



TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY

School of Engineering

Automation study of the cabinet frame assembly for ABB

AS

Kabineti raami automatiseeritult koostamise uuring ettevõttele

ABB AS

Master's Thesis

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Tallinn, 2019

AUTHOR'S DECLARATION

Hereby I declare, that I have written this thesis independently.

No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

This is completed under the supervision of Martinš Sarkans

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"....." 2019

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Accepted for defence

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THESIS TASK

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Study programme, main speciality: MATM02/15, Product Development and Production Engineering, mechanical engineering specialization

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Thesis topic:

Automation study of the cabinet frame assembly for ABB AS

Kabineti raami automatiseeritult koostamise uuring ettevõttele ABB AS

Thesis main objectives:

1. Research the sections of the cabinet assembly which could be assembled using an automated robot cell
2. Set focus on frame section and analyze the necessity of an automated robot cell line for ABB
3. Provide the first draft of the automated robot cell efficiency, cost and appearance

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Overview of different cabinet sections that could be assembled using an automated robot cell with minor or no re-designing	31.12.18
2.	Overview of how the automated robot cell should work for the frame assembly	24.03.19
3.	Researching necessary tools for the automated robot cell	14.04.19
4.	Comparing automated robot cell with current hand-made assembly	05.05.19
5.	Writing the summary and finalizing the thesis	17.05.19

Language: English

Deadline for submission of thesis: 27.05.2019

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Terms of thesis closed defence and/or thesis restricted access conditions to be formulated on the reverse side

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PREFACE

The subject of this thesis was devised after going through some assembly drawings which are needed for every cabinet production. Although there are different assembly drawings for different cabinets, most of them look quite similar. The author thought that if there are multiple cabinets made every day only by hand, then assembling these cabinets with an automated assembly line would be faster. Since the cabinet assembly automation has not been studied very much before, the idea of studying it was practical and the outcome feasible.

There was a big amount of data that had to be researched and studied thoroughly during this thesis. The author would like to thank the supervisor Martinš Sarkans and consultant Kaarel Lahtvee foremost, but also all the other people who helped in various ways during the thesis.

INTRODUCTION

The subject of this thesis is automation study of the cabinet frame assembly for ABB AS. This subject is chosen, because the cabinet assembly automation has not been studied very much as of now, while the module assembly automation has been studied. Because the cabinets and modules are very different, the same study cannot be taken into consideration. Also, currently the cabinets and modules are assembled both in factories in Estonia and Finland. But lately the trend has been so that only cabinets would be assembled in factory in Estonia and modules in factory in Finland. Therefore, the amount of cabinets produced in Estonian factory will likely be higher in the near future.

In this thesis, only the cabinet frame assembly is studied more thoroughly, because the cabinet assembly in whole is very big and complex and would require more wide-ranged research than possible during this thesis. In the beginning of writing this thesis, various sub-assemblies were studied. The frame sub-assembly was chosen for more thorough research, because frames are always needed for every cabinet and they have the least variables during assembly.

The first chapter of this thesis includes a short description of ABB, what is a cabinet and in which portfolio the cabinets in question are offered. The second chapter is about the cabinets in overall - it is explained what kind of cabinets are produced and how many of them are produced in Estonian factory. Descriptions are provided on different sub-assemblies including the frame sub-assembly that this thesis is focused on. In the third chapter, the frame sub-assembly is studied thoroughly, which includes the first drafts of the grippers and the new workstation layout. Also, the new assembly sequences of the frame sub-assembly are researched. In the fourth chapter, the new devices which are needed for the automated assembly line are researched. In the last chapter, the current and hypothetical new assembly times are compared and also the return of investment is calculated.

1. CABINET DESCRIPTION

To get a better understanding of what is meant by a „Cabinet“ in this thesis, the whole ABB portfolio is explained shortly. The last product explained is the one studied within this thesis.

1.1 ABB

There are five separate businesses in ABB which offer different products [1]:

- a) Electrification;
- b) Industrial Automation;
- c) Motion;
- d) Robotics & Discrete Automation;
- e) Power grids.

In this thesis, the product that is being studied belongs to the motion business. ABB's Motion business is the largest supplier globally for motors and drives. The vast range of generators, electrical motors, drives and services, together with integrated digital powertrain solutions and mechanical power transmission products is provided for customers within the Motion business. And lastly, a broad range of automation applications in infrastructure, transportation and the discrete and process industries is provided [2].

There are different products offered for the drives, but for this thesis, low voltage AC drives are relevant. The low voltage AC drives are used to boost the productivity of processes, cut maintenance costs and improve energy efficiency. To ensure that the mentioned aims are fulfilled, a wide portfolio of low voltage AC drives is offered. The portfolio includes drives, such as industrial drives for controlling processing lines and micro and machinery drives for machine building, also specifically designed drives [3].

Only the low voltage AC drives are researched, because the most important one for this thesis is the industrial drive [4][5].

1.2 Industrial drives

There are five different products offered within the industrial drives' portfolio, which are [5]:

- a) ACS880 single drives – wall-mounted and cabinet-built [6];
- b) ACS880 drive modules;
- c) ACS880 multidrives;
- d) Industrial ACS800 series;
- e) ACS880 liquid-cooled modules.

The industrial drives portfolio is shown on the figure 1.1 below.



Figure 1.1 Industrial drives portfolio [7]

All of the products above can be separated based on four of the biggest differences, which are:

- 1) Cabinet and module. The cabinet usually includes the module, but the module does not need a cabinet with it;
- 2) Old and new generation. The old generation is named ACS800 and the new generation is named ACS880;
- 3) Cooling type. There are two types - liquid-cooled and air-cooled. The product's main purpose and size stay the same, but only how the inside of the cabinet is cooled changes;

- 4) Cabinet lineup width. There are two types – single drive and multidrive. In single drive, there is usually only one cabinet used, which is up to 1200 mm wide, but sometimes more than one is allowed as well. In multidrive, there is always more than one cabinet in the lineup, and the widths can go up to 20 m.

Only the cabinets are researched more thoroughly, but not the modules, because this thesis is only focused on the cabinet automation. Also, because most of the cabinets built in Estonian factory are newer generation ACS880, air-cooled and single drive cabinets, the research for this thesis is only made based on these cabinets.

1.3 Cabinet summary

In general, the product that is being studied for this thesis comes from the following: ABB -> Motion -> Drives -> Low voltage AC -> Industrial drives -> ACS880 single drives -> cabinet-built single drive.

Although ABB in overall has a very large product portfolio, only one small portfolio is studied more thoroughly for this thesis. The portfolio itself is called ACS880 single drives and one of the products within the portfolio is cabinet-built single drive which is mentioned as „cabinet“ in this thesis. The cabinets that are studied more thoroughly for automation purposes in this thesis are the newer generation ACS880, air-cooled single drive cabinets.

2. CABINET

In the last paragraph, the biggest cabinet differences and the cabinets themselves were explained. But the single drive cabinets are also divided into two cabinet versions – low power and high power. The only difference between low power and high power cabinets is the power rating, but in overall, the cabinets still look alike and are assembled in the same way. The single drive cabinets are named like shown below, where LP stands for Low Power and HP stands for High Power:

- a) ACS880-07 LP;
- b) ACS880-07 HP;
- c) ACS880-17/37 LP;
- d) ACS880-17/37 HP.

2.1 Cabinet versions

The biggest cabinet version differences are related to the cabinet widths. Although there can be more than one cabinet in a lineup and one lineup can be up to 4200 mm, the cabinet widths below are only about single cabinets. There are 8 widths in total:

- a) W200 – 200 mm wide;
- b) W300 – 300 mm wide;
- c) W400 – 400 mm wide;
- d) W500 – 500 mm wide;
- e) W600 – 600 mm wide;
- f) W700 – 700 mm wide;
- g) W800 – 800 mm wide;
- h) W1000 – 1000 mm wide;
- i) W1200 – 1200 mm wide.

Because this thesis is only about the single drive cabinets built in Estonian factory and only for the single cabinets, only the following widths are necessary:

- a) W400 – 400 mm wide;

- b) W500 – 500 mm wide;
- c) W800 – 800 mm wide;
- d) W1200 – 1200 mm wide.

2.2 Cabinet production volumes

To understand how big percentage of the cabinets built in Estonian factory are single cabinets, some calculations are made. All of the calculations are about year 2018. The calculations are not shown, because the actual cabinet numbers are confidential manufacturing information. Therefore, approximate values are used.

In Estonia thousands of cabinets were built. Because this thesis only focuses on single drive cabinets, the unnecessary cabinet amounts were removed, after which the amount of single drive cabinets was still in thousands. Because only the single cabinets are researched, not the lineups which consist of 2 or more cabinets, only those are taken into account. Finding out the actual amounts that are necessary requires some filtering of data.

The filtering process is described more thoroughly below:

- 1) Every cabinet that is built has its own Bill of Material (BOM) generated. The BOM consists of different things, including all the parts required to assemble the cabinets, customer name etc., but for the filtering process, only the type code is needed;
- 2) Type code is the basis of what the BOM will consist of and the customer is the one who says what the type code will look like. For example, if the customer needs an empty cabinet, the type code will include an option named +C199. All the options that the customer needs are added to the type code;
- 3) Based on the type code, the actual cabinet size is generated. There are certain options that add an additional cabinet to the lineup, which means that the cabinet is not a single cabinet anymore. Those options need to be filtered out to find out only the cabinets that are single cabinets;

Every single drive cabinet also has a specific power ratings range and these power ratings equal with a certain cabinet width. For example, if the power rating chosen is between 0105A-3 and

0293A-3, the cabinet is 400 mm wide. But if the power rating chosen is between 0363A-3 and 0880A-3, the cabinet is 800 mm wide.

Typically, a type code which is for a single cabinet, looks like the following: ACS880-07-0583A-5. And if the empty cabinet is needed, the type code will look like the following: ACS880-07-0583A-5+C199. If an additional option is chosen, the cabinet is not a single cabinet anymore. Instead, there would be two cabinets combined and with the empty cabinet adding an additional width of 400 mm, making the lineup to be 1200 mm wide. However, in this thesis, only single cabinets are researched.

After all the filters are applied and the unnecessary cabinets removed, the total amount of single drive cabinets that only consist of a single cabinet is thousands of cabinets. From all of the single drive cabinets that were produced in Estonian factory in 2018, 60,3 % were single cabinets. The total amount of these single cabinets is already enough for a study.

2.3 Basic cabinet structure

The basic cabinet structure, such as outer dimensions (other than the widths) and parts used to assemble the cabinets, are quite similar for all different cabinets. One basic cabinet structure with a width of 400 mm is shown on a figure 2.1.

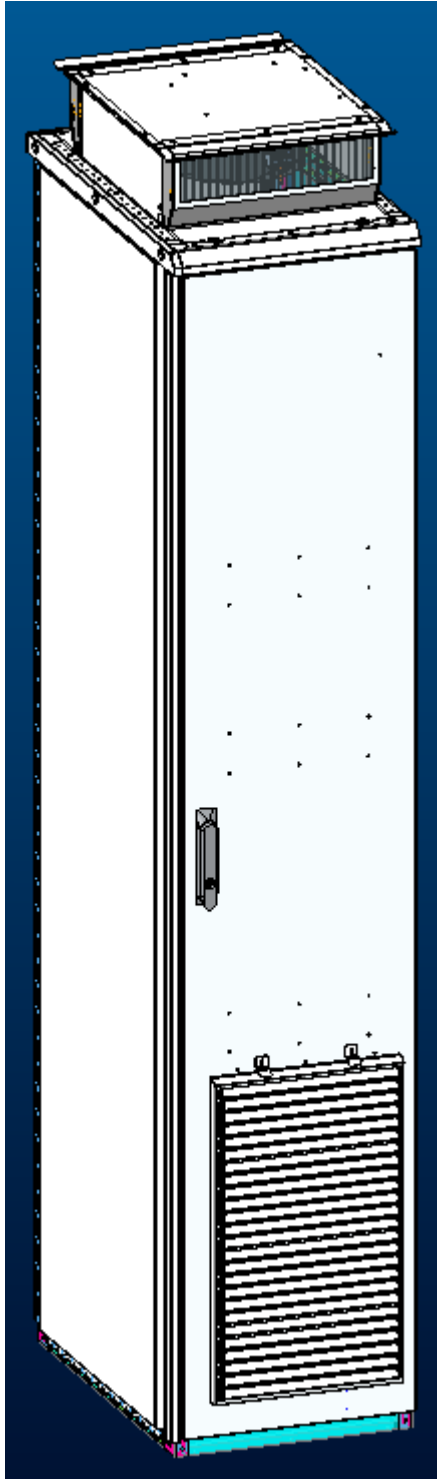


Figure 2.1 Basic cabinet structure with a width of 400 mm

In the next five sub-paragraphs, the five most basic cabinet sub-assemblies are explained more thoroughly. The reason those could be assembled using automated robot assembly line with little or no changes to the design are explained. Those sub-assemblies are chosen, because they consist of only standard parts.

