Easy to align	0
Difficult to align	0.7
F. Insertion force	
No resistance to insertion	0
Resistance to insertion	0.6
Restricted	1.5

Figure 6. Fitting values for calculation of fitting index with Lucas DFA method (Mital et al. 2008, p. 145).

4.3 The Boothroyd Dewhurst method

Development for the Boothroyd Dewhurst method started by Boothroyd in 1970s but first complete version of the method was not ready until 1980s. Idea of this method is quite straightforward. It aims to reduce amount of parts in order to reduce assembly operations and to ease assembly operations. Boothroyd Dewhurst method gives four indicators for DFA evaluation. Those indicators are assembly time, assembly cost, minimum number of components and design efficiency. (Ezpeleta et al. 2019, p. 674.)

Implementation of the Boothroyd Dewhurst method is done in following order:

1. Parts and their quantity need to be listed in an order of the assembly sequence.
2. Handling time for each part need to be defined by the handling analysis.
3. Insertion time for each part need to be defined by the insertion analysis.
4. Total assembly time need to be calculated for each part by adding handling time to insertion time. After that total assembly time for the product can be calculated by summing total assembly times for each part.
5. Total assembly cost for each part and products total assembly cost needs to be calculated.
6. Parts need to be classified to essential and to nonessential parts. After that minimum number of parts can be determined.
7. Designs efficiency need to be calculated.
8. Results need to be evaluated.

This implementation can be done manually or with a computer program. (Ezpeleta et al. 2019, p. 674.)

In handling and insertion analyses there is customized tables for evaluating parts handling and insertion times. Each part gets a two-digit handling code and a two-digit insertion code. Those codes are determined by parts orientation, size and materials characteristics. Those codes determine handling time and insertion time for the part. After all parts have been analyzed with handling analysis and insertion analysis based on those two-digit codes that shows handling and insertion times from the tables, times can be summed up. (Mital et al. 2008, p.146-149.)

5 PROTOTYPE DESIGN

Prototype design is being done guided by VDI 2221 design process and selection between different solutions is being made with morphological analysis. This chapter represents different stages of the design work.

5.1 List of requirements

List of requirements presented in Table 3. List of requirementsTable 3. List of requirements. is been made to meet requirements and wishes of the target company. List is divided to five different categories: use, geometry, force and budget. In different categories there is different requirements and wishes to fulfill while designing the prototype.

Table 3. List of requirements.

Category	Requirements	Requirement (R) / Wish (W)
Use	Enable rotor attachment to stator with zero stator reorientations	R
	Enable rotor attachment without special tool for moving stator	R
	Enable rotor attachment without special tool for moving rotor	W
	Able to be used for one product family	R
	Able to be used for two product families	W
	Operating must be able to be done without risk of injury	R
Geometry	Fitting to the table 1550 mm x 750 mm where motor assembly is done	W
	Designed in the way that other assembly work is not going to be disturbed	R
	Designed to ease assembly work	W

Table 3 continues. List of requirements.

Gategory	Requirements	Requirement (R) / Wish (W)
Force	Thrust force must be enough to locate rotor and bearings to their places There must be enough reinforcement to support mass of the rotor and magnetic force	R R
Material	Non magnetic material	R
Budget	Under 50000€ Target 5000€	R W

In first category, use, there are different tasks that needs to be able to complete with the prototype. There are mentions about what prototype is supposed to be used and what kind of restrictions there are for the prototype to get it way the target company wants it. There is also quite overall mention in use category about safety, safety could have been separated as its own category but because all actions need to be safe ones it was decided just to be mentioned under use.

Under category geometry there is some restrictions about the size of the prototype. Idea is that if prototype can be near target the budget the final tool would be attached to every motor assembly table, that why design should be done in the way that assembly tool can fit to the assembly table, but it will not disturb other assembly work. If that is not found to be possible there will be separate assembly station or stations for this assembly phase and other phases will be done in other stations.

In force category there is two requirements and one wish. Requirements limits the force of the active part of the prototype that is used to move rotor and stator towards each other and to locate the bearings. Requirements limits the thrust force F_t to be between 5 kN < F_t < 100 kN. That is because 5 kN is enough to push rotors and stator towards each other and if the force is over 100 kN end shields are in danger to break. There is wish about pulling force of the same active part. That is for possibility to disassemble rotor stator assembly. Needed pulling force F_p is F_p > 1 kN.

Budget has a quite big variance in this prototype because cost limit is 50000€ and wish cost for it is 5000€.The cost limit is that high because there is no intention to rule out any possibly overwhelming option because it is too expensive, but goal is to achieve solution that can be taken to use at every workstation and that why budget of 5000€ is the goal. If that is achieved, then the price of one tool should not be very high. If solution needs more expensive machinery it will not be implemented for every workstation and the price of one tool can be higher but not over 50000€.

5.2 Function structure

Basic function of the prototype is to be a tool for attaching rotors of the permanent magnet electric motor to the stator frame package. It should be able to do it safely and without external moving and rotating tools for the stator frame package. It should also make possible to assemble bearings to the machine. The basic function can be divided to three subfunctions that can still be divided to subfunctions. The subfunctions are moving stator and rotor towards each other, D-end (drive end) attachment and guiding shaft. Solutions for locating bearings and guiding shaft are tightly attached to how moving of the rotor and stator to each other is being implemented. Function structure of the prototype is shown in Table 4.

Table 4. Function structure

		Solutions						
		S1	S2	S3	S4	S5	S6	S7
Functions	F1.1 Moving part	Rotor moves	Stator moves	Both parts are moving				
	F1.2 Movement power	Operator applies straight force	Crank and transmission	Hydraulic press	Servo motor	Winch	Industrial robot	Overhead crane
	F1.3Movement platform	Rail	Roller deck	Wheels	Operating without separate platform	Sliding sleeve	Ball bearings (3x)	
	F1.4 Second movement platform	Rail	Roller deck	Wheels	None	Sliding sleeve	Ball bearings (3x)	
	F2 D-end shield attachment	Before rotor attachment	After rotor attachment					
	F3 Shaft guidance	Guide to N-end of the shaft	Guide from both ends of the shaft	Support to D-end				

While thinking about attaching rotor and stator to each other it can be still divided to parts and there should be figured out which part is moving? What powers the moving? What platform moving is going to happen? For the question which part is moving, answer can be stator, rotor or both of those.

Movement power can be implemented in several ways. If moving platform is good and guiding of the shaft and locating of the bearings are excellent the moving could be done by simply pushing it by manpower. Other man powered solution could be a crank. With the crank there should be some transmission to transfer rotating movement to linear movement. Hydraulic press is being used in current solution and it could be a solution for this also. Another option would be a servo motor with ball screw. An industrial robot or an overhead crane could also be used for powering the movement. All those solutions are doing pushing. As another possibility is to pull one part towards another. Pulling could be done with a winch.

Platform for moving a motor or a rotor or both while assembly work can also be done in several ways. Basically, it can be thought that these solutions can be divided to two groups. The ones that need a sledge an those that does not need one. First some solutions that needs the sledge. A rail is one potential solution, a rail would do part of the alignment. Moving could also be done by a roller deck. Benefit of the roller deck is that it could easily to be attached to a bigger roller deck line to keep assembly going on next workstation. Quite common wheels could also be implemented to a sledge and that could be used for moving purposes. If powering of the movement is being done by an industrial robot or an overhead crane any platform is not needed. In these cases, neither a sledge is needed. A sliding sleeve or ball bearings could be used by themselves or as a hybrid solution with some of those solutions that require use of a sledge. Need for the hybrid depends on forces that applies to the system. Good thing about the hybrid solution is that the sledge helps moving and reduces forces in a sliding sleeve or ball bearings, but a sliding sleeve or ball bearings gives good guidance for shaft.

For locating of the bearings there are shoulders in shaft and in both end shields. The N-end shield is being attached to the frame where the stator is while assembling the rotor into it. The N-end bearing must be attached before inserting the shaft and it should be supported so it locates correctly regarding the shaft and the shield. The D-end shield can be attached to the rotor shaft before assembly or after it. If the D-end shield is attached to the shaft of the rotos before the rotor is assembled to the stator, the D-end bearing must be supported during the assembly so that it stays in the correct location regarding the shield, that way it will also locate correctly regarding the shaft if the N-end support has done its job correctly. Other possibility is that the D-end shield and the bearing are attached to the shaft after the rotor is assembled to the stator. In this option there must be some tool for pushing the bearing along the shaft so it will settle to its correct location. Also, in this option the D-end bearing must be supported all the time so both the bearings will locate correctly.

The shaft must be guided to the bearing so that the rotor laminates will not touch to the stator or the frame and that the shaft will enter to the N-end bearing at the correct position. Because of big mass of the rotor and magnet force inside the rotor the support must be done with guide through bearings or with some serious forces from the D-end of the shaft. For both options there might be couple of different possible solutions. For guide solutions there could be simple guide, sized along bearings inner diameter, attached to the N-end of the shaft. Other solution could be a long guide that is attached from both ends of the shaft, in this solution moving force for attaching the rotor and the stator must probably to be implemented into support solution. If support is being done only from the D-end there should be a quite massive support element and the rotor assembly should probably be made before attaching the D-end shield to get more space for the support element. Hybrid solutions of moving platform would also give some extra support and guidance for the shaft as mentioned earlier.

5.3 Conceptual overall solutions

While thinking different solutions from function structure some options can be ruled out. In functions category F1.1, moving part, solution S3, all solutions are considered as good options and that why nothing is ruled out.

From category F1.2, different powering options for the rotor or stator movement, the solutions S1, S6 and S7 are ruled out. S1 is the solution where an operator applies straight force. That is ruled out because there is no good meter how much force an operator should be applying. The solution S6, an industrial robot, is ruled out because it is expensive. The solution S7, an overhead crane, is ruled out because with the current factory layout there is one overhead crane over four assembly centers. If there are lots of motor assemblies in the same work phase there would be a lot of waiting time or new investments to cranes. At the moment the overhead crane is reserved almost the whole-time a rotor is assembled to a stator and that is something that now should be avoided.

From the category F1.3, a movement platform, there was not any options ruled immediately out, but because on ruling out the industrial robot and the overhead crane in the category F1.2, movement power, the solution S4, operating without a separate platform, should be ruled out. All the other moving power solutions require some platform.

From category F1.4 rail, roller deck and wheels can be ruled out because in hybrid solutions they can be picked from F1.3 and those three can not be part of hybrid solution together, they need to have sliding sleeve or ball bearings working with them.

For the category F2, the D-end shield attachment, there is no reason to rule out either of the solutions. With company’s current solution there have been problems with the centering of the rotor shaft during the bearing assembly and that have caused some assembly errors with the bearings. That why the solution S1, the D-end attachment before the rotor attachment, should be favored.

In the category F3, the shaft guidance, all three solutions can be used. After ruling out all the solutions mentioned above from the Table 4, conceptual overall solutions must be picked up from the remaining ones. In Table 5 the solutions that are ruled out are marked with red and the remaining white cells in the table are the ones that should be considered in the prototype design.

Table 5. Function structure after ruling some solutions out.

		Solutions						
		S1	S2	S3	S4	S5	S6	S7
Functions	F1.1 Moving part	Rotor moves	Stator moves	Both parts are moving				
	F1.2 Movement power	Operator applies straight force	Crank and transmission	Hydraulic press	Servo motor	Winch	Industrial robot	Overhead crane
	F1.3Movement platform	Rail	Roller deck	Wheels	Operating without separate platform	Sliding sleeve	Ball bearings (3x)	
	F1.4 Second movement platform	Rail	Roller deck	Wheels	None	Sliding sleeve	Ball bearings (3x)	
	F2 D-end shield attachment	Before rotor attachment	After rotor attachment					
	F3 Shaft guidance	Guide to N-end of the shaft	Guide from both ends of the shaft	Support to D-end				

Based on Table 5 three different overall solutions are picked up and evaluated. The best overall solution is being selected and designed to detail, a prototype will be assembled, and it will be tested and compared to the old system. In Table 6 selection of overall selection 1 is shown. In the first overall solution there are same solutions that the target company is using currently. Moving parts in the attachment process will be both, a rotor and a stator and the power for the movement is applied with a hydraulic press. In the overall solution 1 moving platform will be a hybrid with a rail and a sliding sleeve. In the current solution there is no separate platform for movement because before the hydraulic press is being used a rotor is lowered to a stator with overhead crane and a shaft guidance in the N-end is keeping rotor in place. Also, in the overall solution 1, the D-end shield will be attached to a rotor before a rotor is attached to a stator as it is done also in the current solution. The shaft guidance in the overall solution 1 and the current system is the same, the N-end guidance through a bearing, the guidance goes also through the sliding sleeve in the N-end and that gives to the structure more stability during the attachment. In the overall solution 1 idea is to exploit as much of the old system as it is possible and just make some modifications so it can be applied horizontally. Figure 7 and Figure 8 shows how the overall solution 1 could be implemented.

Table 6. Overall solution 1

		Solutions						
		S1	S2	S3	S4	S5	S6	S7
Functions	F1.1 Moving part	Rotor moves	Stator moves	Both parts are moving				
	F1.2 Movement power	Operator applies straight force	Crank and transmission	Hydraulic press	Servo motor	Winch	Industrial robot	Overhead crane
	F1.3Movement platform	Rail	Roller deck	Wheels	Operating without separate platform	Sliding sleeve	Ball bearings (3x)	
	F1.4 Second movement platform	Rail	Roller deck	Wheels	None	Sliding sleeve	Ball bearings (3x)	
	F2 D-end shield attachment	Before rotor attachment	After rotor attachment					
	F3 Shaft guidance	Guide to N-end of the shaft	Guide from both ends of the shaft	Support to D-end				
Overall solution		OS1						

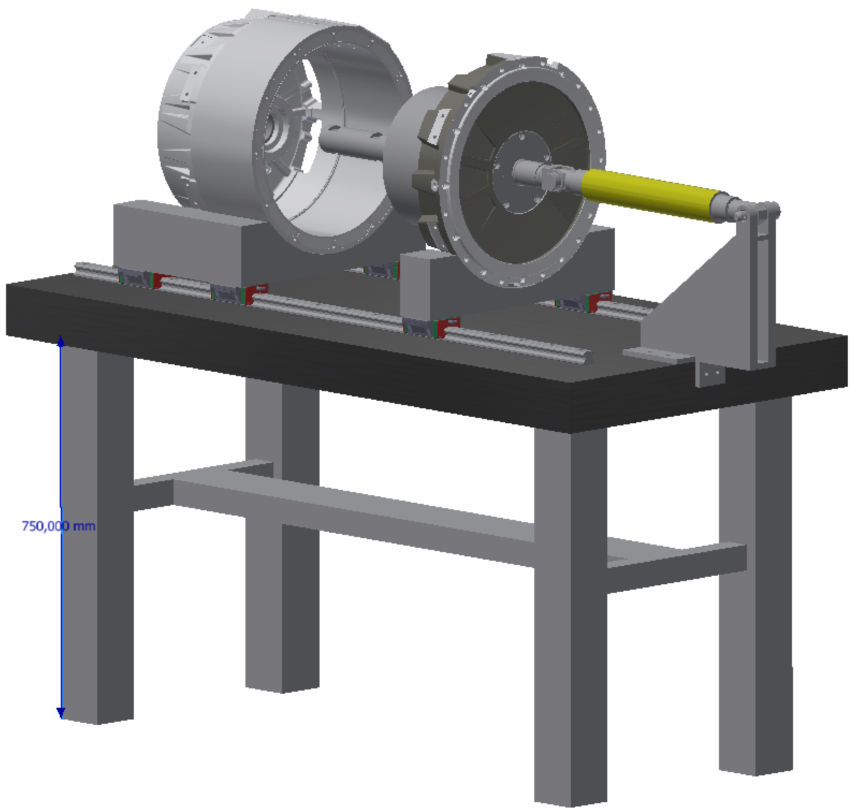


Figure 7. The possible implementation of the overall solution 1.

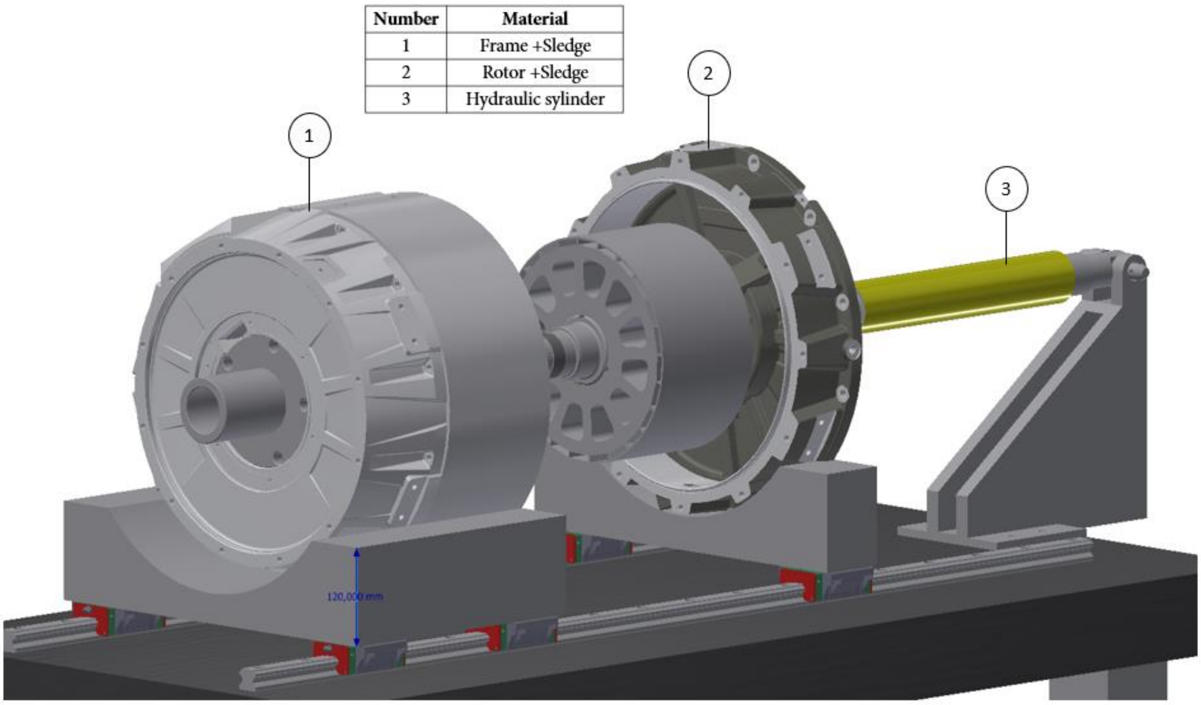


Figure 8. The possible implementation of the overall solution 1 from a different angle.

The overall solution 2 is shown in Table 7. This solution differs from the overall solution 1 in five ways. There only a rotor is moving, and it is not pushed, it is pulled with a winch. The moving platform is not a hybrid of a rail and a sliding sleeve, it is moving only on the rail. The D-end shield will be attached after a rotor is attached to a stator. The shaft guidance is going to be in the both ends of the shaft. There is not much in common between the overall solutions 1 and 2, only thing in common is that in the both solutions there will be a rail to ease moving. Possible implementation of the overall solution 2 is shown in Figure 9 and in Figure 10.

Table 7. Overall solution 2

		Solutions						
		S1	S2	S3	S4	S5	S6	S7
Functions	F1.1 Moving part	Rotor moves	Stator moves	Both parts are moving				
	F1.2 Movement power	Operator applies straight force	Crank and transmission	Hydraulic press	Servo motor	Winch	Industrial robot	Overhead crane
	F1.3Movement platform	Rail	Roller deck	Wheels	Operating without separate platform	Sliding sleeve	Ball bearings (3x)	
	F1.4 Second movement platform	Rail	Roller deck	Wheels	None	Sliding sleeve	Ball bearings (3x)	
	F2 D-end shield attachment	Before rotor attachment	After rotor attachment					
	F3 Shaft guidance	Guide to N-end of the shaft	Guide from both ends of the shaft	Support to D-end				
Overall solution			OS2					

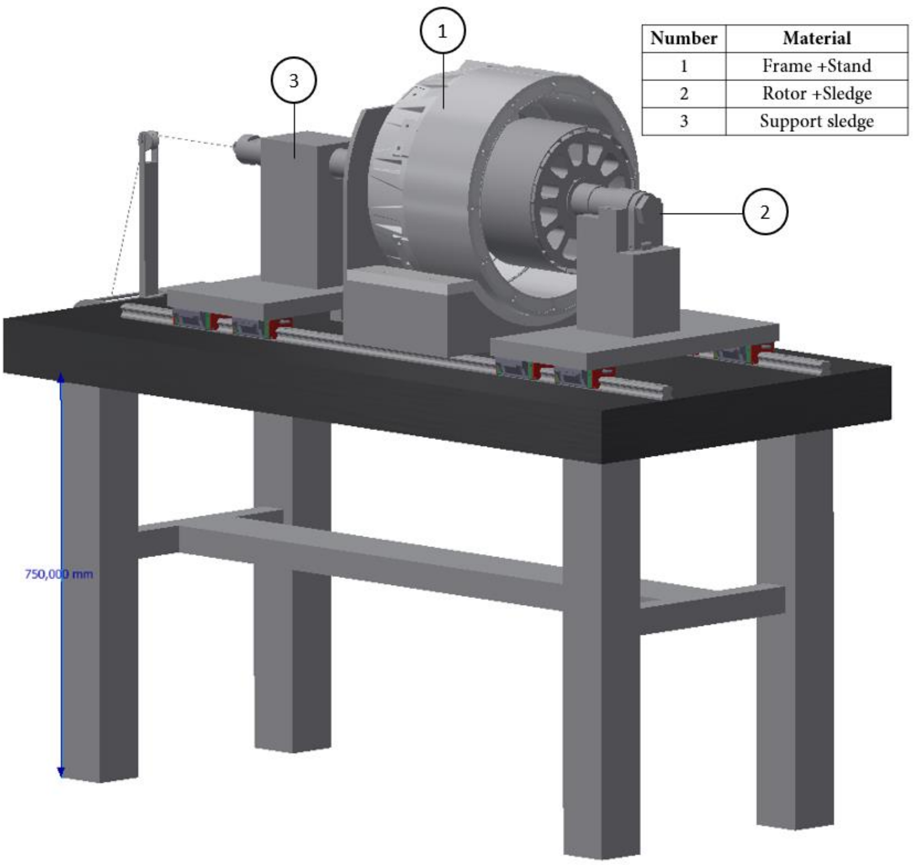


Figure 9. The possible implementation of the overall solution 2.

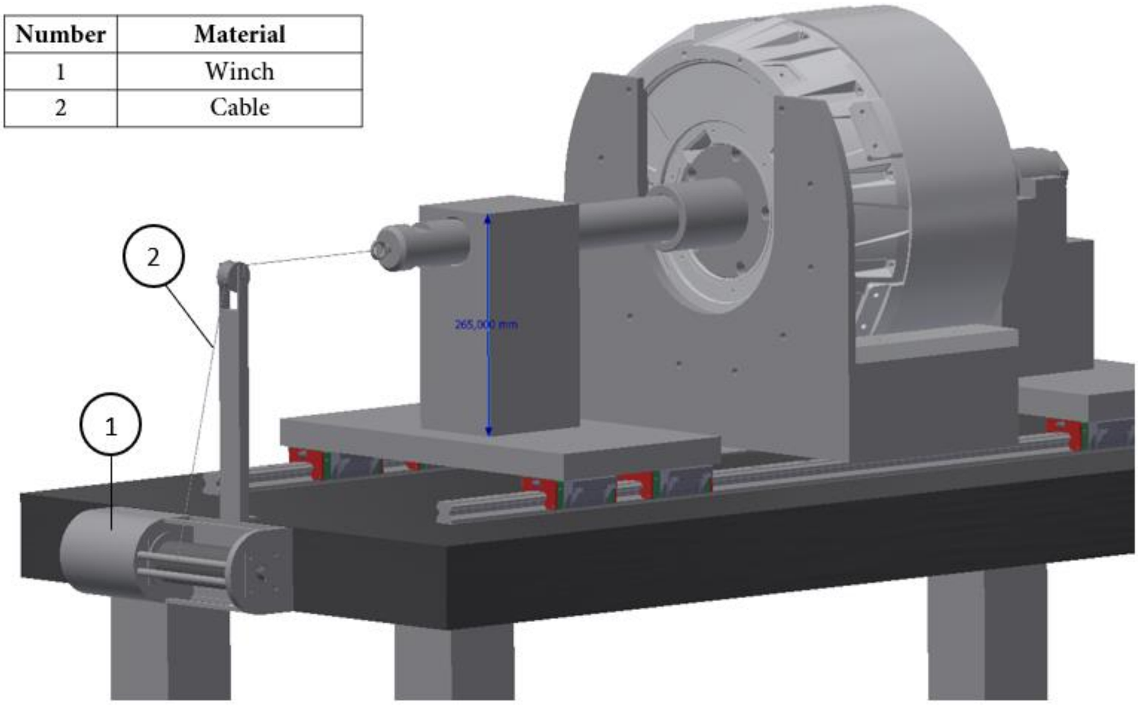


Figure 10. The possible implementation of the overall solution 2 from a different angle.

In the overall solution 3 a stator is the component that moves. It is moved towards a rotor with a servo motor attached to a ball screw mechanism. Movement is going to happen on a rail same way as it is in the overall solution 2. Also, the D-end shield attachment is going to happen before a rotor is attached to a stator as it is going to be in all the overall solutions. a shaft guidance in this solution is going to be done by support in the D-end. A rotor is going to be positioned in the way that a stator can be pushed to its place while being attached to a sledge moved by a ball screw mechanism that is powered by a servo motor. Depending on the design of support elements some guidance piece in the N-end of the rotor might be good to guide a shaft through the N-ends bearing. Selections for the overall solution 3 are shown in Table 8 and the possible implementation in Figure 11 and in Figure 12.

Table 8. Overall solution 3

		Solutions						
		S1	S2	S3	S4	S5	S6	S7
Functions	F1.1 Moving part	Rotor moves	Stator moves	Both parts are moving				
	F1.2 Movement power	Operator applies straight force	Crank and transmission	Hydraulic press	Servo motor	Winch	Industrial robot	Overhead crane
	F1.3Movement platform	Rail	Roller deck	Wheels	Operating without separate platform	Sliding sleeve	Ball bearings (3x)	
	F1.4 Second movement platform	Rail	Roller deck	Wheels	None	Sliding sleeve	Ball bearings (3x)	
	F2 D-end shield attachment	Before rotor attachment	After rotor attachment					
	F3 Shaft guidance	Guide to N-end of the shaft	Guide from both ends of the shaft	Support to D-end				
Overall solution				OS3				

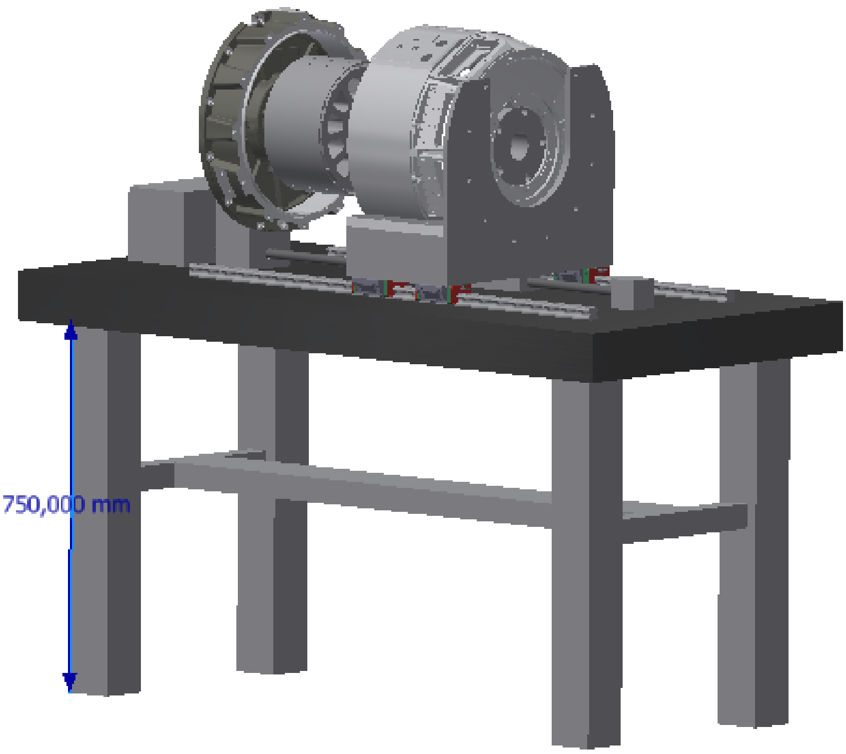


Figure 11. The possible implementation of the overall solution 3.