2.3.1 Sub-assembly 1 – bottom plate

Bottom plates are chosen, because they are always needed and the basic design of them is always the same. The bottom plates would first be assembled separately, depending on the options that the customer has selected, and then assembled onto the frame. The bottom plate is always assembled to the frame using M6x12 screws, with the total amount of screws depending on the width of the cabinet, but there are always atleast 12 pieces needed. A basic bottom plate model is shown on figure 2.2 below.

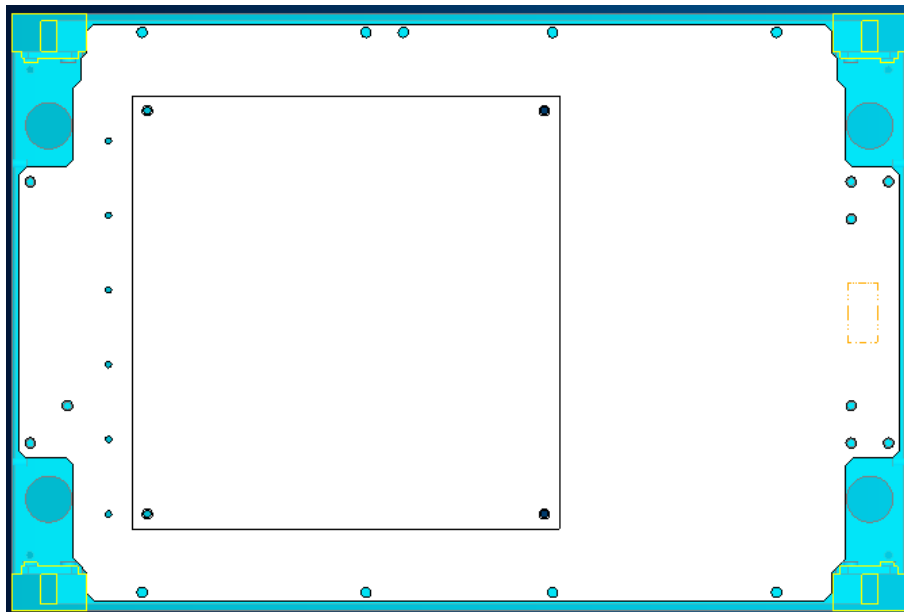


Figure 2.2 Basic bottom plate

2.3.2 Sub-assembly 2 – back plate

Back plates are chosen, because they are always needed and the basic design of them is always the same. The only difference is the width of them. Assembly onto the frame is done using M6x12 screws, with the total amount of screws depending on the width of the cabinet, but there are always atleast 18 pieces needed. Also, the back plate is assembled as one of the last parts in the whole cabinet assembly sequence. Different back plates are shown on figure 2.3 below.

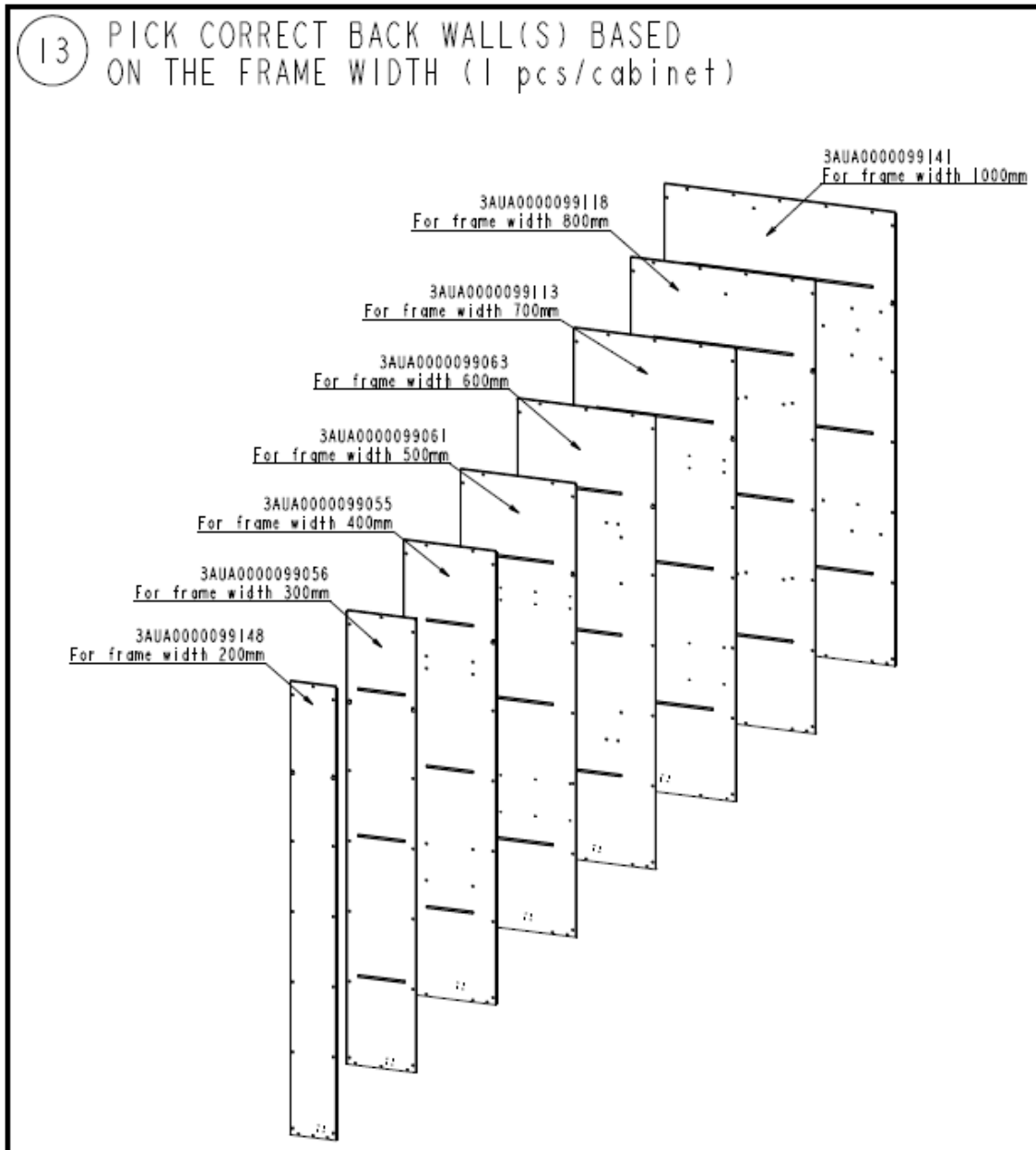


Figure 2.3 Different back plates

2.3.3 Sub-assembly 3 – side plate and strips

Side plates and strips are chosen, because the side plate and strip are always the same for all cabinets. Assembly onto the frame is done using 21 pieces of M6x12 screws. Also, the side plate is assembled as one of the last parts in the whole cabinet assembly sequence. Side plate assembly with end strips and frontal cleats is shown on figure 2.4 below.

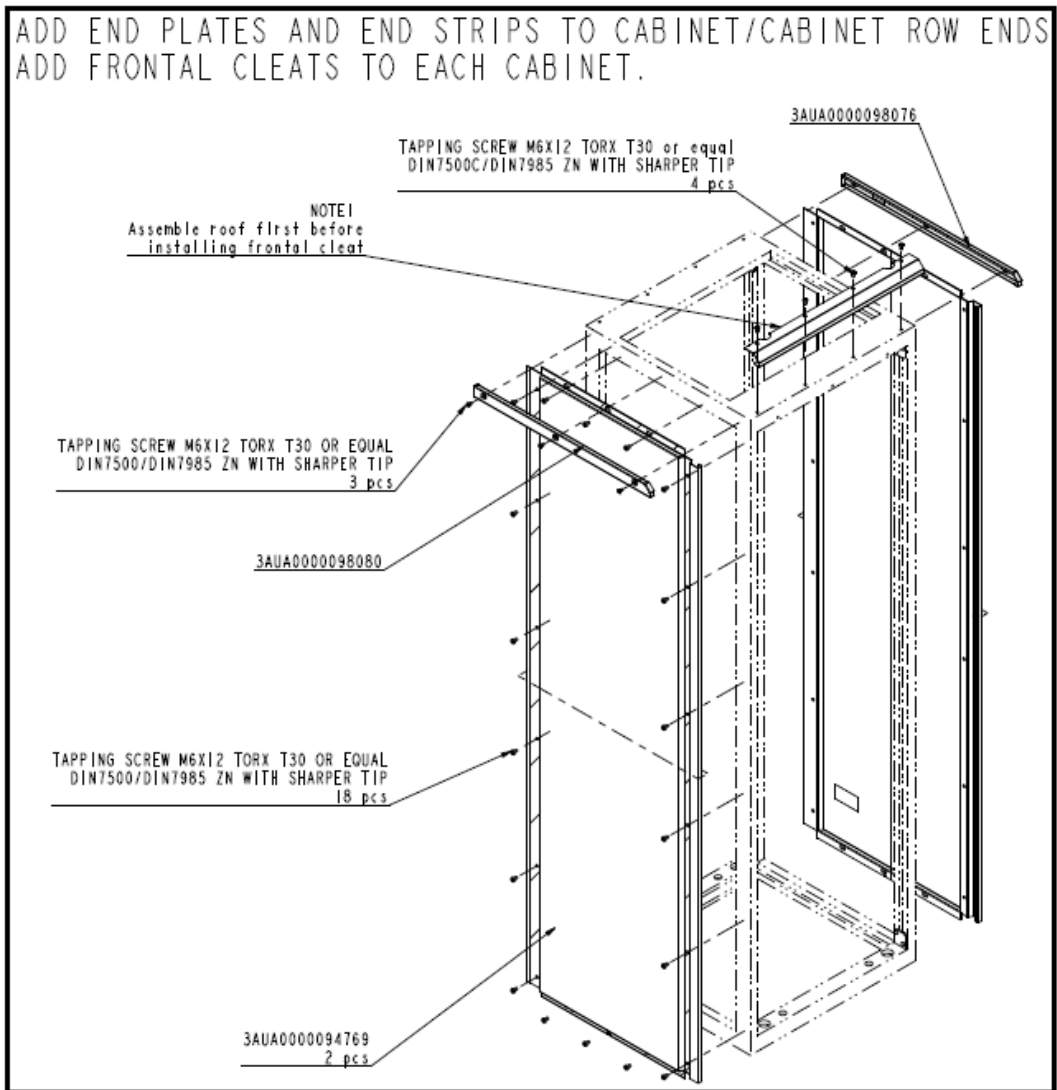


Figure 2.4 End plate, end strip and frontal cleat

The frontal cleats are also shown on the assembly figure, but they are not in the study scope. They are just shown on the same figure with the end plate and strips in the cabinet assembly manual.

2.3.4 Sub-assembly 4 – roof

Roofs are chosen, because they are always needed and have the same basic design. The roof would first be assembled separately, depending on the options that the customer has selected, and then assembled onto the frame. The roof assembly consists of 6 pieces that are assembled together using M6x12 screws. After the roof is completed, it is assembled onto the frame. Assembly onto the frame is also done using M6x12 screws, with the total amount of screws

depending on the width of the cabinet, but there are always at least 10 pieces needed. A basic roof is shown on figure 2.5 below.