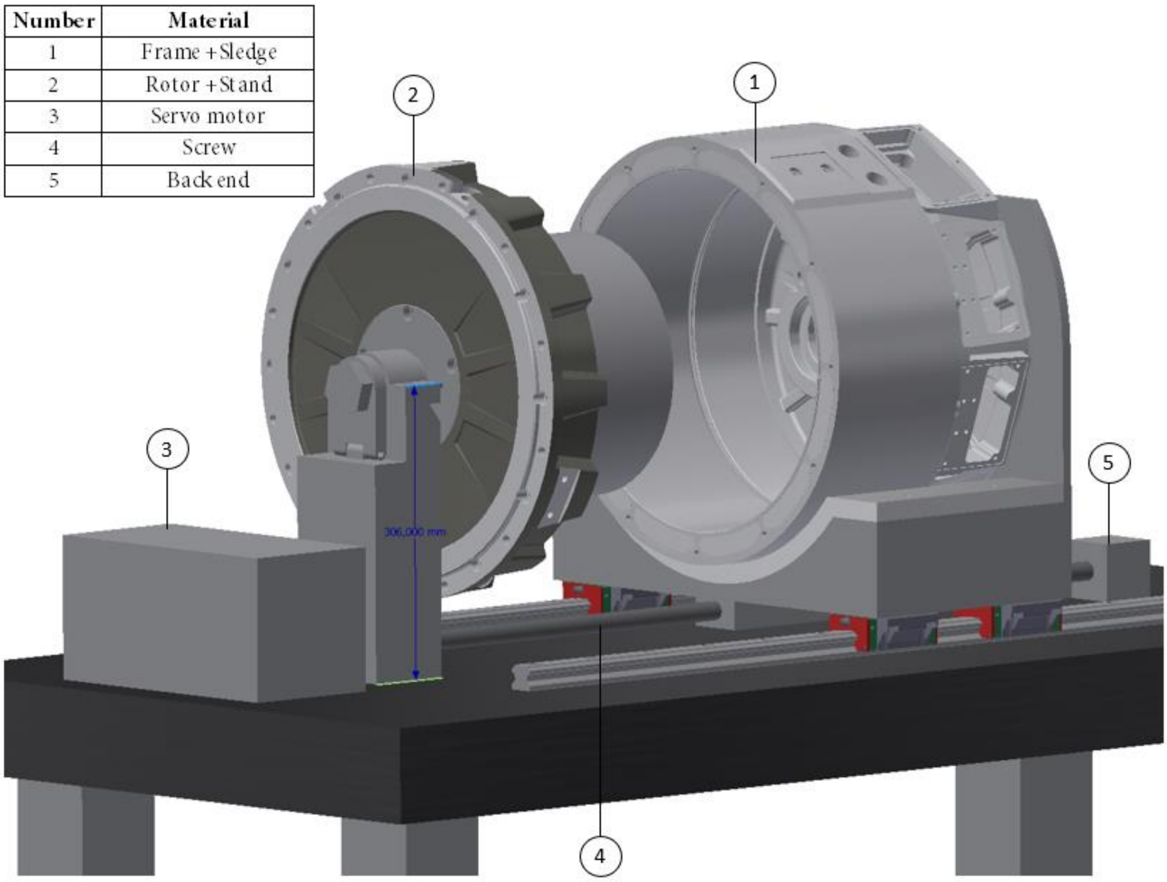


Figure 12. The possible implementation of the overall solution 3 from a different angle.

5.4 Selection between the overall solutions

All three selected overall solutions have been analyzed. All solutions have some issues that have to be considered before the selection of the solution that will be designed.

In the overall solution 1 there need to be considered possibility for a hybrid solution for movement power. For example, an operator can move a rotor near to its final location by a hand and final locating should only be done with a press. That way the stroke of the hydraulic press can be much shorter. Usually when the stroke of the press is long the press is quite large in all ways and then there is a lot of power in the press. Unnecessary power in the press might cause some damage for the motor and that way even possibility for injuries. That why force has a top limit in the requirements list.

In the overall solution 2 there is problem that the D-end shield can not be installed before a rotor is attached to a stator because while pulling the rotor to its place there is no easy way to apply force in the way that the D-ends shield, the bearing and the shaft will be in their correct locations while locating the N-end. If the D-end shield and the bearing are not attached before a rotor is attached to a stator it must be done afterwards. It can not be done afterwards with a winch so there should be some alternative way of attaching the D-end shield and the bearing, for example a hydraulic press. An additional tool will decrease usability and increase assembly time, amount of work phases and costs.

In the overall solution 3 there is good possibility that it will not work at all. Idea with overall solution 3 is that there would be support in the D-end of the shaft that would keep a rotor still and in the correct position while a stator is being attached. The problem is that in the shaft there is not good surface where it could be supported in the way needed to align the rotor decently.

After these observations, comparison of these three overall solutions have been done and is shown in Table 9. Criteria of evaluation are usability, work phases, time consumption in use, acquisition cost and usage cost. All the criteria are estimates. With every criterion there is a number between 1-10 where 10 is the best solution and 1 is the worst. Different criteria are weighted based on their importance. Usability is considered qualitatively based on estimate of difficulty of different work phases for an operator. Different work phases are counted from the overall solutions probable implementation. Points in Table 9 regarding work phases are proportioned from amount work phases and scaled between 1-10. Value of time consumption in use have been done in the same way as the work phases. Acquisition cost and usage costs have been roughly estimated and cheapest solutions have been graded with the highest value.

Table 9. Comparison between overall solutions.

Criteria of evaluation	Weight	Overall solutions		
		OS1	OS2	OS3
Usability	0,4	8	4	5
Work phases	0,15	5,5	4,5	7
Time consumption in use	0,3	7	2	5
Acquisition cost	0,05	7	6	3
Usage costs	0,1	8	8	6
Total points	1	7,3	4,0	5,3

From the Table 9 it can be seen that the overall solution 1 has the highest score. Based on that it will be the overall solution that is selected to be designed. For the solution there is big influence with the issues figured out in the further inspection after forming those three overall solutions. The issues influenced in the comparison to usability and time consumption in use. Costs also had some influence. Usability and time consumption are weighted to be important criteria and that why influence is big.

5.5 Module structure

The structure can be divided to 9 modules. The modules are a rail, brakes, a frame sledge, a rotor sledge, a D-end bearing support, a N-end bearing support, a shaft guide, a cylinder and a end support for cylinder. All modules have some tasks in the whole prototype to take care of to make construction work.

The rails are supposed to cart sledges towards each other in straight line so the alignment of the rotor and the stator frame package would remain correct. The rails should also support the weight of the whole construction.

The brakes are needed for two directions. Because there is idea that both a stator and a rotor are moving there is a need of a brake to stop movement of the stator while the rotor is inserted into it. The stator movement is supposed to be done by an operator pushing it. While a rotor is already alignment to fit in a stator perfectly if an operator pushes a stator too far magnetic force of a rotor will pull a stator in and there is possibility for injury. Whole insertion process needs to be in control all the time and that why there is a need of a stopper or an indicator to indicate how far an operator can push a stator. After a stator is located to its correct place movement of a stator sledge needs to be locked in both ways towards to the rotor and away from it. If the stator movement away from the rotor is not restrained the stator sledge might move before the bearings are located to the rotor shaft correctly.

The most important job of the frame sledges is to carry the frame. But it must also align the frame correctly regarding to the rotor. It is also important that there should be as little as possible free space for the frame moving at the sledge because it complicates the assembly work due the poor alignment. The rotor sledges task is similar to the frame sledges. It needs to move the rotor and keep it aligned with the frame stator package. For the rotor there should not either be any tolerance for misalignment.

The bearing supports and the shaft guide are working together to get the rotor straight in and the bearings located correctly. The bearing support of the N-end is keeping the bearing correctly located according to the end shield while inserting the shaft. In the bearing support of the N-end there should also be some guidance for the shaft to keep it straight while pushing the rotor in. The bearing shield of the D-end should keep the bearing correctly located according to the D-end shield. At the D-end there is no need for the shaft support at the bearing shield because the rotor sledge is in that end and it will give needed support to the rotor in that side. The shaft guide needs to guide the shaft through the bearing and the bearing support of the N-end. The guide and the bearing support of the N-end should give needed support and keep the rotor in the correct position, so that the force from the rotor pushing does not affect on wrong places and keep the rotor from colliding to the shoulders of the N-end shield.

The cylinder and the end support of the cylinder are needed to get the force for the pushing rotor into the stator. The cylinder support needs to locate the cylinder into a correct position, so that the force goes in straight line through both bearings and does not try to push it diagonally. That would cause unwanted tension to the structure and make assembly work harder. The cylinder is supposed to do the pushing to enter the rotor into the stator and locate the bearing of the N-end to its place.

5.6 Modeling of prototype

In this prototype only new parts were modeled. Rotor parts, frame and end shields were downloaded from the target company’s PLM (Product Lifecycle Management) system. For the frame assembly, only the frame was downloaded, there were no need to attach the stator inside it because all the examined contact surfaces are at the frame. Also examining the frames shapes in the assembly is easier when there is no stator inside of it.

Modeling started from creating the table where whole prototype should fit. It was essential to start from the table because it restrained the space that could be used for the prototype. The rails and the rolling elements on the table were selected from the linear guideway catalog of the commercial web site and the CAD models were downloaded (Movetec, 2019). Between the rails and the table there were need for some reinforcement to make sure that the rails are lined with each other and to keep structure steady.

Modeling of the frame sledge started from a quite simply model. The first model was only a simple sledge that conforms the shapes of the frame. Attachment to this model was supposed to be made with a strap from above of the frame. The first model can be seen in Figure 13. That was not eventually good design because the edge of the frame is not dimensionally accurate enough for the alignment for the rotor assembly. After that two different solutions were developed. The new sledge option were the one with the connection from the flange of the N-end shield that has been tolerated to be perpendicular with bearing housing. The other option was to connect the frame to the sledge from the bearing support of the N-end that had to be tolerated to the bearing housing to keep the bearing located while inserting the rotor. Both options were modeled and estimated. The option with the flange attachment is shown in Figure 14 and the option with the bearing support attachment is shown in Figure 15. In all frame options there is four rolling elements and in the flange attachment option and in the bearing support attachment option there is a plastic surface to avoid the frame to scratch.

Number	Material	Weight
1	Sledge	107,5kg
2	Rolling element	1,2kg

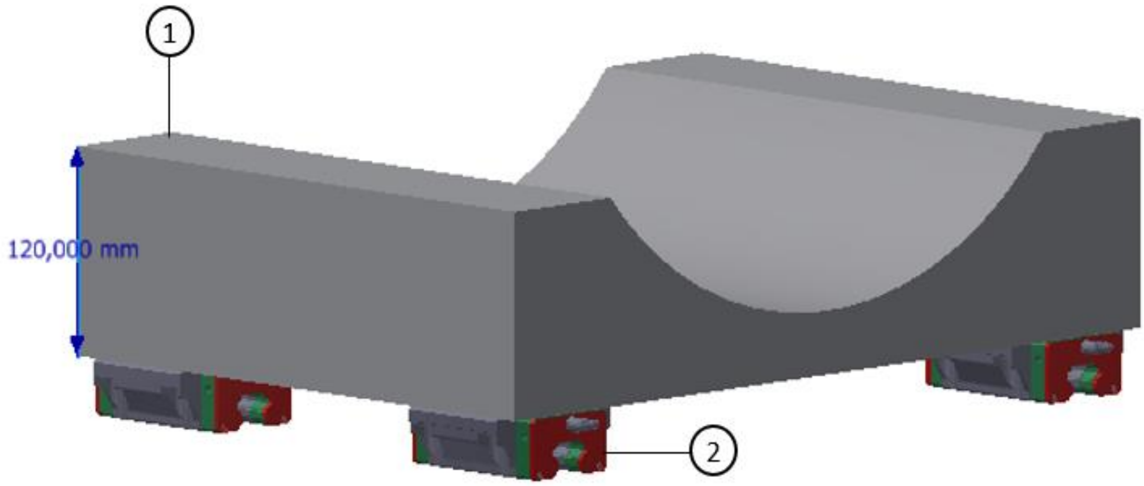


Figure 13. Original frame sledge.

Number	Material	Weight
1	Sledge	72,1 kg
2	Plastic surface	3,0 kg
3	Rolling element	1,2kg

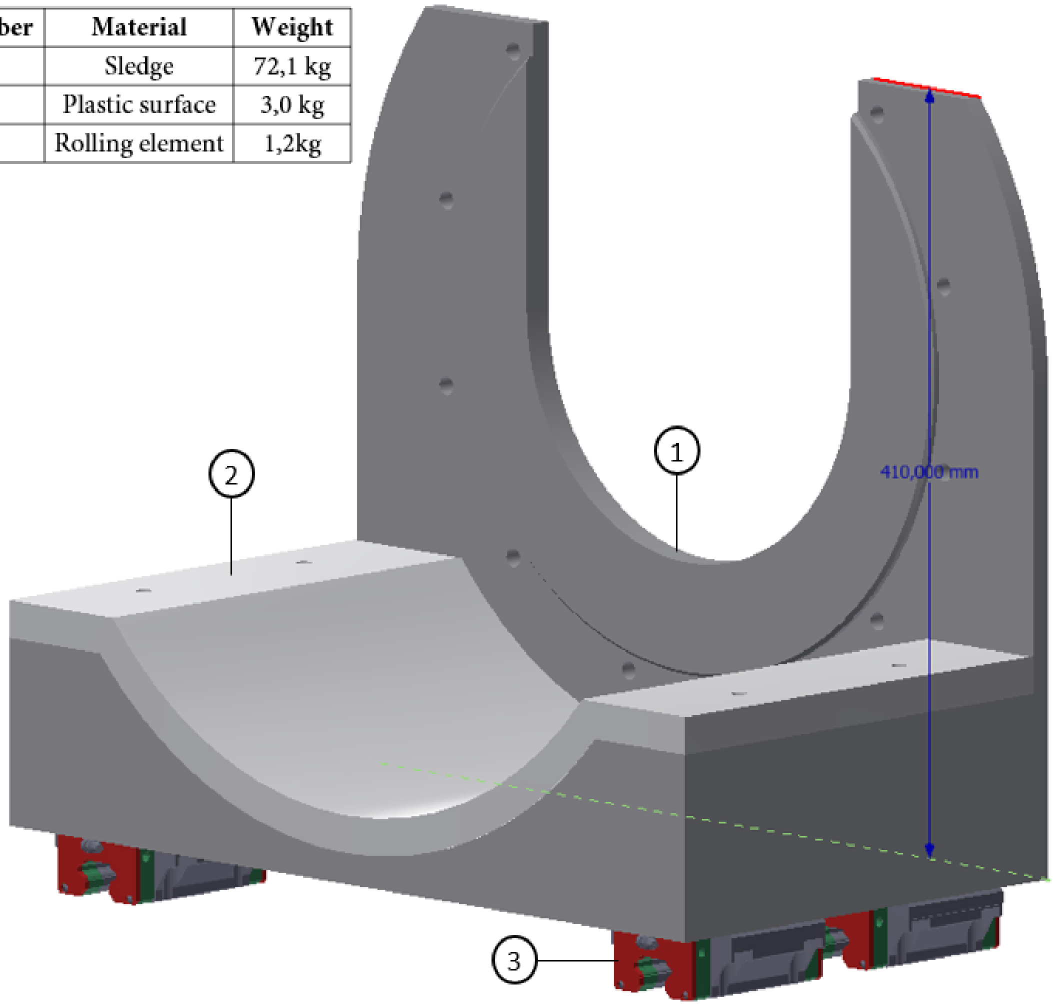
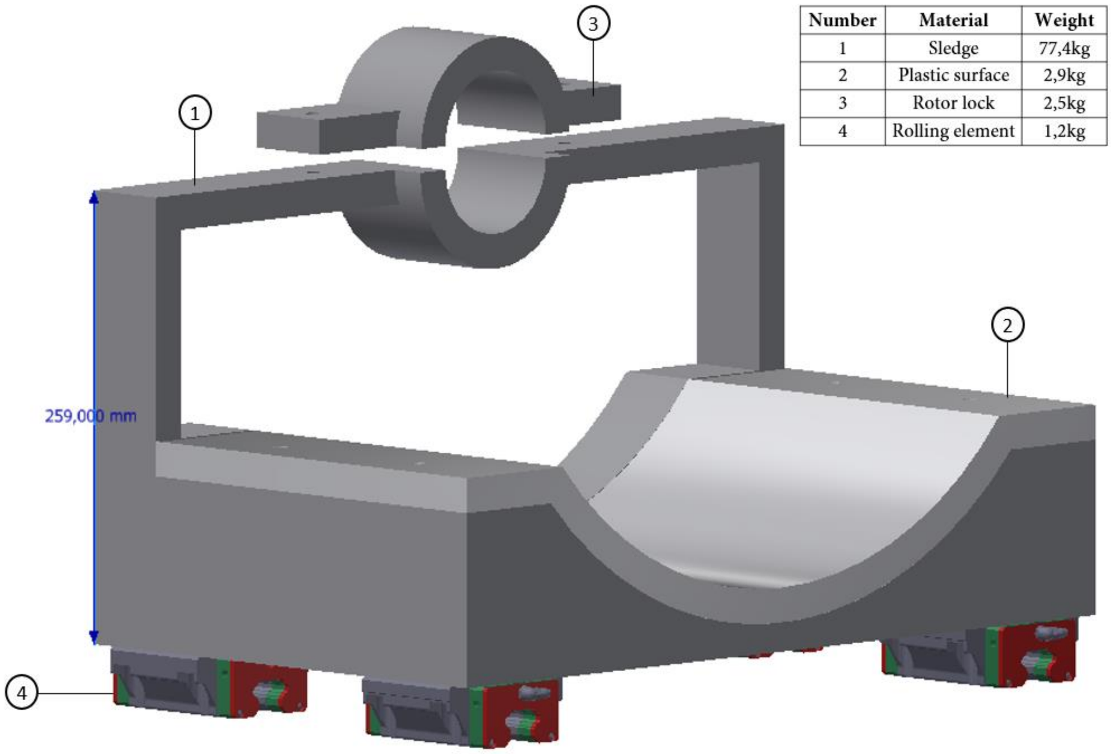


Figure 14. Frame sledge with flange attachment.



Number	Material	Weight
1	Sledge	77,4kg
2	Plastic surface	2,9kg
3	Rotor lock	2,5kg
4	Rolling element	1,2kg

Figure 15. Frame sledge with bearing support attachment.

First idea for the rotor sledge was just to carry the rotor from the D-end shield. In the first option there was nothing else than a small sledge designed to conform shapes of the D-end shield attached to the rotor and two rolling elements. The first rotor sledge option is shown in Figure 16. That is not good design for a many reason. In addition, for transportation there is also need for aligning at the rotor sledge as well as in the frame sledge. Also, the sledge that only has two rolling elements might get quite difficult to move and to balance.

Number	Material	Weight
1	Sledge	26,5 kg
2	Rolling element	1,2 kg

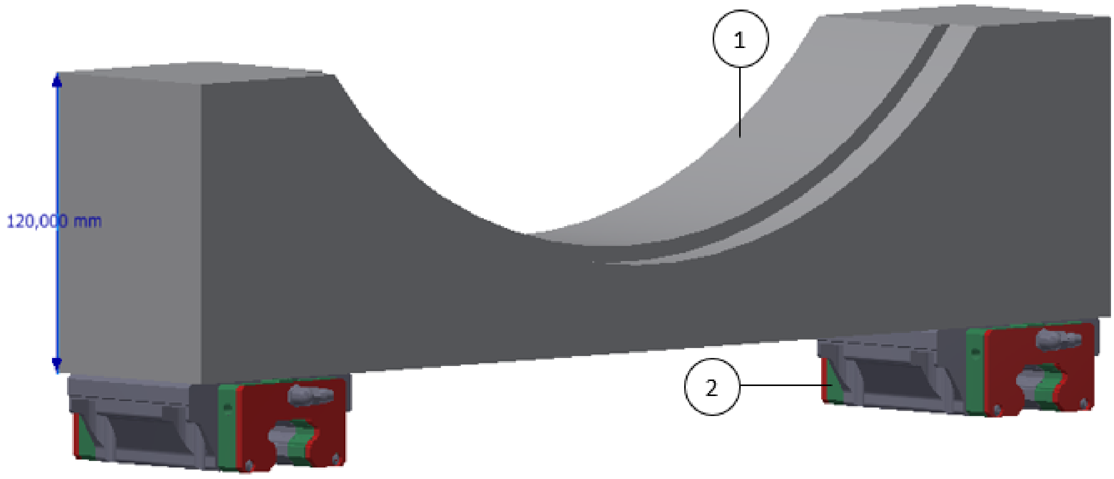


Figure 16. First version of rotor sledge.

Due the poor design of the rotor sledge a new one was designed. To the second version some features were added shown in Figure 17 and Figure 18. In the second version the sledge is a lot bigger than the first version. There are four rolling elements to ease moving and to enhance balance. There is also an attachment to the shaft for alignment with respect to the frame. The shaft attachment also helps with the reorientation of the rotor. The rotor can be lowered from above to the shaft attachment, locked to it and then tilted to the correct position regarding to the frame. The turning tool of the rotor sledge can be in two positions without external help. In the assembly position and in the position in which the rotor can be lowered to the sledge. After the rotor is lowered to the sledge it should be locked into it by screwing the cylinder adapter to the end of the shaft. When the rotor is locked to the tool it can be tilted to the assembly position with the overhead crane that needs to be also used to lower the rotor into the sledge. After the rotor is in assembly position, it should be locked with upper part of the alignment tool of the rotor sledge. Two positions of the rotor sledge are shown in Figure 19.

Number	Material	Weight
1	Sledge	57,8 kg
2	Rotor lock	0,6 kg
3	Rolling element	1,2 kg
4	Cylinder attachment	0,6 kg

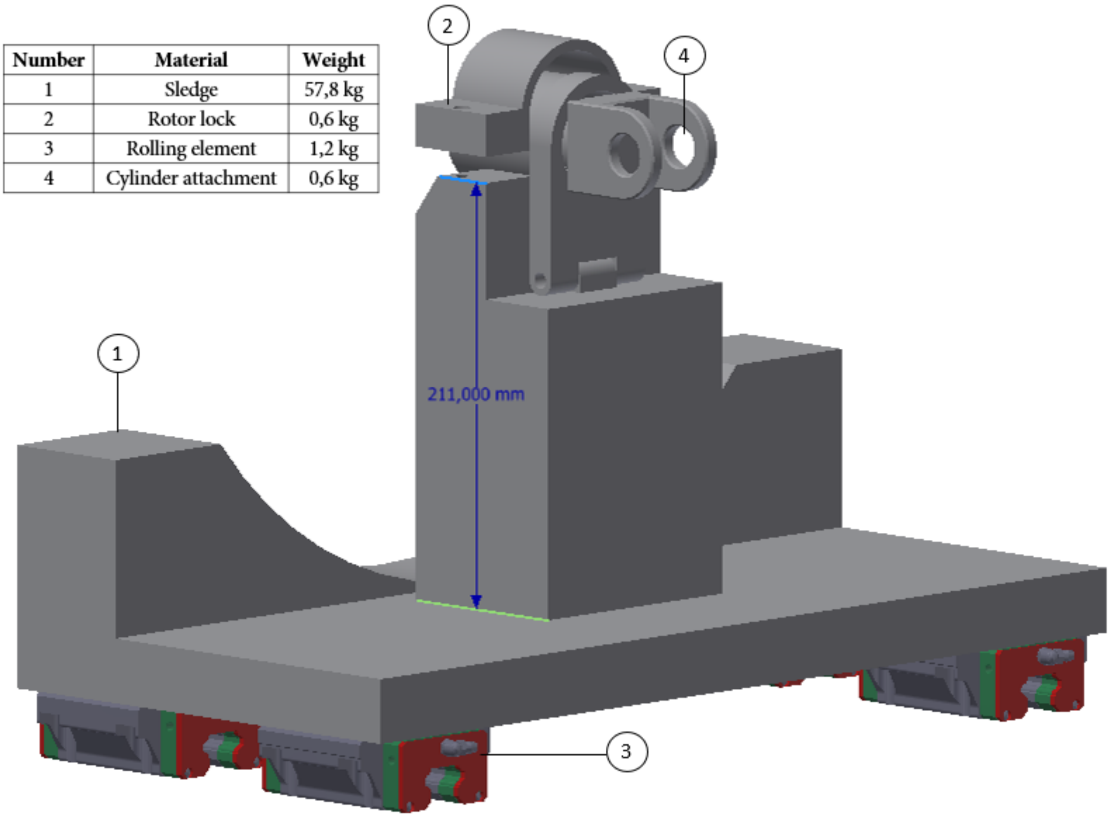


Figure 17. Rotor sledge.

Number	Material	Weight
1	Rotor holder	0,9 kg

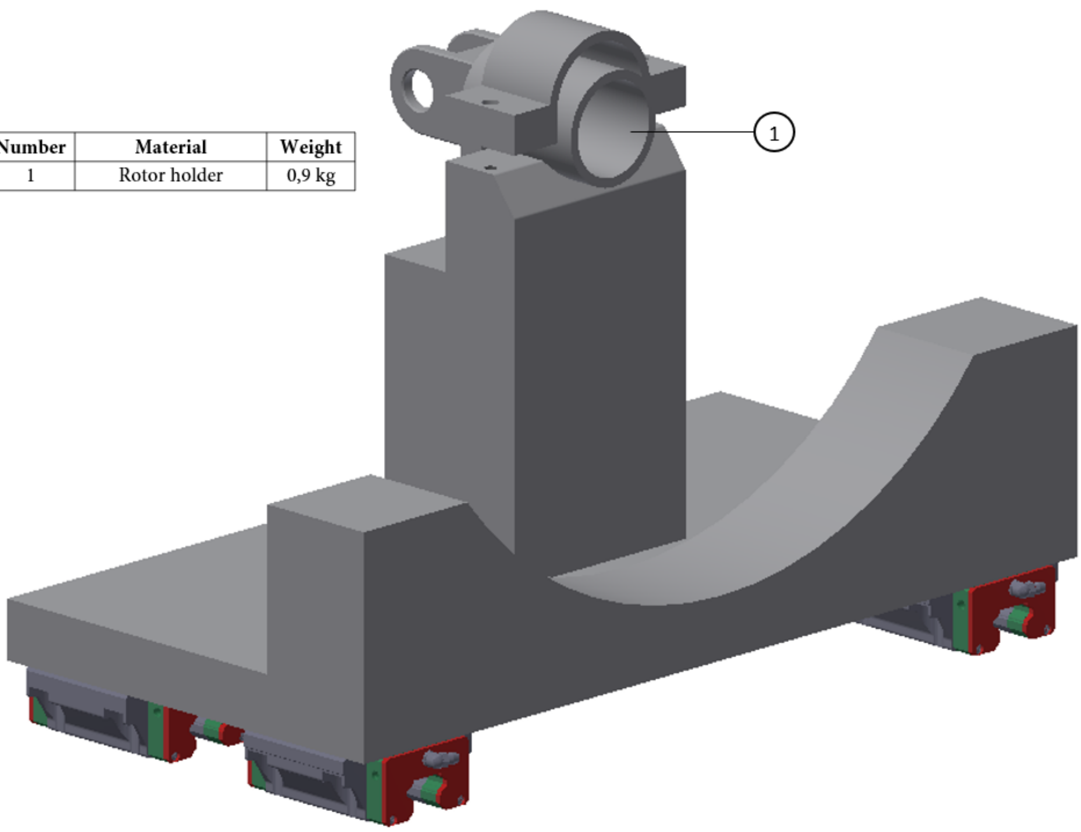


Figure 18. Rotor sledge from another angle.

Number	Material	Weight
1	Sledge	57,8 kg
2	Rotor lock	0,6 kg
3	Rolling element	1,2 kg
4	Rotor holder	0,9 kg
5	Cylinder attachment	0,6 kg
6	Rotor + end shield	63,0 kg

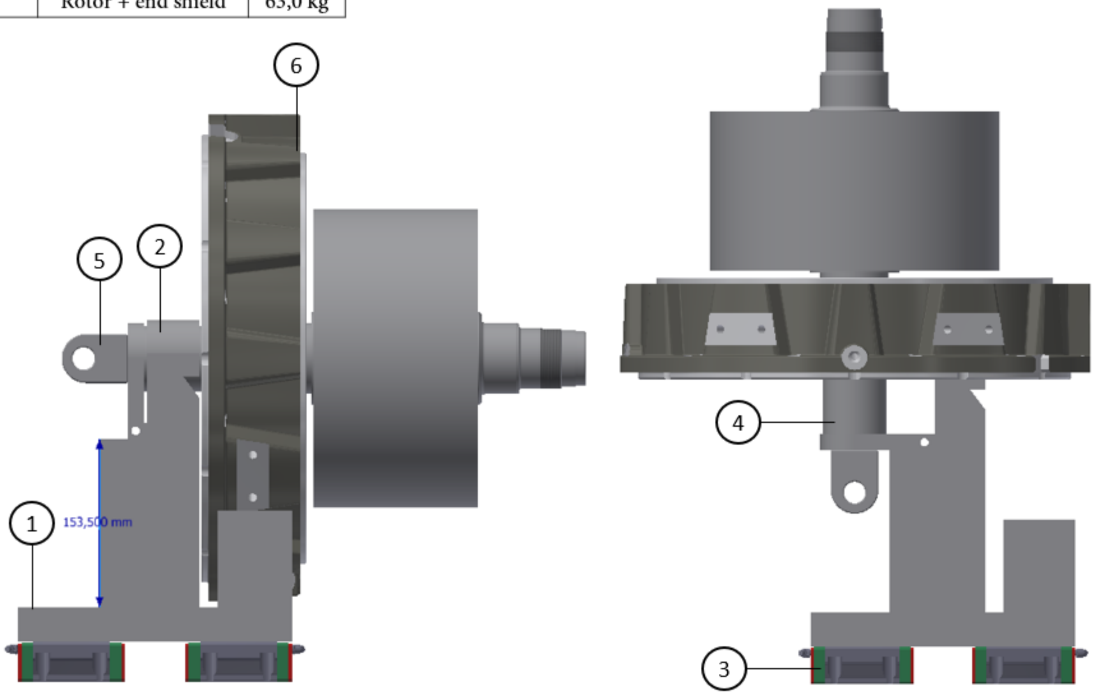


Figure 19. Two position of the rotor sledge.

The hydraulic cylinder and its pump that met the requirements were looked up and downloaded from internet. The selected cylinder is a 2-way cylinder that has a stroke of 257 mm, a thrust force of 80 kN and a pulling force of 44 kN. Due its 2-way action it can also be used to disassemble the rotor from the stator. The selected pump is two speed manually operated hydraulic pump. Its two-speed property reduces needed pumping by 78%. Due to its built-in 4-way valve, it can be used with the 2-way cylinders. (Enerpac, 2018.)

The end support of the cylinder was designed to be attached to the end of the table. The first version was straight up from the end of the table model, where attachment to the table were from two sides. The first version is shown in Figure 20.