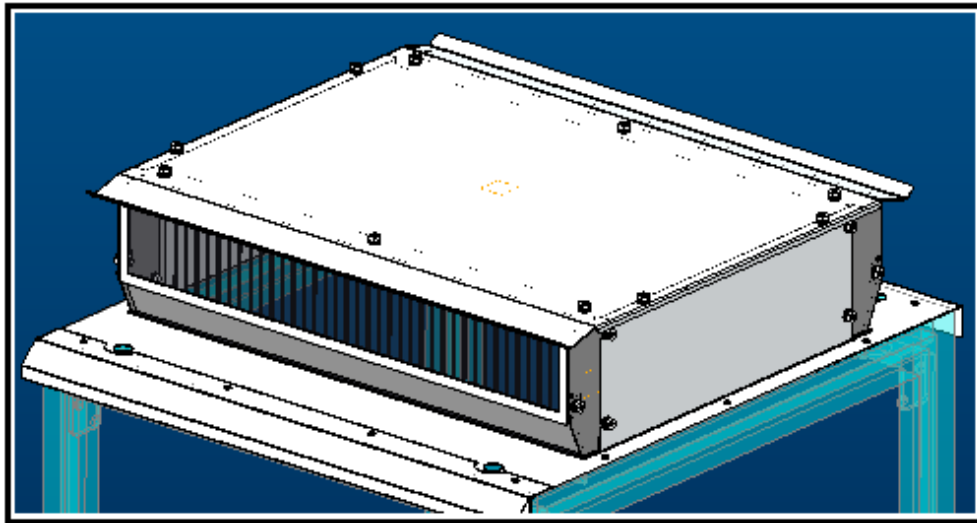


Figure 2.5 Basic roof

2.3.5 Sub-assembly 5 – frame

Frames are chosen, because they are also always needed and have the same basic design. The only difference is the width of the top and bottom beams, although the basic design of them is the same. Assembly onto the frame is done using M6x12 and M6x16 screws. The total amount of M6x12 screws used is 32 pieces and M6x16 screws is 16 pieces. Also, the frame is assembled as the first sub-assembly in the whole cabinet assembly sequence. A basic frame is shown on figure 2.6 below.

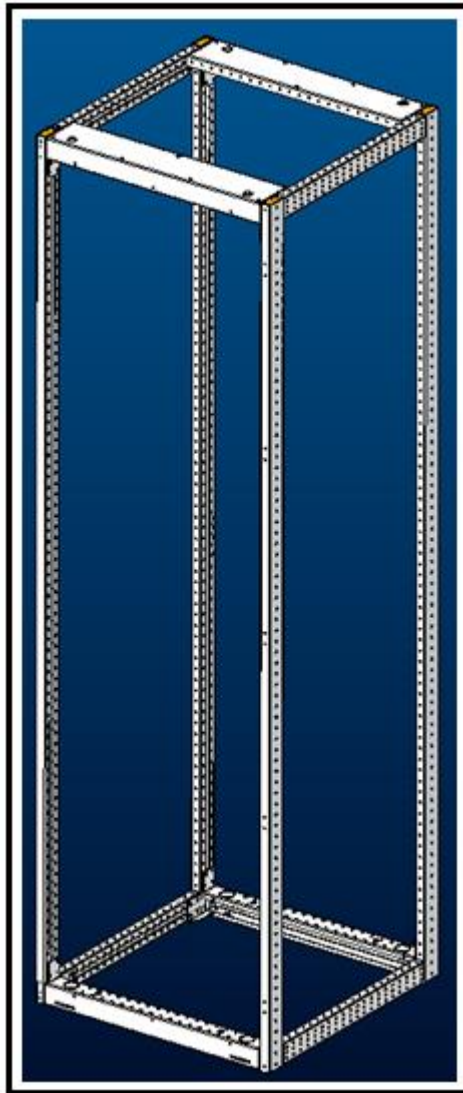


Figure 2.6 Basic cabinet frame

2.3.6 Sub-assembly conclusion

All of the sub-assemblies explained above could be assembled using an automated robot cell with minor or no design changes, but the frame sub-assembly is chosen as the main study topic for this thesis for these reasons:

- 1) Frame parts are the most often needed parts in the factory in the cabinet assembly lines;
- 2) Frame parts have the smallest option variations (the options are explained in chapter 2.2 with the filtering process). The only variation is if either 1 or 2 IP plugs are needed in both ends of frame pillars;
- 3) Most of the frame parts are always the same in cabinets. Only the top and bottom beams, which are related to the cabinet's width, are different. Because most of the frame parts

are always the same, the outcome of this thesis could be utilized for other cabinets, for example multi drives as well.

- 4) Frame sub-assembly is the first phase of the cabinet assembly. The other sub-assemblies are assembled in later phases. Which means that adding a robot assembly cell to the beginning of the cabinet assembly sequence is easier than adding it to the middle of the cabinet assembly sequence.

2.4 Cabinet summary

There are a lot of different cabinets available, but in this thesis, only the single drive cabinets are chosen. More specifically, only the single drive cabinets, which are single cabinet and with the width of 400 mm, 500 mm, 800 mm or 1200 mm, are studied more thoroughly. Only the single cabinets are chosen, because from all the cabinets produced in the Estonian factory in 2018, 60,3 % were single cabinets and the total amount is already enough for a study. Also, only the frame sub-assembly was chosen for more thorough study.

3. FRAME ASSEMBLY

In present situation, the frame assembly is made by hand and by one assembler. Although everyone works a bit differently, the overall process of how the frame assembly is done is still the same. The main steps of how the frame assembly is completed including in the correct order is described below. The steps that are necessary before the frame assembly can be started, for example generating the type code or filling the trolleys with materials, are not described, because they are not related to the actual frame assembly:

- 1) The assembler brings the trolleys, which contain all the parts needed for the cabinet assembly to the workstation. Usually there are 1 or 2 trolleys in total. There are many workstations within the factory, but only one cabinet is assembled per workstation at the same time;
- 2) The assembler takes the assembly manuals from the trolley and looks through them to know what the cabinet size will be. After looking through the manuals, the frame assembly begins;
- 3) The first section that is assembled, is the bottom side. For that, the assembler looks for two bottom beams and two side beams from the trolleys. After finding them, they are placed on the floor and assembled together. The bottom frame parts are assembled together using M6x12 tapping screws;
- 4) After the bottom frame parts are assembled together, the assembler starts looking for the pillar parts from the trolley. After finding them, they are placed next to the trolleys to assemble air blocking plugs on one end of the pillar. After the plugs are assembled, the pillars are assembled onto the bottom frame section one by one using M6x12 and M6x16 tapping screws;
- 5) After all the pillars are assembled, the so-far completed assembly is moved a bit to make room for the top side section. The top side section is first assembled together and then assembled onto the so-far completed assembly;
- 6) To assemble the top side section, the assembler looks for two top beams and two side beams from the trolleys. After finding them, they are placed on the floor and assembled together. The top frame parts are assembled together using M6x12 tapping screws;
- 7) After the top side section is assembled together, the top side is then assembled onto the so-far completed assembly. For that, the so-far completed assembly is placed onto the

floor sideways. After that, the top side section is assembled onto the so-far completed assembly using M6x12 and M6x16 tapping screws. Now the whole frame is assembled;

- 8) Now that the frame is assembled together, the frame is lifted onto the cart, on which the rest of the cabinet will be assembled on. This is also the last step of the frame assembly.

All of the frame parts that were mentioned above, which were the bottom beams, top beams, side beams and pillars are described more thoroughly in the section 3.2.1.

To have an automated frame assembly, all of the steps described above must be made by robots. For that, there should be at least two robots:

- 1) One for moving the frame parts around;
- 2) One for screwing the screws.

For lifting the completed frame assembly onto the cart, a third device is also needed, but it doesn't necessarily have to be a robot, because any kind of lifting device can be used, for example even a crane. Also, the assembly sequence could be changed a bit as well for the new assembly system.

In the next sections, all the necessary steps and devices for the new automated frame assembly that need to be either added or changed are described more thoroughly. The first draft of the whole layout is shown in section 3.6 and the whole automated cabinet frame assembly sequence is explained in section 3.7.

3.1 Robot for moving the frame parts

A robot is needed to move the frame parts around within the new automated frame assembly system and a gripper is needed to grab the frame parts. Before these decisions can be made, the shape of all of the frame parts that are going to be used must be known. In the next sub-sections, first the full list of all of the frame parts is shown. Secondly, the first drafts of the grippers for different frame parts are made. And thirdly, the new assembly sequence is described. The final choice of the robot and gripper is made in section 4.1.

3.1.1 Frame parts

In total, there are 4 different frame parts:

- 1) Bottom beams, example shown on figure 3.1;
- 2) Top beams, example shown on figure 3.2;
- 3) Side beam, shown on figure 3.3;
- 4) Pillars, shown on figure 3.4. The pillars are shown in full scale and the closer view of top and bottom sides is shown:
 - a) Front pillar;
 - b) Rear pillar.

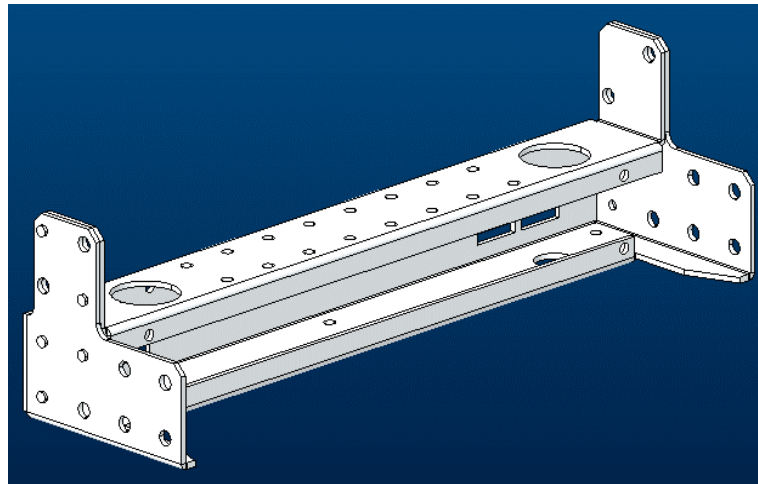


Figure 3.1 Bottom beam example

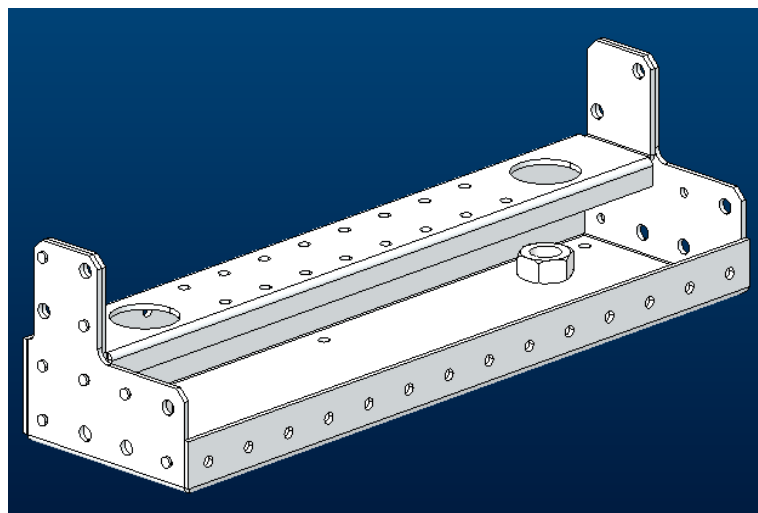


Figure 3.2 Top beam example

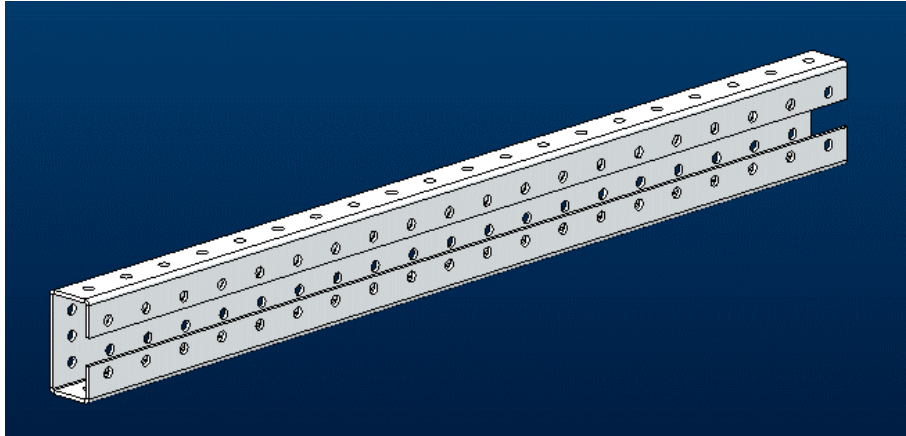


Figure 3.3 Side beam

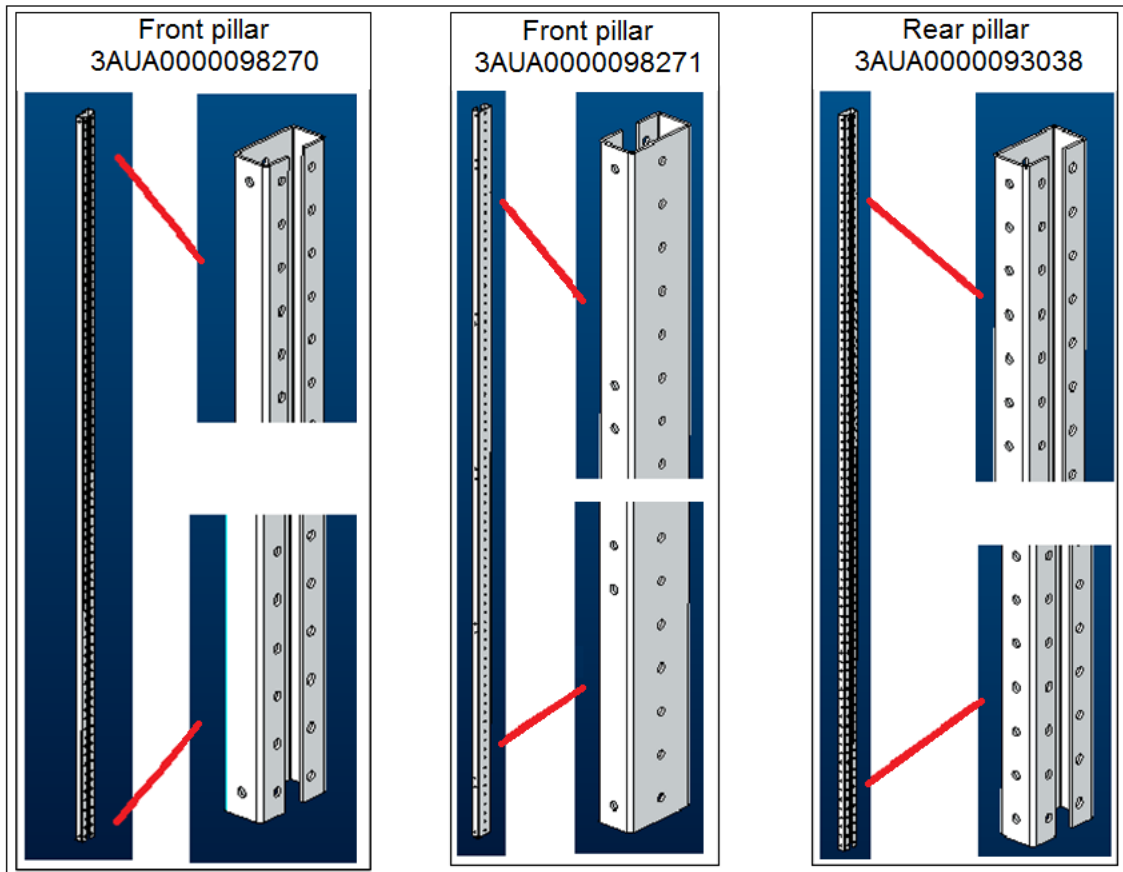


Figure 3.4 Pillars with part codes

All the frame parts that are used within this thesis are shown in the table 3.1 below. The table consists of the part code used in ABB, the width these parts are meant for (only needed for the bottom and top beams), the weight, overall dimensions and a side view.

Table 3.1 Frame parts used within this thesis

Part code	Width	Weight, kg	Overall dimensions, mm	Side view
Bottom beams				
3AUA0000120410	400	1,31	350 x 97.5 x 95	
3AUA0000105236	500	1,62	450 x 97.5 x 95	
3AUA0000118951	800	2,52	750 x 97.5 x 95	
3AXD50000029148	1200	3,69	1150 x 97.5 x 95	
Top beams				
3AUA0000119158	400	1,74	350 x 100 x 95	
3AUA0000119155	500	2,17	450 x 100 x 95	
3AUA0000119150	800	3,52	750 x 100 x 95	
3AXD50000029144	1200	5,26	1150 x 100 x 95	
3AXD50000029145	1200	5,25	1150 x 100 x 95	
Side beam				
3AUA0000093036		0,94	500 x 50 x 25	
Rear pillar				
3AUA0000093038		3,74	2000 x 50 x 25	
Front pillars				
3AUA0000098270		3,84	2000 x 50 x 25	
3AUA0000098271		3,84	2000 x 50 x 25	

Although usually there are two of the same top beams used for the frame assembly, for the 1200 width, there are two different beams used. One is used in the front side of the cabinet and the other one is used in the back side of the cabinet.

3.1.2 Frame part grippers

There are going to be two different types of grippers, which are:

- a) Side beam and pillar gripper;
- b) Top and bottom beam gripper.

They are combined like this, because the overall shape of those parts is similar. In the next sub-chapters, the grippers are explained more thoroughly.

Side beam and pillars are going to be always grabbed from the middle of the part. To ensure smooth assembly, the side beams are picked up a bit differently than the pillars. Both these parts and the picking locations are explained more thoroughly below.

The side beam is going to be grabbing like shown on figure 3.5.

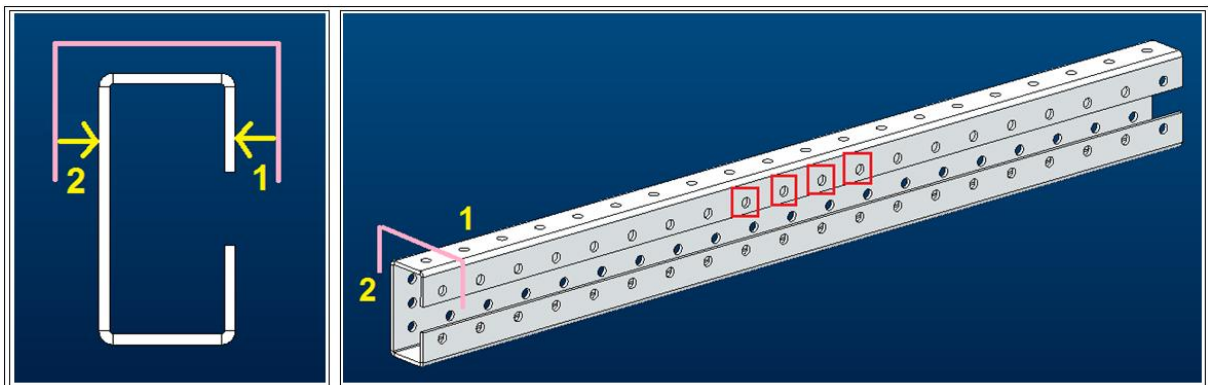


Figure 3.5 Side beam grabbing

The pink colour shows how the gripper would be next to the side beam. First, the right side of the beam would come into contact with the gripper and then the left side. On the right side, there are going to be guide studs on the gripper to ensure that the part is firmly grabbed. The guide studs would come into contact with the holes marked in red on figure 3.5. The holes on the side beam are all with a diameter of 5,3 mm and the distance between them is 25 mm. On the left side, there are going to be sensors, but for the side beam, these are just for precaution to make sure that the correct part is picked up. This means that all of the 4 sensors must be active during the control. The sensors' type should be surface contact sensors.

The pillars are going to be picked up like shown on figure 3.6.

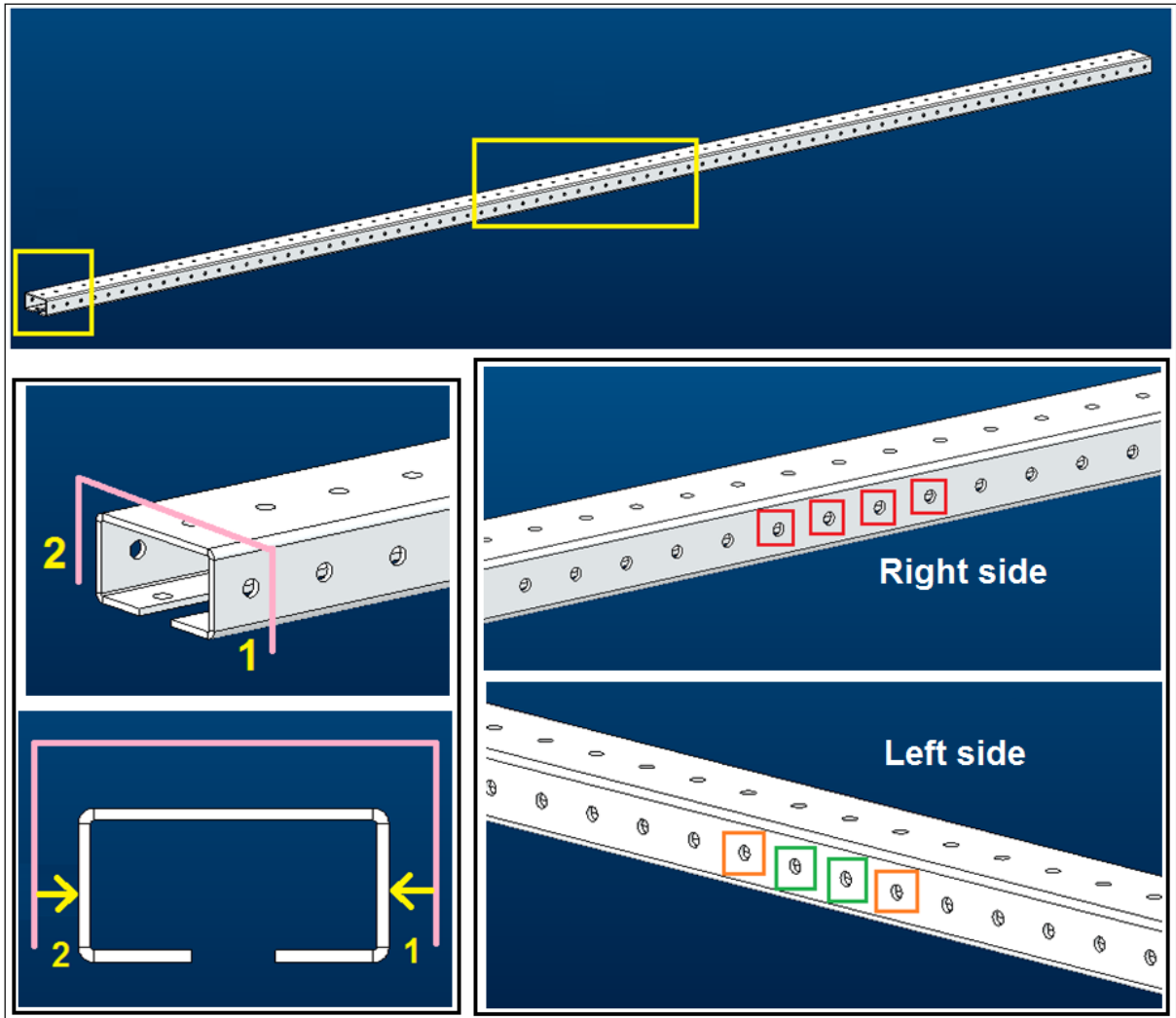


Figure 3.6 Pillar grabbing

Because the pillar parts are 2000 mm long, there are separate pictures made within the figure 3.6 to show the necessary places from closer. The pink colour shows how the gripper would be next to the side beam. First, the right side of the beam would come into contact with the gripper and then the left side. On the right side, there are going to be guide studs on the gripper to ensure that the part is firmly grabbed. The guide studs on the right side would come into contact with the holes marked with red on figure 3.6 and also the distance between the guide studs is 25 mm and the diameter of the guide studs is 5 mm. The holes on the side beam are all with a diameter of 5,3 mm and the distance between them is 25 mm. On the left side, there are going to be sensors, which are needed to control what part was picked up. The sensors are marked with green and orange on figure 3.6 and they are checking if there is a hole at that location or not. The type of the

sensors should be surface contact sensors. On figure 3.4, which is shown before the frame parts table 3.1, it is shown how the holes are aligned on one side of the pillars. On the other side, which is not shown on figure 3,4, all of the pillar parts are covered with holes in full length. The sensors are going to control the following:

- a) If all 4 sensors are active, then the part is 3AUA0000093038;
- b) If only the middle 2 sensors, which are marked with green colour on figure 3.6, are active, and not the 2 sensors on sides, which are marked with orange colour on figure 3.6, then the part is 3AUA0000098271;
- c) If none of the sensors are active, then the part is 3AUA0000098270.