Number	Material	Weight
1	Cylinder support	33,0 kg

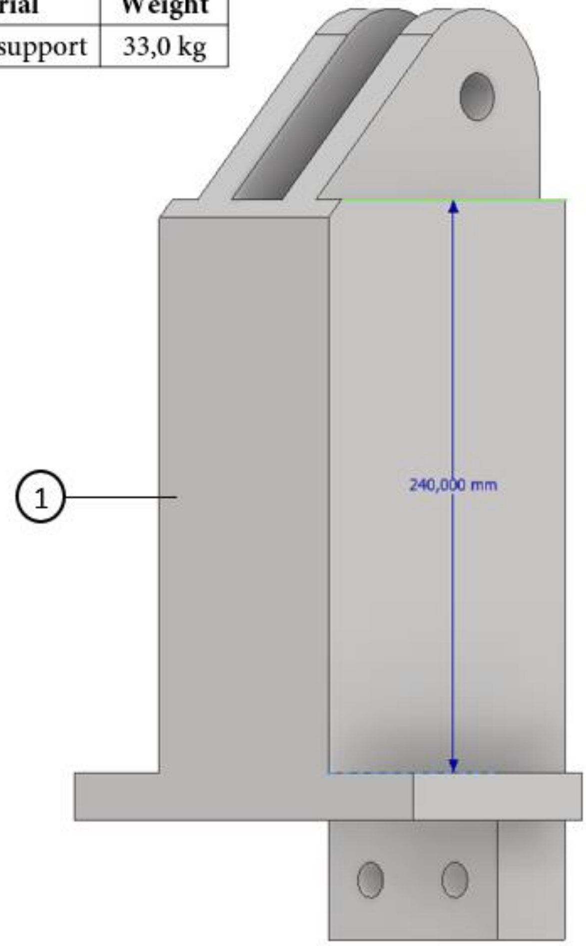


Figure 20. First version of the end support of the cylinder.

That version was not good because there was not room for attaching the shaft guide. The second version was made to be attached same way as the first one, but it took the attachment of the cylinder away from the table. With this decision the wish from requirements list about fitting the prototype to the assembly table was not filled but a needed extra room was achieved. The second version is shown in Figure 21.The design of the second version was functionally working but it needed some tuning to get of some weight off and better details to shapes so the third version was made and it is shown in Figure 22.

Number	Material	Weight
1	Cylinder support	45,0 kg

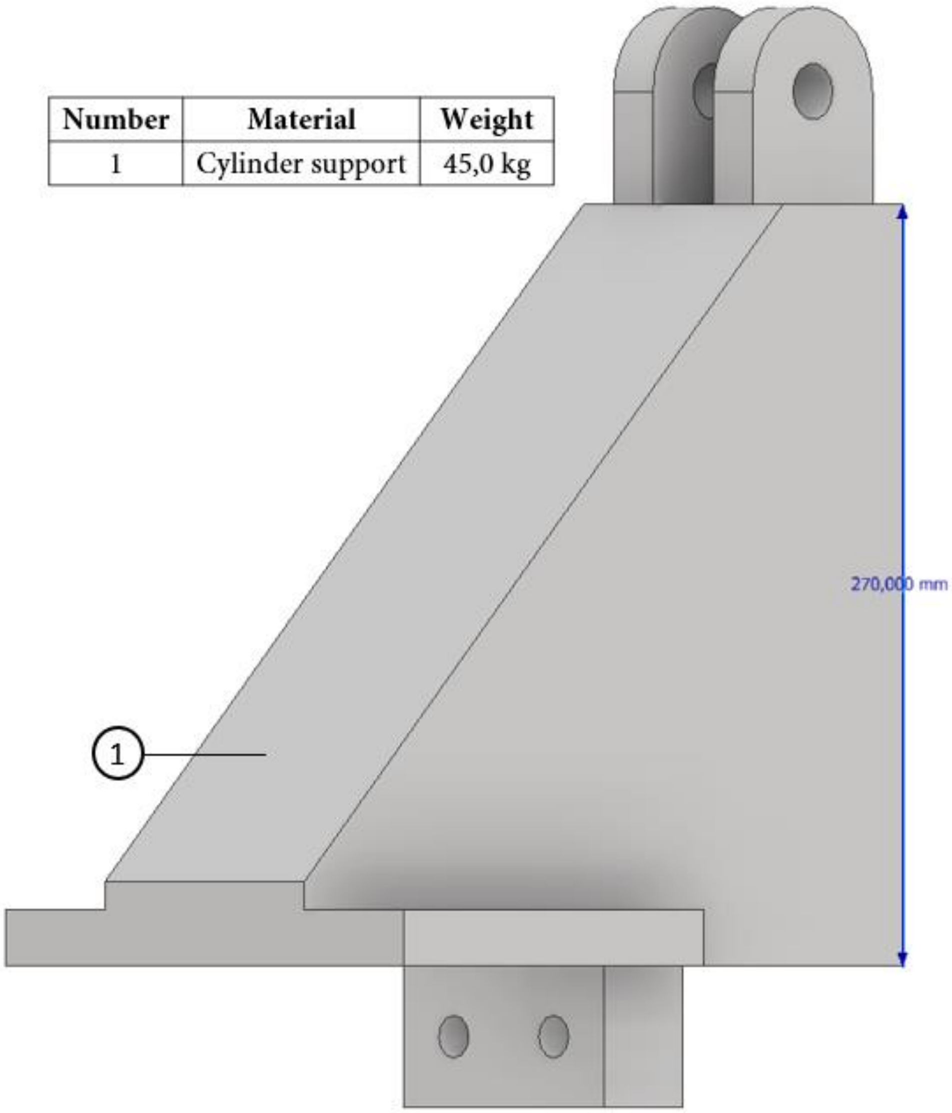


Figure 21. The second version of the end support of the cylinder takes cylinder connection further back.

Number	Material	Weight
1	Cylinder support	19,0kg

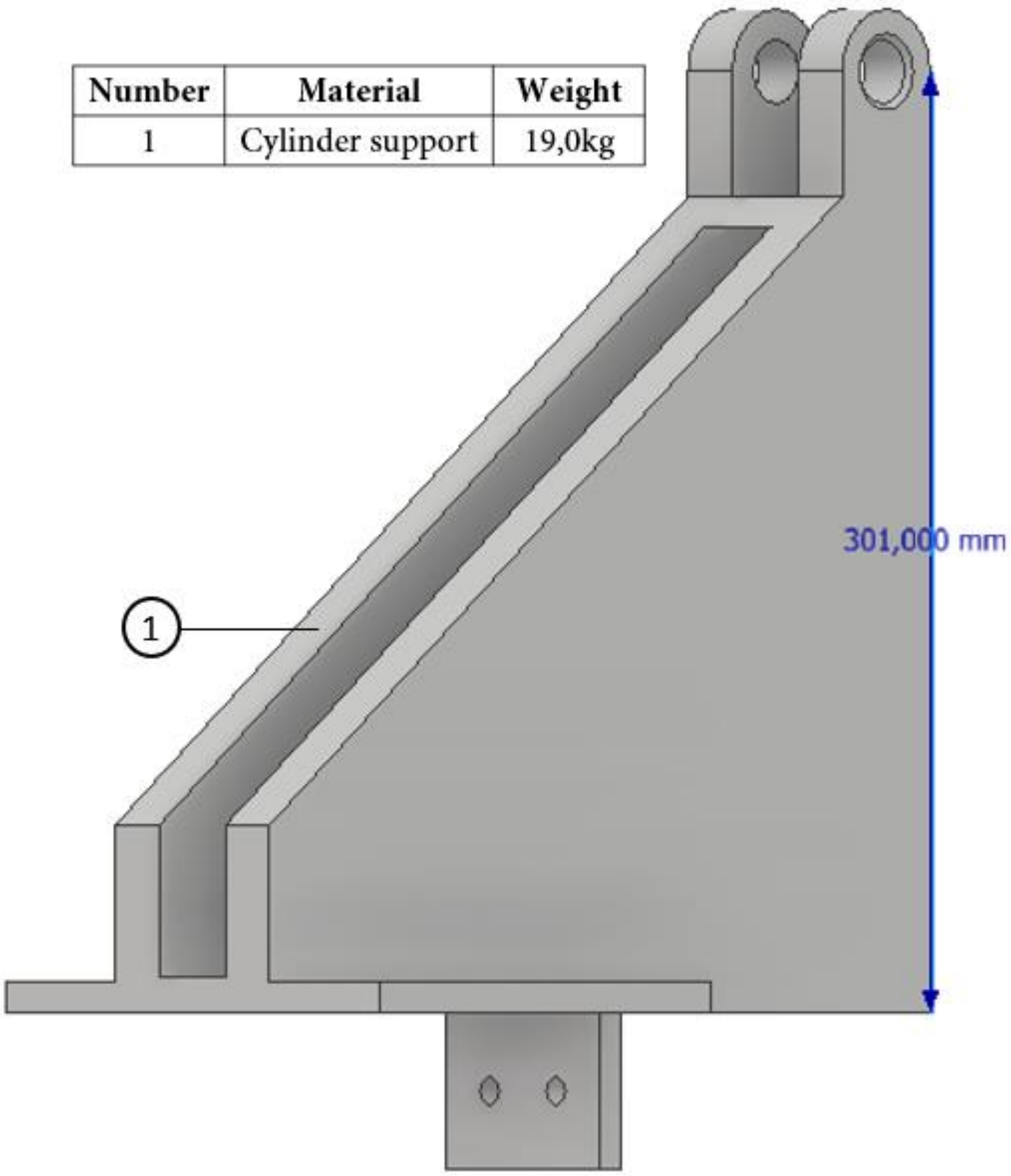


Figure 22. The third version of the end support of the cylinder is the lighter version of the second version.

The bearing support were designed to fit on the end shields to keep the bearings on their places at the assembly housing of the end shields during the rotor assembly. The bearing support of the D-end is supposed to also keep the bearing located at the shaft during the bearing assembly. the shaft guide was designed to ease locating of the rotor during assembly. The design of the shaft guide was done in the way that it would find a right position as easy as possible and slide through the bearing support of the N-end easily.

For brakes there were two options. The first option was to add some mechanical or hydraulic brakes to the frame sledge that brakes from the rail and hold the frame sledge from moving to both directions. That would have been easy to implement and good solution in the respect of DFA. But the problem with that solution is that a user needs to control where the sledge should be stopped and there is chance for error and even for injury. The second option was to create a physical block to prevent the frame sledge from moving to near to the rotor while an operator is moving it by pushing. The block for preventing the frame sledge from moving to that direction was attached to the reinforcement plate that was originally only for the rail attachment. The brake block is shown in Figure 23.

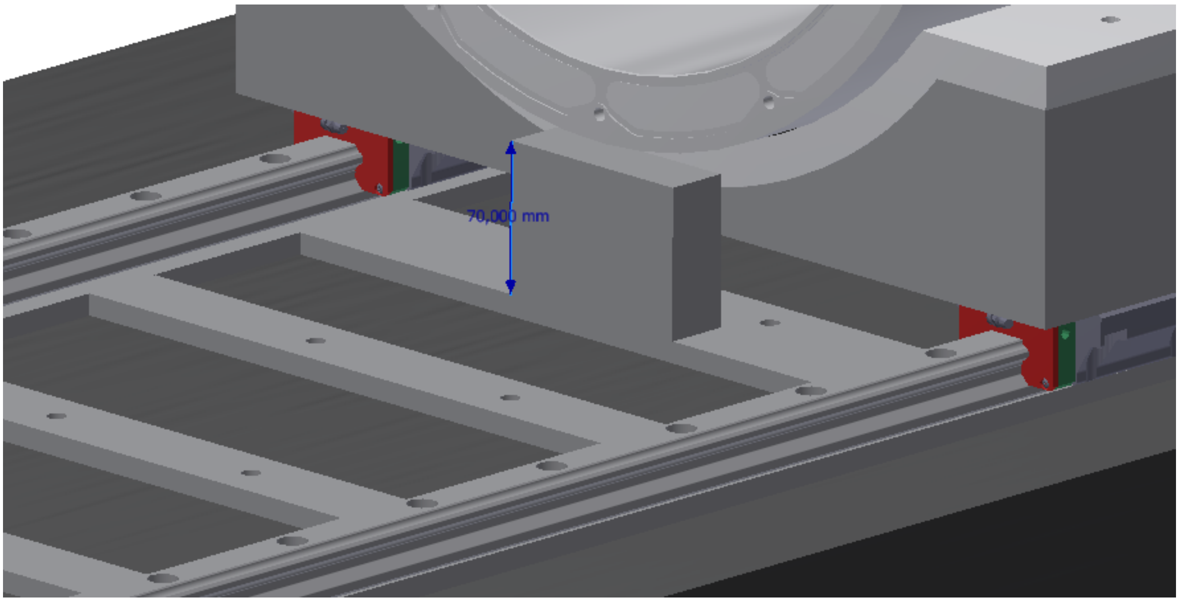


Figure 23. Brake block to prevent frame sledge from moving too close to the rotor.

The brake for preventing the frame sledge from escaping while inserting the rotor with the hydraulic cylinder was made with two blocks attached to the rail. Blocks were designed to fit to the rail as well as the rolling elements. To lock those blocks down one bolt row for the rail attachment is not inserted and the brake blocks will be attached from those. The brake blocks to prevent the frame sledge from escaping are shown in Figure 24.

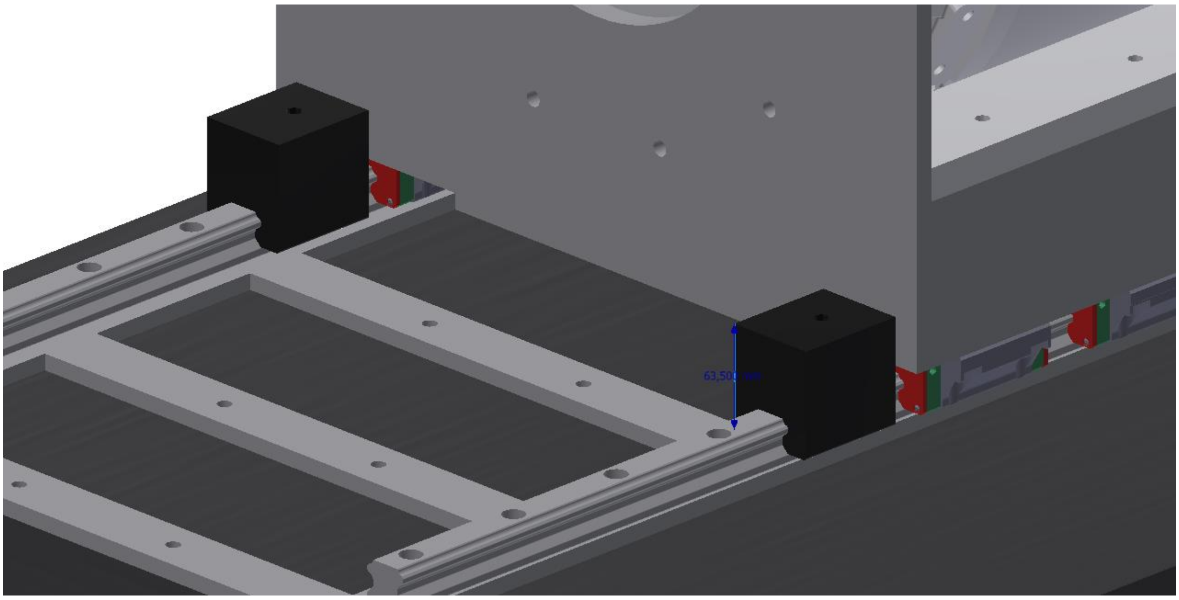
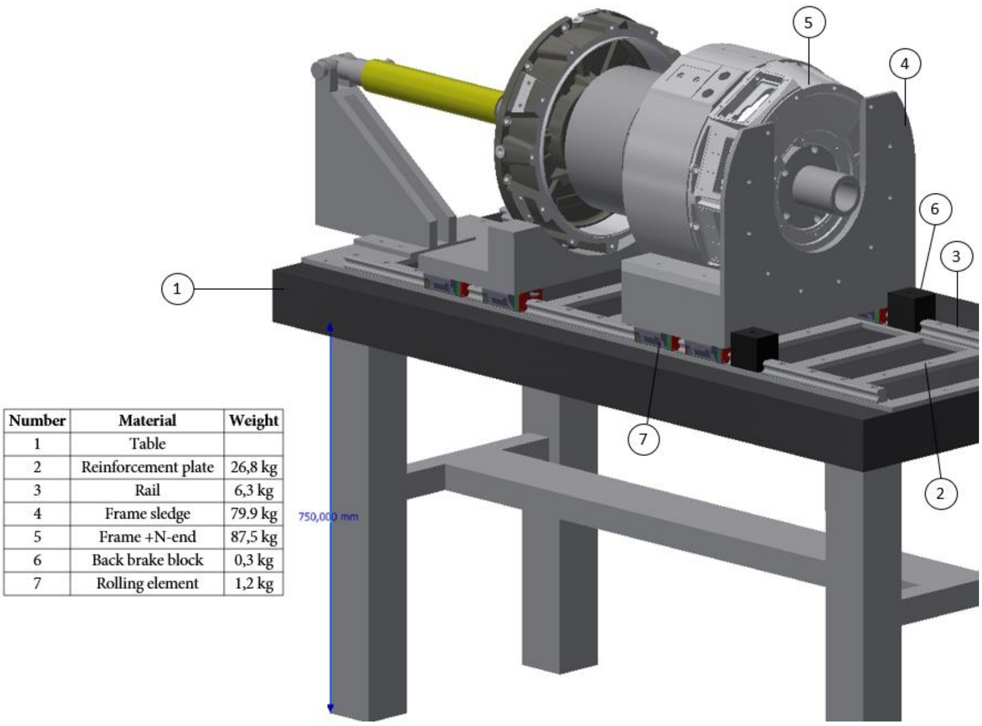