Although the side beam is going to be grabbed a bit differently than the pillars, the gripper shape is still the same. On figures 3.7 and 3.8 below is shown how the hypothetical gripper would look like.

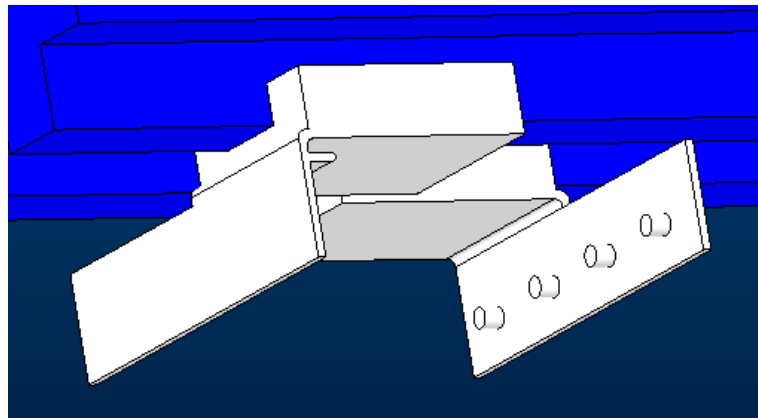


Figure 3.7 Hypothetical gripper for side beam and pillars, side with guide studs

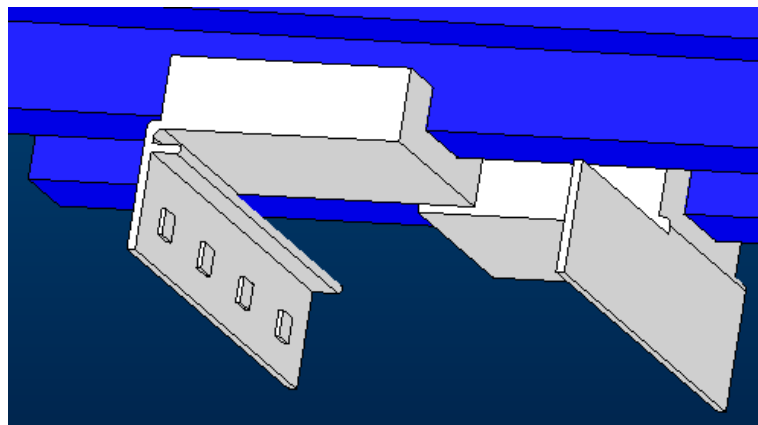


Figure 3.8 Hypothetical gripper for side beam and pillars, side with sensors

Top and bottom beams are going to be always grabbed from the middle of the part. Because the upper side's shape, where the beams are going to be grabbed from, is the same for both the top and bottom beams, the same gripper can be used. The picking location of beams is explained more thoroughly below.

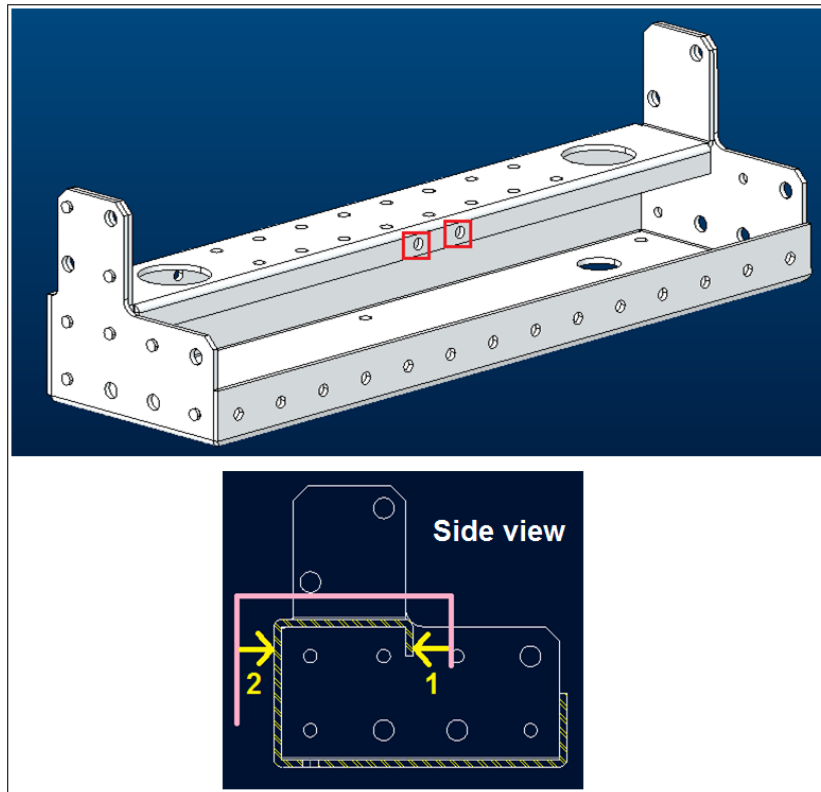


Figure 3.9 Top and bottom beam grabbing

The top and bottom beam are going to be grabbed like shown on figure 3.9. On the side view, the pink colour shows how the gripper would be next to the side beam. The side view is made as a cross-section for better understanding. First, the right side of the beam would come into contact with the gripper and then the left side. On the right side, there are going to be guide studs on the gripper to ensure that the part is firmly grabbed. The guide studs would come into contact with the holes marked in red on figure 3.9. The distance between the guide studs is 25 mm and the diameter of the guide studs is 5 mm. In the current top and bottom beam designs, there are no such holes, therefore they would need to be added there for the automation purposes. Both holes would be with a diameter of 5,3 mm and the distance between them would be 25 mm. On the left side, there would just be a blank gripper with no special holes or sensors, because the top and bottom beam parts don't need such things.

The hypothetical gripper is shown on the figure 3.10 below. The other side is not shown, because it is just a blank side.

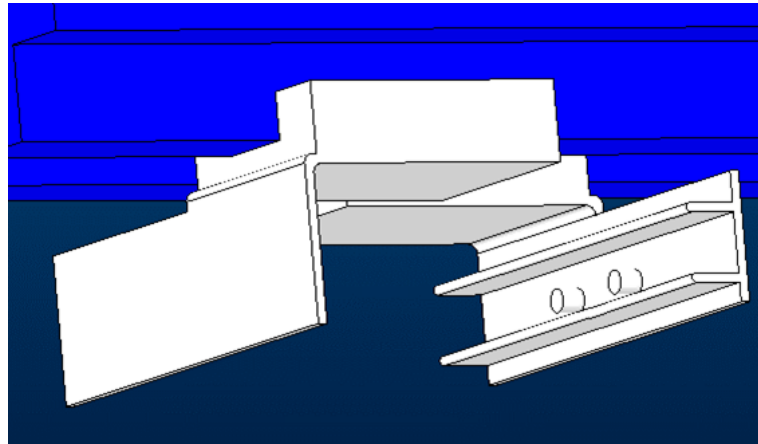


Figure 3.10 Hypothetical gripper for top and bottom beams

3.1.3 Frame parts assembly sequence

For the new automated frame assembly system, a new assembly sequence is also made. The sequence is described more thoroughly below. Figure 3.11 explains the notes and numbers better. The example on figure 3.11 is based on a 500 mm width cabinet:

- 1) Frame's bottom side is assembled, which consists of parts A1, A2, B1 and B2;
- 2) Frame's top side is assembled, which consists of parts C1, C2, D1 and D2;
- 3) Frame's left side is assembled, which consists of parts E and F1;
- 4) Frame's right side is assembled, which consists of parts G and F2.

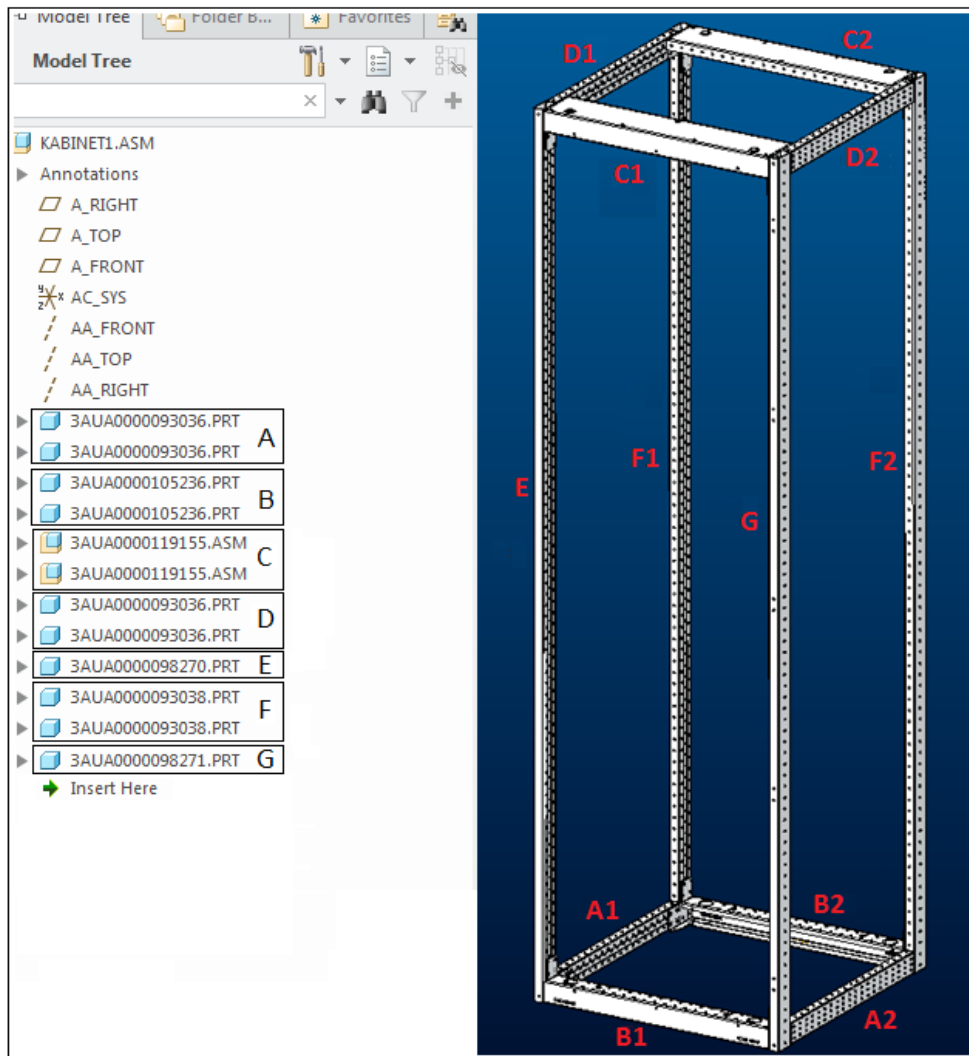


Figure 3.11 New frame assembly sequence

Because there are two different grippers used for different frame parts, the robot would need to change the grippers during the assembly sequence. For that, the frame bottom and top side assembly sequence with changing the grippers is explained more thoroughly:

- 1) The robot would start with the side beam and pillar gripper, because the side beams, marked with letters A1 and A2 on the figure 3.11 above, are the first two parts being assembled. The robot would have this gripper attached in its starting position as well. After assembling the side beams, the robot would need to change the gripper to grab the top and bottom beams;
- 2) After changing the gripper, the bottom beams, marked with letters B1 and B2 on the figure 3.11 above, can be assembled. Now that the bottom side is assembled, the top side is assembled next;

- 3) The top beams, marked with letters C1 and C2 on the figure 3.11 above, are assembled before the side beams so that the same gripper could be used that is currently attached to the robot. After the top beams are assembled, the robot would need to change the gripper to grab the side beams;
- 4) After changing the gripper, the side beams, marked with letters D1 and D2 on the figure 3.11 above, can be assembled. Because all the other parts left to assemble are pillars and the same gripper is used for side beams and pillars, the gripper does not have to be changed anymore.