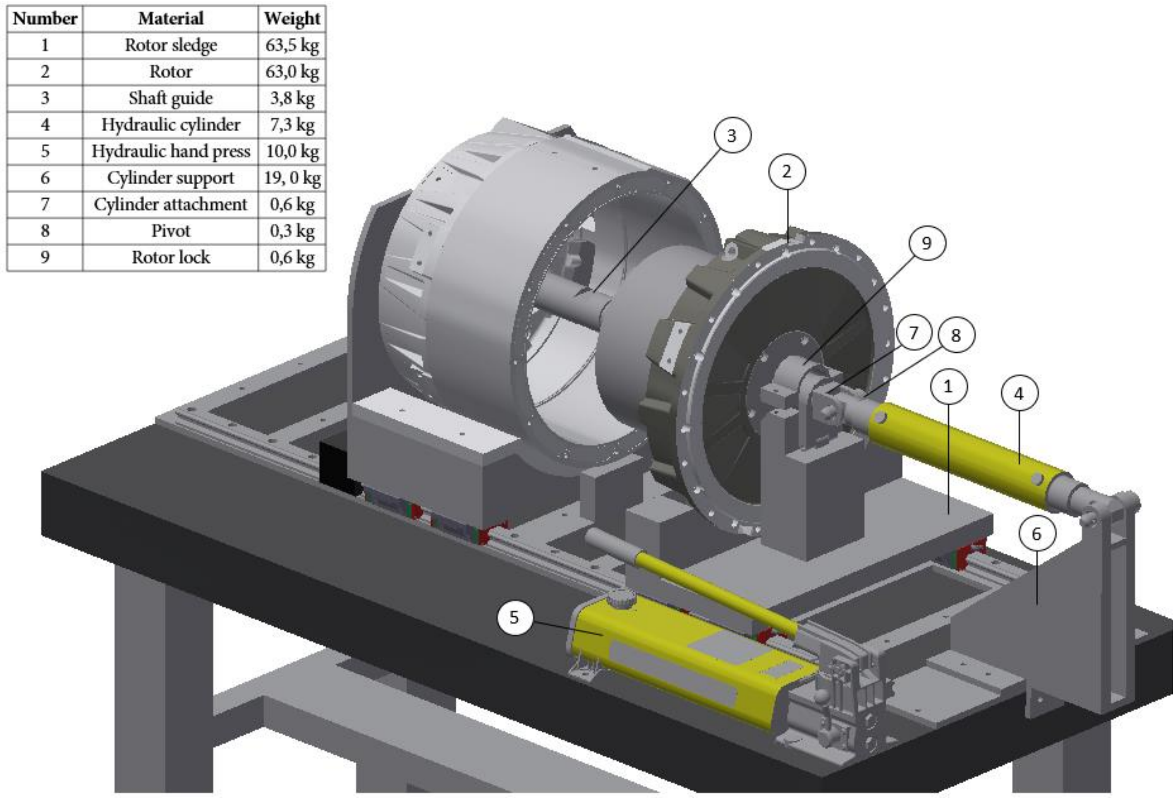
Figure 24. The brake blocks to prevent the frame sledge from escaping during the rotor assembly.

The final prototype is shown from two angles in Figure 25 and in Figure 26 and in it has all the features mentioned above. From Figure 25 an from Figure 26 the modules that were only mentioned above due simplicity of their design or the fact that they were catalog materials that had ready CAD models downloadable from internet can also be seen.



Number	Material	Weight
1	Table	
2	Reinforcement plate	26,8 kg
3	Rail	6,3 kg
4	Frame sledge	79.9 kg
5	Frame +N-end	87,5 kg
6	Back brake block	0,3 kg
7	Rolling element	1,2 kg

Figure 25. Final prototype.



Number	Material	Weight
1	Rotor sledge	63,5 kg
2	Rotor	63,0 kg
3	Shaft guide	3,8 kg
4	Hydraulic cylinder	7,3 kg
5	Hydraulic hand press	10,0 kg
6	Cylinder support	19, 0 kg
7	Cylinder attachment	0,6 kg
8	Pivot	0,3 kg
9	Rotor lock	0,6 kg

Figure 26. Final prototype from another angle.

6 COMPARISON BETWEEN EXCISTING VERTICAL ASSEMBLY TOOL AND PROTOTYPE DESIGNED FOR HORIZONTAL ASSEMBLY

In this research the custom comparison tool is being created. The comparison tool follows mostly the guidelines of the Lucas DFA method represented earlier in this work. But instead of the analyzing only the parts of the assembly the tool focuses to the analyze of different operations during the assembly work. This is done because in this work the design of the product is kept unchanged and the assembly tool is being redesigned. The workflow goes as shown in Figure 27. Five different indicators are obtained from the comparison. Functional analyze gives out ratio of essential and all used parts. Operations analyze gives out difficulty of the assembly by the point system and knowledge of the assembly times. Risk and cost analysis give out risk probability of the assembly errors and cost effects of those errors.

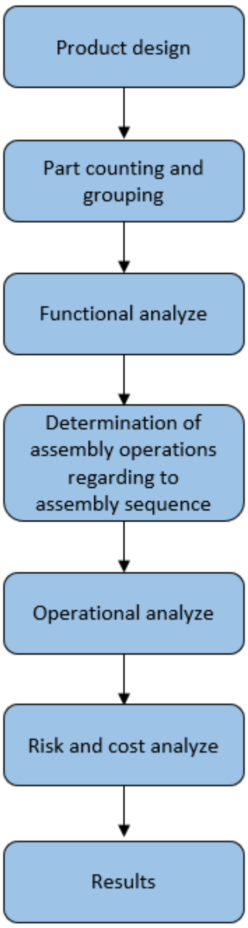


Figure 27. Workflow for using the comparison tool.

After the product is designed all parts that are used in the assembly work are counted. That includes parts of the assembly tool and subassemblies from the product. All parts are divided to two categories, essential parts and nonessential parts. After categorizing the parts functional analyze can be implemented by calculating the ratio of essential parts and all parts to the Table 10. In optimal design the ratio represented as percent is 100%. When the percentage of essential the parts decreases it means that there might be some redesign possibilities in the design.

Table 10. Example of the comparison table.

Essential parts	Nonessential parts	Parts in total		Ratio
Assembly operation	**Points**	**Quantity**	**Total points**	**Assembly time**
Operation 1				
Part 1				
Part 2				
Tool 1				
Operation 2				
Part 3				
Part 4				
Tool 2				
In total				

After the functional analyze has been done, assembly operations are determined and marked to the comparison table. In example of the comparison table shown in Table 10 there is shown operations 1 and 2, parts from 1 to 4 and tools 1 and 2. To those fields user needs to add all operations and parts and tool used in those to get total points. Rows need to be added to table as many as there is needed. All assembly operations and estimation of the ease of those operations are being marked to the comparison table as well as all the parts used to the operation and their properties. Estimation about ease of assembly is being done by giving points to all assembly operations. The point system gives points to the operation based on assembly operations directions, essentiality of the used parts, properties and dimensions of the used parts and ease of handling of the used parts in the assembly operation. Also, assembly tools needed in the assembly work are marked to the table. If the same tool is used in exactly same way for multiple times it is enough that it is marked to the table once. The point system is shown in Appendix I. To the comparison table it is possible to measure or estimate assembly times and those can also be compared. Based on fillings in the comparison table, the operational analyze can be made. In operational analyze the points of each assembly operation added together. In this point system the lowest score is better and optimal design gets zero points. This tool is only for comparing two or more designs against each other. With this pointing system giving of some limit value for good design is not possible. That is because points varying is directly proportional to the varying of the assembly operations.

When the operational analyze is done the risks of the assembly work is being mapped. The risks of the assembly errors are being evaluated and cost effects of those errors are also to be evaluated. The risks are evaluated by considering the likelihood of the error in the assembly operation. Cost effects of the errors are evaluated by considering what is the most likely error in each assembly operation and cost of fixing that is considered as an error cost.

6.1 Currently used design

As it is shown in Appendix II, there is 29 essential parts and 9 nonessential ones. That gives ratio of 0,76 between essential parts and all parts used in that assembly phase.

The assembly steps and the used parts are shown in Appendix II and the assembly steps are reviewed in this chapter in writing. In the current design assembly work begins with attaching the end shield of the D-end to the rotor. To do that the rotor needs to be lifted with overhead crane to the assembly station, the wear sleeve needs to be attached to the rotor and then the end shield of the D-end can be lifted to the rotor. The bearing is already assembled to the end shield at this point. After the end shield of the D-end is at the rotor, it needs to be pushed down with the two space blocks and a tool so that bearing is located correctly related to the shaft.

After the end shield of the D-end is attached to the rotor, the frame is lifted away from the assembly table by the special lifting tool and an overhead crane. The frame is reoriented in the air with the lifting tools mechanism and then it is placed to the sledge that moves it to the press. Under the sledge there is need for bearing block, that supports the N-end bearing and keeps it in the correct location while pressing the rotor in.

Next step is to lift the rotor with an overhead crane to the stator. Before the rotor can be lowered to the stator, the mechanism of the lifting tool needs to be reoriented to the side so that the rotor can have space to fit in to the frame. Also, the shaft guide needs to be screwed to the N-end of the shaft. The shaft guide helps guiding the shaft of the rotor through the N-end bearing and it also helps keeping the rotor aligned while inserting. After the rotor is dropped inside to the frame the D-end shield should be aligned correctly regarding to the frame and the guidance bolts needs to be attached through end shields attachment holes. With those guidance bolts the end shield and frame locates correctly while pressing the rotor to its place.

For the rotor pressing the sledge where the whole package is to be pushed in the way that the shaft of the rotor is under the piston of the press and space blocks need to be placed. Pressing is done by pushing with the automated hydraulic press to space block that has contact to the bearings outer and inner rings. While pushing from the both, inner and outer ring, the bearing keeps its place regarding to the end shield and the shaft and there are no forces going through the bearing. After the rotor is pressed to its place the end shield is being attached with attachment bolts, the guidance bolts are removed, and the attachment bolts of the end shield are tightened to the correct torque. Then the N-end bearing is being located by a hand press that presses the bearing block under the sledge towards to the N-end bearing. Both presses are released at the same time, the space blocks are removed, and the motor is pulled in the sledge away from the press. At this point the location of the bearing is checked with the caliper, if the bearing is not correctly located the pressing can be done again.

After the bearings are on their places the axle nut of the D-end and its locking are being attached. Before tightening the axle nut the rotors rotation needs to be locked by connecting stators phase cables with the cable brake. After the axle nut is placed the motor can be lifted back to assembly table. It happens by a changing the lifting tools mechanism back to the lifting position, lifting the motor with the lifting tool and the overhead crane, reorienting the motor, removing the shaft guide and finally moving the motor to the table. When the motor is at the table the lifting tool can be removed. Finally, the axle nut of the N-end is installed same way as the one of the D-end.

When assembly times of all these steps were counted together as shown in Appendix II the total time is 1870 seconds. That is 31 minutes and 10 seconds. Total score that this design got from the pointing system is 609 points. Evaluations for risk and cost analysis for the currently used design are shown in Table 11. When all the risks are added up the probability for the error is 0,0394 and the average of the error cost is 688,65€ the probable error cost is 27,12€ per machine.

Table 11. Results of the risk and cost analysis for currently used design.

Assembly operation	Risk of error	Error cost (€)	Error
Lifting rotor for attaching D-end shield	0,00001	1250	Dropping the rotor
Attaching speedy sleeve	0,03	25	Destroying wear sleeve
D-end attachment to the rotor	0,005	20	Damage bearing during the assembly
Attaching lifting tool to frame	0,00001	1500	Destroying threads from frame
Frame reorientation	0,00001	1500	Dropping the frame
Frame to sledge	0,00001	1500	Dropping the frame
Lifting tool reorientation	0	0	
Lifting rotor	0,00001	1490	Dropping the rotor
Attaching shaft guide	0,00003	300	Destroying threads from the shaft
Lifting rotor to stator/frame	0,004	1250	Damaging rotor laminates
Attaching guidance bolts	0,00001	50	Destroying threads from the end shield, need for rethreading
Pushing sledge to the press	0	0	
Pressing	0,00001	20	Misalignment that leads to destroying bearing
Bolting frame to D-end shield	0,00001	50	Destroying threads from the end shield, need for rethreading
Removing guidance bolts	0,00001	50	Destroying threads from the end shield, need for rethreading
Bolting frame to D-end shield	0,00001	50	Destroying threads from the end shield, need for rethreading
Tightening D-end shield bolts to torque	0,00001	0,5	Destroying bolt head
Locating N-end bearing	0,00002	230	Destroying end shield with too much pressure
Removing space blocks	0	0	
Pulling sledge away from press	0	0	
Checking bearing locations	0,0001	20	Missing bearing dislocation that leads to bearing failure
Attaching axle nut	0,00003	7	Destroying axle nut
Lifting tool reorientation	0	0	
Lifting motor	0,000015	3200	Dropping the motor
Motor reorientation	0,000015	3200	Dropping the motor
Removing shaft guidance	0,000001	240	Destroying threads from the N-ends end shield
Motor to the table	0,000015	3200	Dropping the motor
Removing lifting tool	0,00001	1500	Destroying threads from frame
Lifting tool to its place	0	0	
Attaching second axle nut	0,00003	7	Destroying axle nut

6.2 Prototype design

As shown in Appendix III prototype got from functional analysis score of 0,55. That is because in the design there is 27 essential parts and 22 nonessential parts. That makes in total of 49 parts.

The assembly sequence of the prototype has almost same start as the currently used one. First step is to attach the N-end bearing support to its place. After that as in currently used design the end-shield of the D-end should be attached to the rotor. This differs from the currently used method only little bit. With the prototype in this step there is used a bearing support and one space block instead of two space blocks. Other difference is that the bearing support is not removed after end shield is located, it is attached to the end shield with bolts.

After the rotor is prepared, the frame can be lifted and attached to the frame sledge. Also, the rotor can be lifted, reoriented and placed to the rotor sledge. After it is on the sledge and the cylinder attachment have been screwed to the D-end of the shaft to lock it to the sledge it can be turned to the assembly position and shaft guide can be screwed to the N-end of the shaft. At this point the hydraulic cylinder can be attached to the attachment in the D-end of the rotor with a pivot and a pin. When everything is lined up the frame can be pushed to the assembly position and the frame sledge can be locked to its place. Then the guidance bolts can be attached to keep sure that the end shield of the D-end and the frame are aligned during the pressing. When the guidance bolts are attached the pressing can be done. Pressing is done by a hydraulic hand press. When the rotor is correctly located with the press, the end shield of the D-end can be attached to the frame with the bolts, the guidance bolts can be removed, and the end shields bolts can be tightened to the correct torque.

After the rotor package is attached to the frame package the shaft guide can be removed and so can the hydraulic cylinder and its rotor attachment. The rotor sledge can be pushed away, and the motor can be lifted back to the assembly table. At the assembly table the bearing supports can be removed from both ends and the bearing locations should be checked. When the bearing locations are correct, the axle nuts and their locking can be attached to the both ends. Before tightening the axle nuts the rotors rotation should be locked by connecting stator phase cables with the cable brake.

As shown in Appendix III the overall assembly time of this design is 1810 seconds. That is 30 minutes and 10 seconds. While considering the ease of the assembly, the Appendix III shows that this design gets total score of 559 points in the point system. Evaluations for risk and cost analysis of the prototype design are shown in Table 12. When all the risks are added up the probability for the error is 0,0362 and the average of the error cost is 506,02€ the probable error cost is 18,31€ per machine.

Table 12. Risk and cost analysis for prototype design

Assembly operation	Risk of error	Error cost (€)	Error
Attaching N-end bearing support	0,0002	240	Destroying threads from the N-ends end shield
Lifting rotor for attaching D-end shield	0,00001	1250	Dropping the rotor
Attaching speedy sleeve	0,03	25	Destroying wear sleeve
D-end attachment to the rotor	0,005	20	Damage bearing during the assembly
Frame to the sledge	0,00001	1500	Dropping the frame
Rotors reorientation	0,00001	1490	Dropping the rotor
Rotor to the sledge	0,00001	1490	Dropping the rotor
Rotor reorientation at the sledge	0,000001	1490	Dropping the rotor
Attaching pivot and pin	0,0001	3	Destroying the pin
Attaching shaft guide	0,00003	300	Destroying threads from the shaft
Moving frame and locking it	0,0005	20	Unsuccessful locking, leads to misalignment during pressing and destroying the bearing
Attaching guidance bolts	0,00001	50	Destroying threads from the end
Pressing	0,00001	20	Misalignment that leads to destroying bearing
Bolting frame to D-end shield	0,00001	50	Destroying threads from the end
Removing guidance bolts	0,00001	50	Destroying threads from the end
Bolting frame to D-end shield	0,00001	50	Destroying threads from the end
Tightening D-end shield bolts to torque	0,00001	0,5	Destroying bolt head
Removing shaft guidance	0,000001	120	Dropping the shaft guidance and
Removing cylinder	0,0001	3	Destroying the pin
Lifting motor back to assembly table	0,000015	3200	Dropping the motor
Removing bearing supports	0,000001	240	Destroying threads from the N-ends end shield
Checking bearing locations	0,0001	20	Missing bearing dislocation that
Attaching axle nuts	0,00003	7	Destroying axle nut

7 CONCLUSIONS AND DISCUSSION

In this research prototype design was created based on request of the target company and literature search findings. The comparison tool for measuring ease of the assembly was created based literature search and risk and cost analysis were made based on researcher's knowledge from the target company.

7.1 Interfaces to earlier researches

Purpose of this research was to find out if the horizontal assembly method would be more productive than the currently used vertical one. Assumption for that was based on eliminating frame reorientations from the assembly operation. Assembly sequence planning and assembly reorientations are been researched and turned out that it goes case by case on reorientations but more often eliminating reorientations reduces assembly time.

However, eliminating frame reorientations from assembly operations forced to design an assembly method where the rotor is assembled to the stator horizontally. That creates conflict to DFA based design. In DFA based design removing extra parts, like attachments, and using assembly directions from above are recommended. Now while designing horizontal tools for a rotor assembly gravity could not be used as an attachment method anymore and external attachment methods need to be added. Horizontal assembly direction has been proven to be more difficult than the assembly from above.

Lean manufacturing was taken into account in this research only briefly. Aim in this was to use as much same tools in different assembly phases as possible. In addition to this there should also be possibility to design an assembly layout and tool placing in the way that an operator that is doing the assembly work need to move as little as possible.

Different assembly evaluation methods that were introduced earlier in this work inspects mostly different properties and quantities of the parts used in the assembly. When this work instead focuses evaluating time consumption and ease of different assembly phases.

7.2 Objectivity, reliability and validity of the research

Objectivity of this research can be looked in three sections. In literature research there were several sources for most of the topics. There were no many valid researches about reorientations found and that why there is only citations from one. In addition, information gathered about Lean manufacturing to this work is in such a basic level knowledge about the subject that there was only one source used.

Objectivity of the choices made during prototype design should also be reviewed. Requirement list have been done in co-operation with the target company and all of the modular solution options have been reviewed with a development engineer from the target company. Some of the choices made during the prototype design have been made while thinking to the future of the company and have not that why been ideal for the current situation. Weights in comparison seen in Table 9 have been estimated as well as values in that table. Values have been thought by thinking DFA based assembly. Values were hard to evaluate based on only possible theoretical solution and that shows in comparison table by lack of very high and very low values.

Time comparison between designs is quite objective because assembly times of the currently used assembly methods seen in Appendix II are measured. Measurements were made while an experienced operator was doing the assembly work and he had no problems during the assembly work. For the prototype, assembly times shown in Appendix III should also be quite accurate. Some of the operations are quite similar for the operations used in current assembly solution and times were estimated based on those. Some of the assembly operations are similar to the assembly operations used in bigger machines made by the target company. Also, the assembly of the bigger machine was timed while an experienced operator was assembling the machine. Based on those times the estimations were made to get remaining assembly times for the prototype design.

While considering objectivity of the evaluation of the ease of assembly the evaluation values of the comparison tool shown in Appendix I should be looked. Values have been decided arbitrarily but nonetheless adapting values from Lucas DFA method. Creating of the new comparison tool that focuses on evaluating assembly phases instead of parts used in assembly was considered necessary because the parts from assembly were not allowed to customize and all the improvements needed to be done to the assembly tools. Objectivity of risk analysis is not very high. All of the risk values are estimations based on researcher's knowledge about occurred errors during the motor assembly from past three years. Cost analysis instead is quite accurate because rounded value estimations in the analysis are based on estimations about work time needed to fix the error and accurate material costs.

Research was implemented by methods introduced earlier in this work. All the used methods, keywords and tools are introduced in the text. While considering reliability of the research the basis for repeating the research are same for all. However, there is a lot of subjective choices during the research. In the work the opinion of the designer influences to the design of the prototype as well as requirements of the target company. Also, the creation of customized comparison tools made for this research would be quite difficult to repeat identically even there is theoretical possibility for that.

Research aim was to find out is it more profitable to assemble permanent magnet electric motors rotor to stator horizontally or vertically? In addition, aim was to figure out how reorientations effect to assembly productivity and what other factors effects? While considering horizontal and vertical assembly methods in assembly, the solution needs quite more designing that just turning the tool sideways. While turning vertical assembly to horizontal in order to reduce reorientations of the motor frame/stator package the amount of attachment needed in construction rises. That creates conflict for investigating only effect of the reorientations.

7.3 Error and sensitivity analysis of the research

Sources in literature research are scientific articles, science handbooks or standards. Some sources cited later in the text are from commercial websites, but they are only used for to get some CAD-models or dimensions for them. Negative thing while considering error analysis of this research is that while designing prototype, most of the design decisions were made by designer's experience on the assembly operation currently in use. Even that the target company gave requirements and limitations for the work and methods and ideas learned from literature research were implemented to the design a lot of decisions were made based on experience and that experience was not necessarily up to date.

While considering sensitivity analysis of this research, need to be noted that all measurements were made with only one machine type even that the current assembly method is working with the product family of 4 different kind of motors. Only difference between those motors when thinking this assembly face is their length. Because the length is only difference between motors in the product family the results of the comparison would stay rather same even that it is noticed that weight slows down the reorientations. Measurements were made the second to the shortest model and effect on the reorientations should only raise to establish the results of this research with longer motors.

By sensitivity aspect the reconsideration of values in comparison tools would change the outcome from the tools. Current values are subjectively chosen and that creates uncertainty for the research. Also estimated values in the evaluation form of the comparison tool for the ease of assembly can be rather subjective while person who is filling the comparison table can have different opinion on some point than some other person. If the person who is filling the comparison table is keeping the same line through the whole comparison, there should not be any uncertainty in the results.

7.4 Key results

As a key result from this research there is Table 13. Table shows the results of the comparison tools for the currently used assembly method and the prototype one. Table shows that even when the prototype design has a 21 percentage points worse ratio of essential and all parts, it is having better values in all other analyses.

Table 13. Key result from the comparison

Analysis	Currently used design	Prototype design
Functional analysis	0,76	0,55
Operational analysis	609	559
Time comparison	1870 s	1810 s
Risk Analysis	0,0394	0,0362
Error cost analysis	27,12 €	18,31 €

The research questions were asking following questions.

1. Is it more profitable to assemble the rotor of the permanent magnet electric motor rotor to the stator horizontally or vertically? How does reorientations affect on profitability of the assembly work?
2. What different factors affect on profitability of the assembly work?
3. How manufacturing volume affects on profitability of both assembly method?

The Table 13 answers to the question about profitability between horizontal and vertical assembly directions. It is needed to notice that there was a lot of other changes in the assembly tool as well than only changing the assembly direction. Those effect to the results in comparison tool as well, but mainly as deteriorating factor so the horizontal assembly method with no frame reorientations is better in this case. Effecting factors for profitability of the assembly work were researched with the literature search and most effecting factors are assembly sequence planning and defecting number of reorientations with that and DFA based design.

Effects of manufacturing volume in this current assembly case are shown in Figure 28. This chart is made by assumptions that these assembly faces are possible to repeat one after another for the 7,5 hours a day and 21 days a month with one assembly station. Difference in production volume is 3,2%. That makes annually difference of 120 motors.

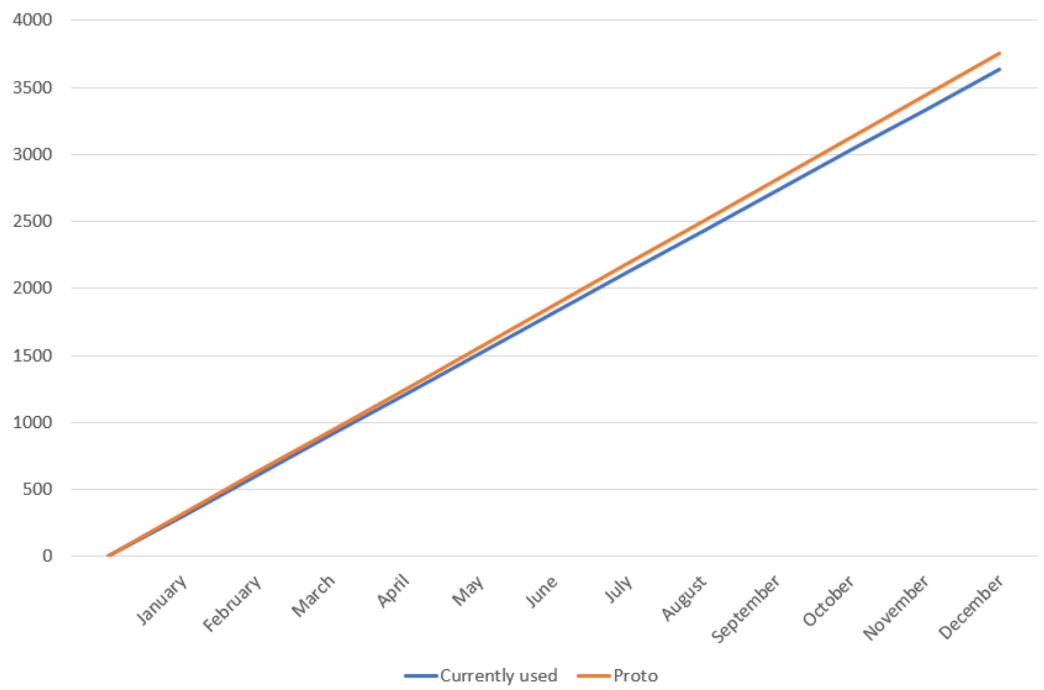


Figure 28. Annual manufacturing volumes with different assembly methods.

Difference is not big but if the assembly face is operated with multiple assembly stations and volume comparison is based on usability of the overhead crane with same restrictions of daily and monthly use as the previous comparison the theoretical annual capacity raises a lot and difference between solutions rises to 18,7%. Chart for that kind of production volumes can be seen in Figure 29. That is due the fact that in current solution the overhead crane is in use for 910 seconds when with prototype solution it is in use only for 740 seconds. These numbers are of course theoretical, but they are directive numbers. Use of 100% capacity of the overhead crane only for this assembly phase is not even possible. Use of the overhead crane is critical because there is operating only one overhead crane over the motor production where motors considered in this work are assembled.