On figure 3.11 above, frame parts A, D, F and G are always the same, no matter what the cabinet width is. Frame part E is usually the same as well, but in case the 1200 mm wide cabinet is assembled, this part is the same as G. The correct frame parts and the letters related to them are shown in the table 3.2 below.

Table 3.2 Letters from the assembly sequence related to the correct part code

Part code	Letter from the assembly sequence
Bottom beams	
3AUA0000120410	B
3AUA0000105236	B
3AUA0000118951	B
3AXD50000029148	B
Top beams	
3AUA0000119158	C
3AUA0000119155	C
3AUA0000119150	C
3AXD50000029144	C1
3AXD50000029145	C2
Side beam	
3AUA0000093036	A, D
Rear pillar	
3AUA0000093038	F
Front pillars	
3AUA0000098270	E
3AUA0000098271	G

3.2 Frame assembly bottom plate

Currently, the whole frame assembly is done on the regular factory floor and the assemblers hold the frame parts together while tightening the screws. Because in section 2.1 it is mentioned that this thesis is only about the single drive cabinets built in Estonian factory and only for the single cabinets, the bottom plate is currently designed only for the 400 mm, 500 mm, 800 mm and 1200 mm cabinet widths. Hence for the automated frame assembly, a special bottom plate for the frame assembly is made and the first draft is shown on figure 3.12. The bottom plate dimensions are shown in appendix 1.

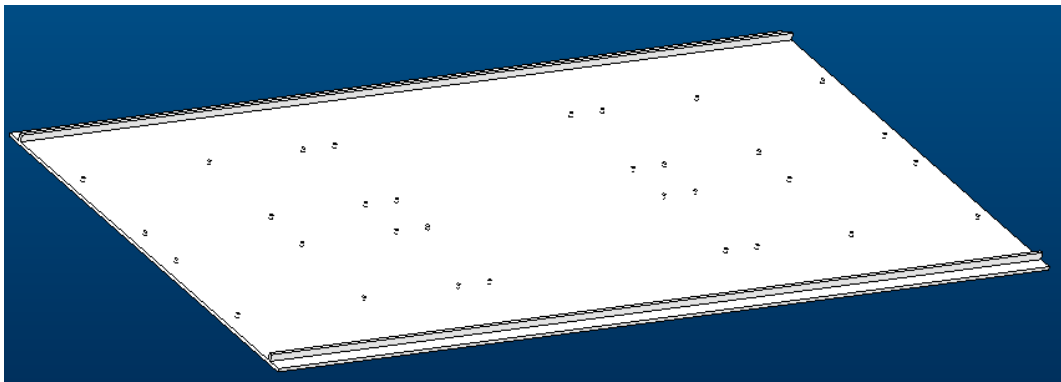


Figure 3.12 Frame assembly bottom plate CAD model

There is a total of 32 guide studs with a height of 5 mm placed on the frame assembly bottom plate. These are necessary to hold the side beams in the correct places and therefore don't allow the frame to move during the assembly process. The distances between the guide studs are chosen so that each cabinet width has its own guide studs to be used. So in total, 8 guide studs are in use for one frame assembly. Two example figures of how the frame bottom parts would be assembled onto the frame assembly bottom plate are shown in appendix 2.

3.3 Robot for assembling the screws

A robot and a screddriver are needed to assemble the screws within the new automated frame assembly system. Before the robot and the screwdriver can be chosen, the list of all of the necessary screws must be known. In the next sub-sections, first the list of all of the screw types

used is shown with the new proposed variants. Secondly, the new assembly sequence is described. The final choice of the robot and the screwdriver is made in section 4.2.

3.3.1 Types of screws

There are two types of screws used for the whole frame assembly and the only difference is in the length of those:

- 1) Tapping screw M6x12 TORX - DIN7500-D – 5 Nm;
- 2) Tapping screw M6x16 TORX - DIN7500-D – 5 Nm.

Both of these screws are self tapping, with a hexagon head and need a moment of 5 Nm to be tightened. But the amounts needed are different. Also, the types of screws don't depend on the width of the frame, hence are always the same. The current amounts used with the new proposed variants are shown in the table 3.3 below. In total, there are always 48 screws needed to assemble all the frame parts together.

Table 3.3 Types and amounts of screws

Frame parts that are assembled together	Screw type	Amount needed per corner	Amount needed in total
Current situation			
Bottom base beams assembled onto side beams	M6x12	4	16
Bottom base beams assembled onto pillars	M6x12	1	4
	M6x16	2	8
Top base beams assembled onto pillars	M6x12	1	4
	M6x16	2	8
Top base beams assembled onto side beams	M6x12	2	8
For all frame parts in total	M6x12		32
	M6x16		16
Proposed variant A			
Bottom base beams assembled onto side beams	M6x16	4	16
Bottom base beams assembled onto pillars	M6x16	3	12
Top base beams assembled onto pillars	M6x16	3	12
Top base beams assembled onto side beams	M6x16	2	8
For all frame parts in total	M6x16		48
Proposed variant B			
Bottom base beams assembled onto side beams	M6x12	4	16
Bottom base beams assembled onto pillars	M6x16	3	12
Top base beams assembled onto pillars	M6x16	3	12
Top base beams assembled onto side beams	M6x12	2	8
For all frame parts in total	M6x12		24
	M6x16		24

The first proposed variant A could be used, so that there would be only one type of screw used for the whole assembly, which would be M6x16. Also, with only one type of screw, only one screw feeder would be needed. The second proposed variant B could be used, so that the pillars would be assembled onto the bottom and top beams only with one type of screws, which would be M6x16. Currently the pillars are assembled onto the bottom and top beams with two types of screws, which are M6x12 and M6x16. And with two types of screws, two screw feeders would be needed. Although there are two different proposed variants, at present they are not going to be changed. So the screw assembly sequence in the next sub-section is also made based on the current types of screws.

3.3.2 Screw assembly sequence

For the new automated frame assembly system, a new screw assembly sequence is also made. The sequence is described more thoroughly below and there are separate figures for each step to show the sequence more precisely:

- 1) Frame's bottom side is assembled using M6x12 screws, which is shown on figure 3.13 below in more detail. The assembly sequence of the corners is A -> B -> C -> D and in every corner, the screw assembly sequence is 1 -> 2 -> 3 -> 4. In total there are 16 pieces of M6x12 screws assembled for the bottom side;
- 2) Frame's top side is assembled using M6x12 screws, which is shown on figure 3.14 below in more detail. The assembly sequence of the corners is A -> B -> C -> D and in every corner, the screw assembly sequence is 1 -> 2. In total there are 8 pieces of M6x12 screws assembled for the top side;
- 3) Frame's left and right side pillars are assembled using M6x12 and M6x16 screws. First the left front side pillar (shown on figure 3.15), secondly the left rear pillar (shown on figure 3.16), thirdly the right front side pillar (shown on figure 3.17) and at last the right rear pillar (shown on figure 3.18) is assembled. The assembly sequence of all of these pillars' corners is A -> B. In the bottom corner, the screw assembly sequence is 1 -> 2 -> 3, while in the top corner, the screw assembly sequence is 4 -> 5 -> 6. Screws 1 and 6 are M6x12 type and screws 2 to 5 are M6x16 type.

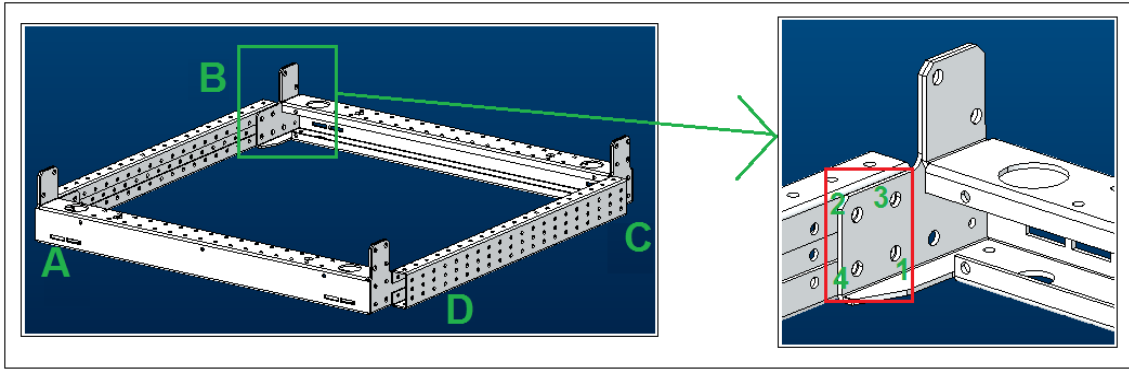


Figure 3.13 Frame's bottom side screw assembly sequence

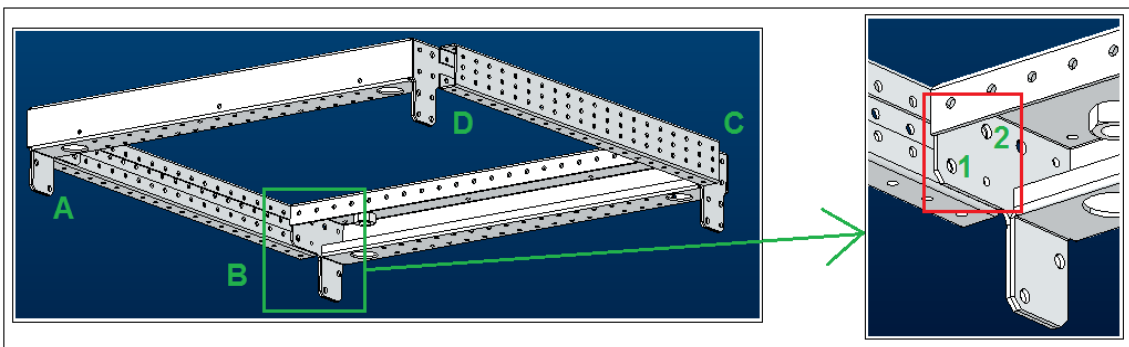


Figure 3.14 Frame's top side screw assembly sequence

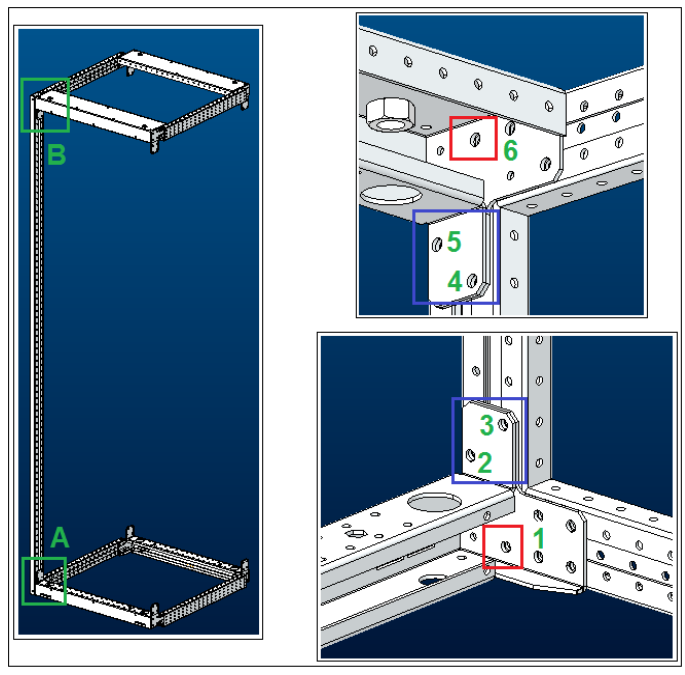


Figure 3.15 Frame's left side front pillar's screw assembly sequence

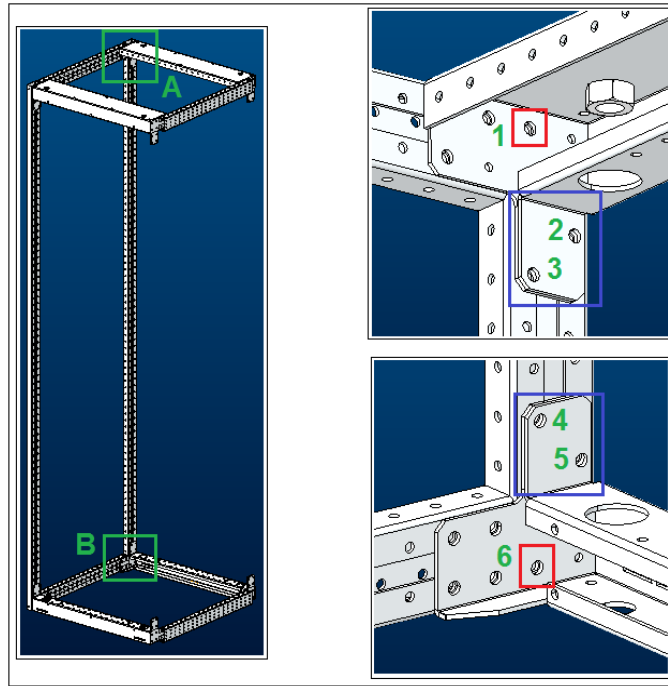


Figure 3.16 Frame's left side rear pillar's screw assembly sequence

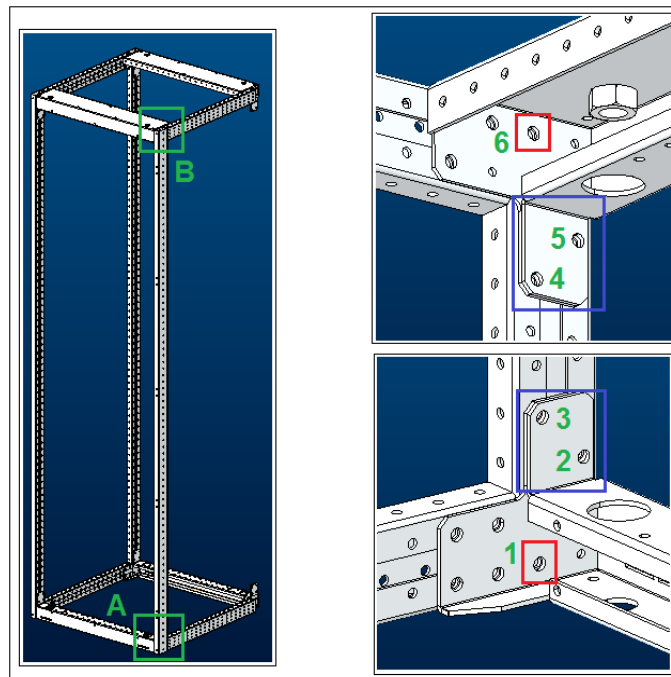


Figure 3.17 Frame's right side front pillar's screw assembly sequence

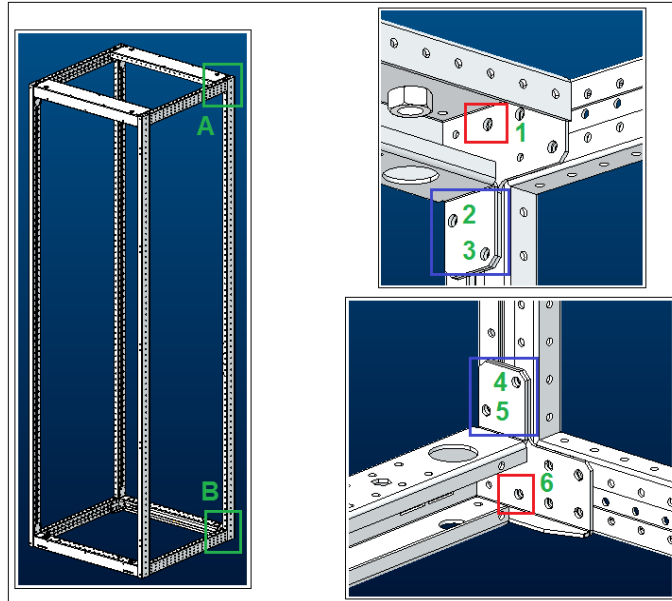


Figure 3.18 Frame's right side rear pillar's screw assembly sequence

The screw assembly sequence is chosen as described above so that the robot with the screwdriver would need to move as little as possible. Because there are M6x12 and M6x16 screws assembled in turns, the screwdriving solution, that is chosen in section 4.2, must be able to cope with this. Either the screwdriver needs to be changed to assemble different screw types or the screwdriver itself must be able to assemble two different screw types.

3.4 Lifting device

A lifting device is needed to move the completed frame to a cart and hold the top side part of the frame during the assembly within the new automated frame assembly system. The lifting device would work in a manner that it would hold the top beams in the correct place during the assembly and screwing sequence. And after the frame is completely assembled, the device would lift the completed frame onto the cart waiting on the side. The cart has similar dimensions to the frame assembly bottom plate, because the cart needs to be big enough for the frame to fit on it.

The top beams are grabbed like shown on figures 3.19 and 3.20.

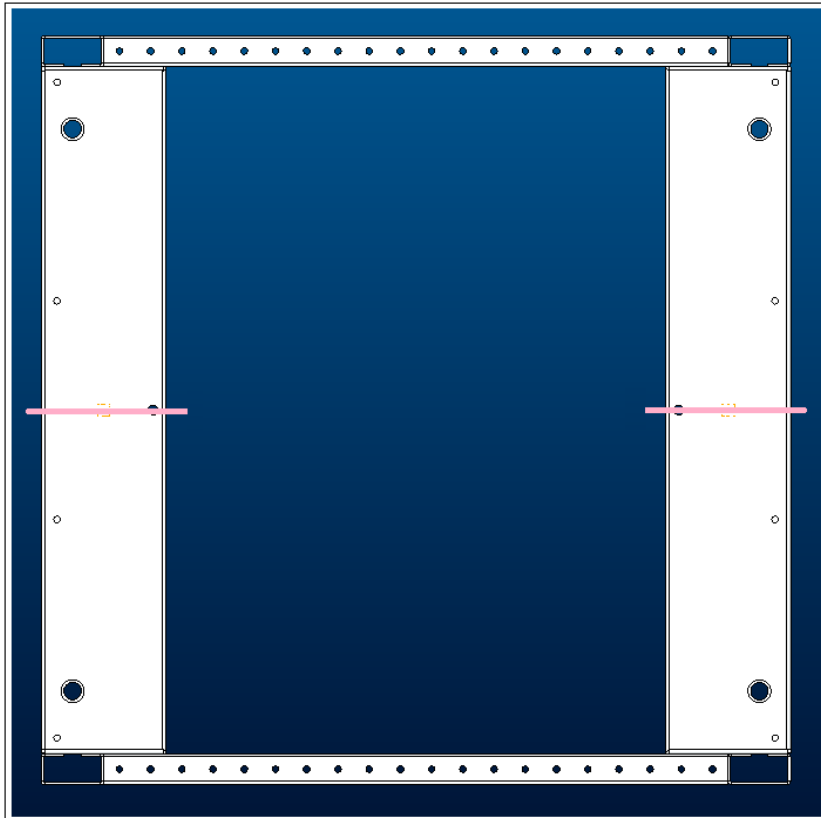


Figure 3.19 Both top side top beam grabbing

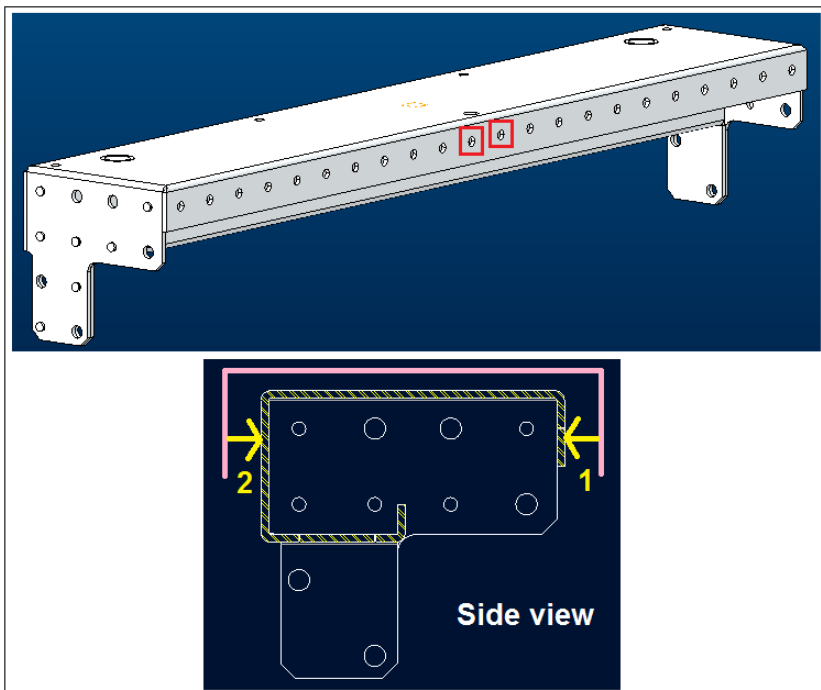


Figure 3.20 One top side beam grabbing

The grippers next to the top beams are shown on the figure 3.19 with pink. In total there are two grippers needed on both sides, one for each top beam. In order to use the same grippers for different frame widths, the top beam must be grabbed from the middle of the beam to ensure that the centre of gravity is always in the middle. The gripper's and top beam's side view is shown on the figure 3.20 with pink. The side view is made as a cross-section for better understanding. First, the right side of the beam would come into contact with the gripper and then the left side. On the right side, there are going to be guide studs, which are needed to get a firm grip of the part. The guide studs would come into contact with the holes marked with red on figure 3.20. The distance between the guide studs is 25 mm and the diameter of the guide studs is 5 mm. On the left side, there would just be a blank gripper with no special sensors or holes, because these are not needed for this gripper.

The hypothetical gripper is shown on the figure 3.21 below. The other side is not shown, because it is just a blank side.

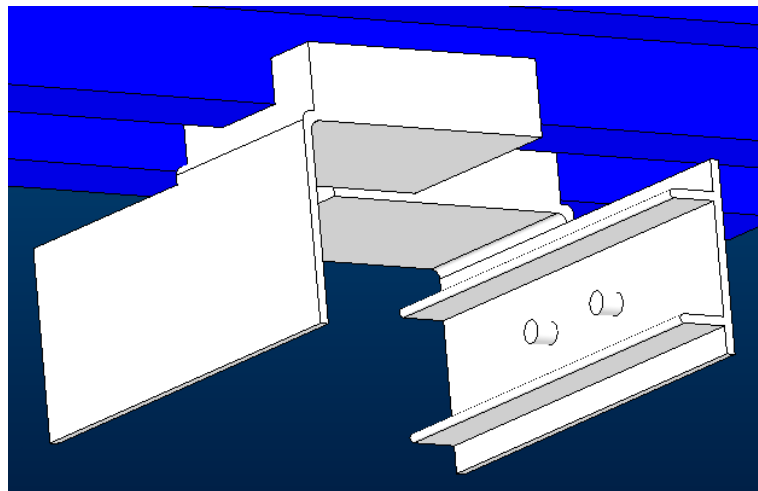


Figure 3.21 Hypothetical gripper for the lifting device

In the next sub-sections, first the top side holding sequence of frame is described. Secondly, moving the completed frame to cart sequence is described. The final lifting device and gripper's choice is made in section 4.3.

3.4.1 Top side holding sequence of the frame

During the frame parts' assembly, the top side is the second frame section within the assembly sequence. And to assemble the top side, the lifting device with some holding gripper is needed. The starting position of the lifting device is always at the same height as the top beams are assembled at, which is 2000 mm from the ground and with grippers open. The lifting device sequence is described more thoroughly below, and the sequence starts when the frame assembly has started:

- 1) When the top side assembly is started, and the first top beam is lifted to position, the lifting device's gripper on the first side grabs the top beam. The robot that moves the frame's parts holds the top beam in place until the system says that the lifting device's gripper has grabbed the top beam;
- 2) Step one is repeated for the second top beam;
- 3) When both of the top beams are being held, the top side's assembly can continue. The lifting device now waits for the whole frame to be completed.