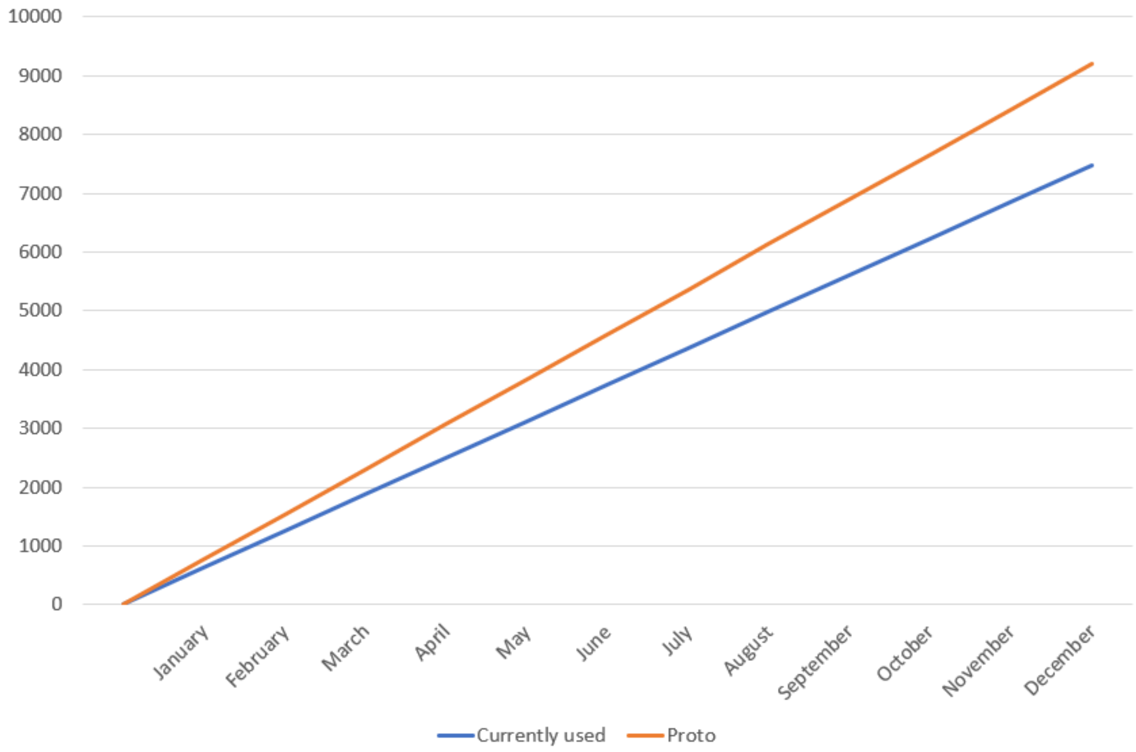


Figure 29. Annual manufacturing volumes with different assembly methods while considering usage of multiple assembly stations and capacity of overhead crane as a limiting factor.

About the requirements list point of view the work was success. All the requirements were met as were many of the wishes as well. From use category only wish that was not met was the ability to use prototype for multiple product families. From geometry category fitting the prototype for 1550mm x 750mm table was not able to be implemented. The prototype works on such a table, but the cylinder support is designed in the way that it takes cylinder end outside of that range. Wish of budget was not ether met when wish was under 5000€ and the estimated manufacturing cost for the prototype is little over 7500€.

7.5 Generalizability, usability and the novelty value of the results

Value of this research is mostly important for the target company. The research found answer to the question about the profitability of the horizontal assembly compared to the vertical one and effects of the reorientations during assembly work. Based on these findings and evaluations of the effect of overhead crane usage the target company can make decisions about the further development of the horizontal assembly method for assembling electric motors rotor into the stator.

Value of the research in general is quite small, because it focuses in quite specific assembly phase on certain electric motor. Value about effect of the reorientations in this case is not either directly shown from the research because the other ease of assembly factors effect in the comparison as well.

7.6 Future research

As a future research of the subject, the development of the comparison tool concentrating on evaluation of assembly phases instead of evaluation of the parts. In this case the customizing of the motor parts were not allowed and that why all the improvements to the assembly work needed to be done to assembly tools. That affects directly on the assembly operations and that why those were the ones that were evaluated in this work. Development of such a comparison tool would need more different kind of assembly tool pairs to be compared and tested. With the collected data the values in tool seen in Appendix I could be toned to be more general and tool would be more reliable.

Other future research could be further development and testing of the prototype designs idea by the target company. Further development could mean development engineers evaluation of the prototype and possible changes based on their experience. After that the assembly tool should be ordered, bringing it for use and testing it. After tests the evaluations made in this research could be confirmed or declined.

LIST OF REFERENCES

Alfadhlani, T & Samadhi, A & Ma´Ruf, I & Toha, I. 2018. A Framework for the Development of Automatic DFA Method to Minimize the Number of Components and Assembly Reorientations. IOP Conference Series: Materials Science and Engineering. Vol 319. Iss 1.

Boothroyd, G. Dewhurst, P & Knight, W. 2002. Product Design for Manufacture and Assembly. Second Edition Revised and Expanded. Taylor and Francis Group. 698 p.

Enerpac. 2018. Teollisuuden työkalut. [WWW document] Available: https://dunlophiflex.fi/wp-content/uploads/2018/04/E329e_teollisuuden_tyokalut_FI_.pdf (Accessed 1.6.2020)

Ezpeleta, I & Justel, D & Bereau, U & Zubelzu, J. 2019. DFA-SPDP, a new DFA method to improve the assembly during all the product development phases. Procedia CIRP. Vol 84. p. 673-679.

Hamrol, A & Kujawinska, A & Barraza, MFS. 2019. Advances in Manufacturing II: Volume 2- Production Engineering and Management. 1st edition. Springer International Publishing. 400 p.

Lai, H & Huang, C. 2004. A systematic approach for automatic assembly sequence plan generation. The International Journal of Advanced Manufacturing Technology Vol 24. p.752-763

Leaney, P & Wittenberg, G. 1992 Design for Assembling: The Evaluation Methods of Hitachi, Boothroyd and Lucas. Assembly automation. Vol 12. Iss 2.

Mital, A & Desai, A & Subramanian, A & Mital, A. 2008. Product Development – A Structured Approach to Consumer Product Development, Design, and Manufacture. Elsevier. 416 p.

Moultrie, J & Maier, A. 2014. A simplified approach to design for assembly. Journal of Engineering Design. Vol 25. Iss 1-3.

Movetec Oy. 2019. Kuulajohteet Hiwin. [WWW document] Available: https://www.movetec.fi/fi/tuotteet/lineaariliikkeen-mekaniikka/lineaarijohteet/kuulajohteet/kuulajohteet-hiwin (Accessed 1.6.2020).

Ohashi, T & Iwata, M & Arimoto, S & Miyakawa, S. 2002. Extended Assemblability Evaluation Method (AEM). JSME International Journal, Series C: Mechanical Systems Machine Elements & Manufacturing. Vol 45. Iss 2. pp. 567-574

Pan, C & Smith, S. 2006. Case study: The impact of assembly reorientations on assembly time. International Journal of Production Research. Vol 44. Iss 21. p. 4569-4585.

Tooley, M. 2010. Design Engineering Manual. Elsevier. 651 p.

VDI 2221. 1993. VDI 2221. Verlag des Vereins Deutscher Ingenieure. 2 p.

Vuorinen, T. 2013. Strategiakirja: 20 työkalua. Helsinki: Talentum.284 p.

Category	Part:	Score	Aplies to part	
1 Features that complicate assembly				
1.1 Need for reorientation				
1.1.1 No reorientation		0		
1.1.2 Light object < 1kg		2		
1.1.3 Medium object >1kg, <20kg		5		
1.1.4 Heavy object >20kg, <70kg		10		
1.1.5 Very heavy object >70kg		20		
1.2 Assembly ergonomics				
1.2.1 Assembly standing or sitting without obstacles		0		
1.2.2 Assembly standing or sitting with obstacles		3		
1.2.3 Assembly laying down without obstacles		3		
1.2.4 Assembly laying down with obstacles		8		
1.3 Assembly direction				
1.3.1 Straight line from above		0		
1.3.2 Straight line horizontally		1		
1.3.3. Straight line from below		3		
1.3.4 Not a straight line		3		
1.3.5 Bending		10		
1.4 Vision				
1.4.1 Direct vision		0		
1.4.2 Undirect vision		5		
1.4.3 No vision		20		
1.5 Allignment				
1.5.1 Easy to allign		0		
1.5.2 Easy allign but allignin requires holding while attaching		3		
1.5.3 Difficult to allign		5		
1.5.4 Difficult to allign and alligning requires holding while attaching		10		
1.6 Insertion force				
1.6.1 No resistance		0		
1.6.2 Some resistance		3		
1.6.3 A lot resistance		10		

2 Part properties			
2.1 Handling			
2.1.1 Possible to handle with on hand <2kg	0		
2.1.2 Reguires two hands >2kg, <20kg	5		
2.1.3 Reguires two peoples or machinery >20kg	10		
2.2 Attachment			
2.2.1 Self attaching with orientation	0		
2.2.2 Self attaching with snapping	2		
2.2.3 Self attaching with screwing	3		
2.2.4 Self attaching with riveting	5		
2.2.5 Needs attachment	5		
2.3 Symmetry			
2.3.1 Symmetrical	0		
2.3.2 Asymmetrical, easy to notice	3		
2.3.3 Asymmetrical, not easy to notice	8		
2.4 Material properties			
2.4.1 Delicate	5		
2.4.2 Flexible	2		
2.4.3 Sticky	4		
2.4.4 Abrasive	5		
2.4.5 Slipery	5		
2.4.6 Magnetic	5		
2.5 Designed properties			
2.5.1 No Chamfer	3		
2.5.2 No Guidance	1		
3 Tools			
3.1 One hand tool			
3.1.1 One hand mechanical tool	5		
3.1.2 One hand automatic tool	2		
3.2 Two hands tool			
3.2.1 Two hands mechanical tool	10		
3.2.2 Two hands automatic tool	15		
In total			0

Essential parts	Nonessential parts	Parts in total		Ratio
29	9	38		0,76
Assembly operation	**Points**	**Quantity**	**Total points**	**Assembly time**
Lifting rotor for attaching D-end shield				60
Rotor	16	1	16	
Overhead crane	2	1	2	
Assembly station	0	1	0	
Lifting lug	3	1	3	
Attaching speedy sleeve				120
Rotor	0	1	0	
Speedy sleeve	2	1	2	
Speedy sleeve tool	5	1	5	
D-end attachment to the rotor				150
D-end	8	1	8	
Rotor	0	1	0	
Space block	3	1	3	
Threaded rod with nuts	3	1	3	
Size 13 spanner	5	1	5	
Attaching lifting tool to frame				360
Lifting tool	22	1	22	
Frame	0	1	0	
Bolts	4	4	16	
Frame reorientation				90
Frame	32	1	32	
Frame to sledge				30
Frame	10	1	10	
N-end bearing block	8	1	8	
Sledge	0	1	0	
Lifting tool reorientation				30
Lifting tool	12	1	12	
Lifting rotor				60
Rotor	10	1	10	

Attaching shaft guide				30
Rotor	0	1	0	
Shaft guide	11	1	11	
Lifting rotor to stator/frame				60
Rotor +D-end shield	18	1	18	
Stator/frame	0	1	0	
Attaching guidance bolts				70
Guidance bolts	3	4	12	
Frame	0	1	0	
Pushing sledge to the press				50
Sledge	6	1	6	
Pressing				60
Frame	0	1	0	
Rotor + D-end shield	5	1	5	
Space block	8	2	16	
Hydraulic automatic press	2	1	2	
Bolting frame to D-end shield				150
Frame	0	1	0	
Rorot + D-end shield	5	1	5	
Bolts	6	8	48	
Removing guidance bolts				20
Guidance bolts	6	4	24	
Bolting frame to D-end shield				50
Frame	0	1	0	
Rorot + D-end shield	5	1	5	
Bolts	6	4	24	
Tightening D-end shield bolts to torgue				70
Bolts	6	12	72	
Torque wrench + size 6 internal hexagon socket	5	1	5	

Locating N-end bearing				20
Hydraulic hand press	5	1	5	
Removing space blocks				10
Space block	8	2	16	
Pulling sledge away from press				20
Sledge	6	1	6	
Checking bearing locations				20
Caliper	5	1	5	
Attaching axle nut				80
Cable brakes	5	1	5	
Nuts for cabel brakes	3	3	9	
Axle nut	6	2	12	
Axle nut lock	3	2	6	
Axle nut tool	10	1	10	
Lifting tool reorientation				25
Lifting tool	12	1	12	
Lifting motor				35
Motor+lifting tool	10	1	10	
Motor reorientation				30
Motor+lifting tool	32	1	32	
Removing shaft guidance				20
Shaft guide	9	1	9	
Motor to the table				35
Motor+lifting tool	10	1	10	
Removing lifting tool				25
Motor	0	1	0	
Lifting tool	16	1	16	
Bolts	4	1	4	
Lifting tool to its place				50
Lifting tool	10	1	10	
Attaching second axle nut				40
Axle nut	7	2	14	
Axle nut lock	4	2	8	
In total			609	1870

Essential parts	Nonessential parts	Parts in total		Ratio
27	22	49		0,55
Assembly operation	**Points**	**Quantity**	**Total points**	**Assembly time**
Attaching N-end bearing support			0	60
N-end bearing support	14	1	14	
Bolts	4	5	20	
Cordless driver +size 6 internal hexagon socket	2	1	2	
Lifting rotor for attaching D-end shield			0	60
Rotor	16	1	16	
Overhead crane	2	1	2	
Assembly station	0	1	0	
Lifting lug	3	1	3	
Attaching speedy sleeve			0	90
Rotor	0	1	0	
Speedy sleeve	2	1	2	
Speedy sleeve tool	5	1	5	
D-end attachment to the rotor			0	210
D-end	8	1	8	
Rotor	0	1	0	
D-end bearing support	5	1	5	
Bolts	3	5	15	
Space block	3	1	3	
Threaded rod with nuts	3	1	3	
Size 13 spanner	5	1	5	
Frame to the sledge			0	210
Frame	19	1	19	
Frame sledge	0	1	0	
Bolts	4	4	16	
Rotors reorientation			0	240
Rotor	20	1	20	
Second lifting lug	6	1	6	
Second overhead crane	2	1	2	
Rotor to the sledge			0	130
Rotor	15	1	15	
Rotor sledge	0	1	0	
Adapter to connect rotor to the cylinder	6	1	6	

Rotor reorientation at the sledge			0	40
Rotor	20	1	20	
Rotor lock	5	1	5	
Bolts	3	2	6	
Attaching pivot and pin			0	15
Pivot	4	1	4	
Pin	2	1	2	
Adapter to connect rotor to the cylinder	0	1	0	
Cylinder	0	1	0	
Attaching shaft guide			0	30
Rotor	0	1	0	
Shaft guide	9	1	9	
Moving frame and locking it			0	30
Frame+sledge	6	1	6	
Back brake block	6	2	12	
Bolts	3	2	6	
Attaching guidance bolts			0	85
Guidance bolts	4	4	16	
Frame	0	1	0	
Pressing			0	60
Frame	0	1	0	
Rotor + D-end shield	19	1	19	
Hydraulic hand press	5	1	5	
Bolting frame to D-end shield			0	150
Frame	0	1	0	
Rorot + D-end shield	0	1	0	
Bolts	4	8	32	
Removing guidance bolts			0	20
Guidance bolts	4	4	16	
Bolting frame to D-end shield			0	50
Frame	0	1	0	
Rorot + D-end shield	0	1	0	
Bolts	4	4	16	
Tightening D-end shield bolts to torgue			0	60
Bolts	4	12	48	
Torque wrench + size 6 internal hexagon socket	5	1	5	
Removing shaft guidance			0	20
Shaft guide	9	1	9	

Removing cylinder			0	30
Rotor lock	5	1	5	
bolts	3	2	6	
Pivot	1	1	1	
Pin	2	1	2	
Adapter to connect rotor to the cylinder	4	1	4	
Rotor sledge	6	1	6	
Lifting motor back to assembly table			0	60
Motor	10	1	10	
Bolts	4	4	16	
Removing bearing supports			0	60
Bearing supports	1	2	2	
Bolts	4	10	40	
Checking bearing locations			0	20
Caliper	6	1	6	
Attaching axle nuts			0	80
Cable brakes	6	1	6	
Nuts for cabel brakes	4	3		
Axle nut	7	2	14	
Axle nut lock	4	2	8	
Axle nut tool	10	1	10	
In total			559	1810