3.4.2 Moving the completed frame to a cart sequence

After the whole frame assembly is finished, the lifting device continues its working sequence, which is described more thoroughly below:

- 1) When the lifting device gets a signal from the assembly system that the frame assembly is finished, the lifting device lifts the whole frame up from the frame assembly bottom plate by about 10 mm (the guide studs on the bottom plate are 5 mm in height);
- 2) The lifting device now moves the whole frame away from the assembly area and on top of the area where the cart is located at;
- 3) The frame is lowered down by 10 mm so that the frame is now placed onto the cart;
- 4) When the frame is on the cart, the assembly system will know it and open the grippers so that the frame is not held anymore at all;
- 5) The lifting device goes higher by 10 mm;
- 6) The lifting device goes back to its starting position. This is also the last step of the whole automated frame assembly system.

3.5 New shelves for robot assembly system

Currently all of the parts that are necessary for the cabinet assembly, arrive at workstations on one or two trolleys. But for the automated frame assembly robot cell, only frame parts are necessary. Because of that, a new shelf only for frame parts is needed. On figure 3.22 below is a first draft of the shelf.

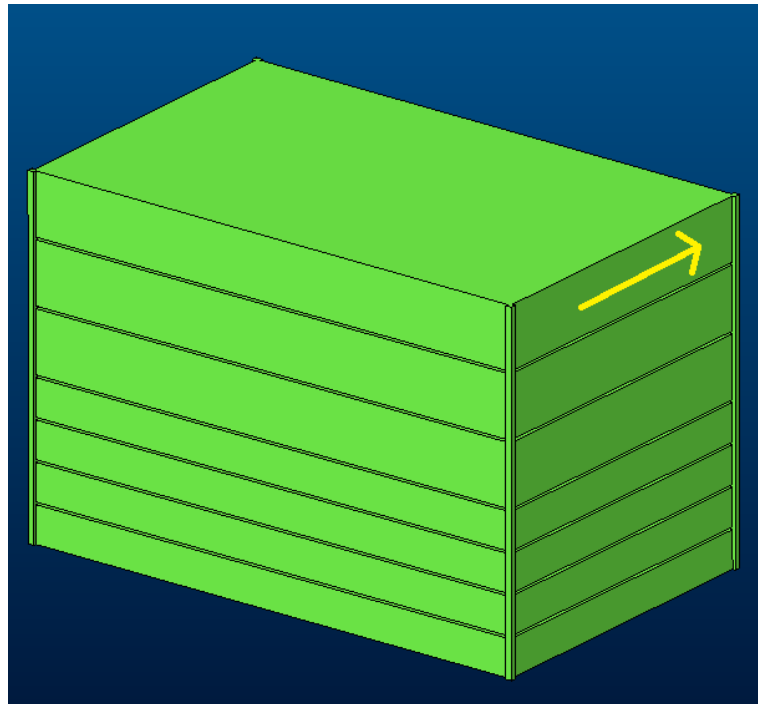


Figure 3.22 First draft of shelf

The yellow arrow on the side shows the direction of the shelves' movement. Shelves need to be pulled out so that they could be refilled. There are sensors inside the shelves which notify when the shelves are empty. The sensors are chosen in section 4.4.

The first draft of the shelf's dimensions and where specific frame parts are located at is shown in appendix 3. The current width and depth dimensions are chosen so that there could be placed enough frame parts on the shelves to assemble an optimal amount of cabinets before refilling, which is chosen to be 12 cabinets for this thesis. The shelf's specific heights are chosen in a way so that the robot with the gripper could fit inside the specific shelves, lift the parts and move them out of the shelves.

Because the grippers have to pick up the frame parts always from the same position (in the middle of the part), special shelves for stocking the parts are needed. Special shelves are necessary to ensure that the frame parts are always placed in the same positions on shelves so that the robot could always pick up the frame parts from the same specific positions. In the next sub-paragraph, part-specific shelves are explained and shown. There are no dimensions shown on the part-specific shelves, because those are just the first draft versions, but the overall idea of how and why the shelves look like that are explained.

3.5.1 Part-specific shelves

Side beams are placed on the shelves like shown on figure 3.23 below.

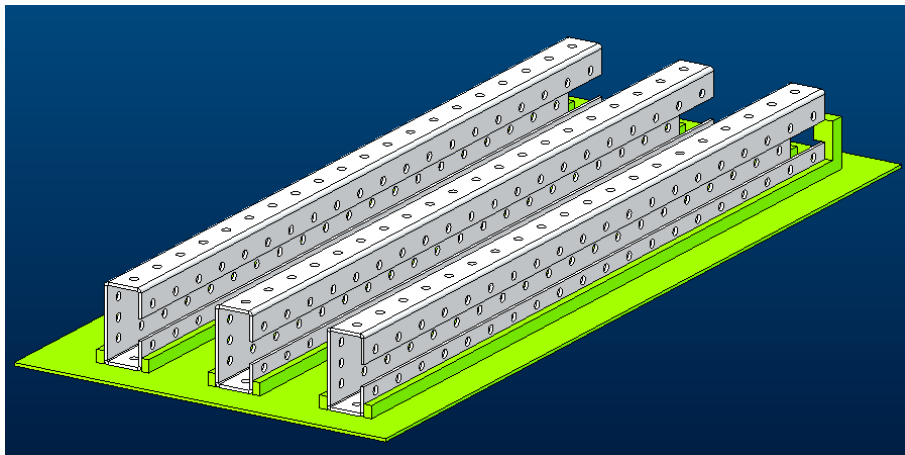


Figure 3.23 Side beam shelf

It is important that the side beams are always placed in the same position and on the same side for the robot. The side beam shelf design is made to ensure that the gap on one side of the side beam is always on side A on the shelf. So that when the side beams are placed onto the shelves, the gap must be on side A of the beam. The side A is shown on figure 3.24 below. Otherwise the side beam couldn't be sled onto the shelf. On figure 3.24 below is shown how the side beam shelf looks like from the back side, with the special gap currently only added for one side beam to get a better understanding of how it works.



Figure 3.24 Side beam shelf, back view

Rear and front pillars are placed on the shelves like shown on figures 3.25 and 3.26 below.

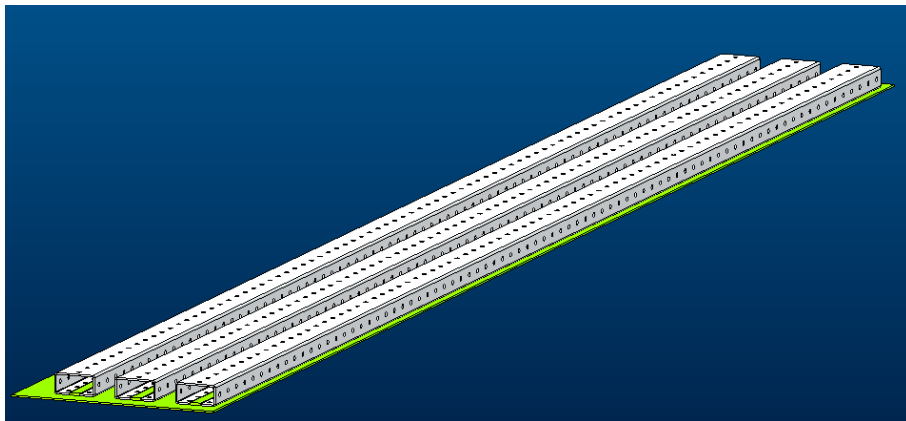


Figure 3.25 Rear and front pillar shelf

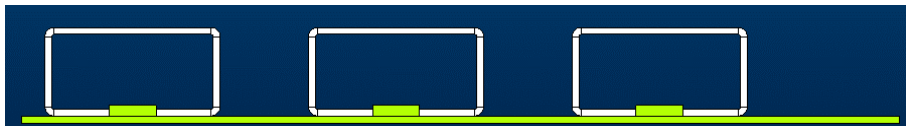


Figure 3.26 Rear and front pillar shelf, front view

The pillar shelf's design is made to ensure that the gap on one side of the pillar is always facing downwards. By placing the pillars like shown above, it is easier for the robot to pick up the parts – there is no need to check which side the gap is on. Also, it is easier to place the pillars on the shelves if they always have the same specific location.

Top beams are placed on the shelves like shown on figure 3.27 below.

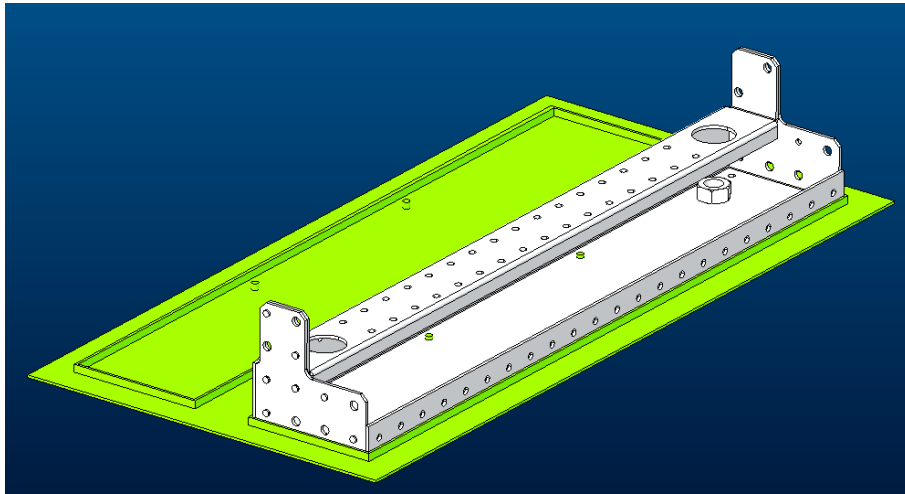


Figure 3.27 Top beam shelf

The top beam shelf design is made to ensure that only the top beams fit there. Although the outer dimensions for bottom and top beams are similar, the additional guide studs in the middle rule out the possibility that bottom beams could be assembled in top beam positions, because bottom beams don't have such holes at all.

Bottom beams are placed on the shelves like shown on figure 3.28 below.

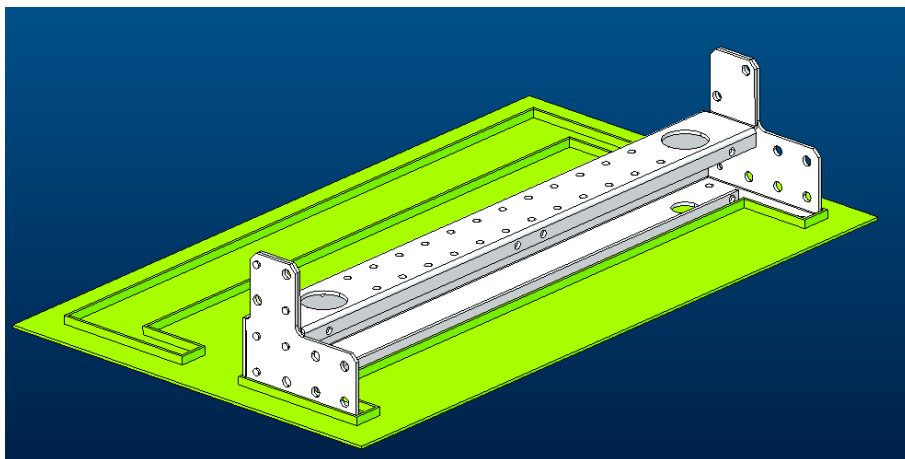


Figure 3.28 Bottom beam shelf

The bottom beam shelf design is made to ensure that only the bottom beams fit there.

3.5.2 Taking parts from the shelves

The distance between different shelves is made so that:

- a) The gripper could fit between shelves;
- b) The gripper could move between the shelves – move down to grab the part and move back up.

The frame part picking sequence from the shelves is explained below in the correct order and it is the same for all frame parts. Some example pictures which explain the sequence are also shown in appendix 4:

- 1) The gripper goes to the middle position of the frame's part and stays a bit higher from the parts;
- 2) The gripper goes closer to the part (picture 1 in appendix 4);
- 3) The guide studs on the first side of the gripper go inside the part (picture 2 in appendix 4);
 - 3.1) If the guide studs can't move inside, then;
 - 3.2) The gripper would go back to position 1 and rotate 180 degrees so that the guide studs are now on the other side;
- 5) If the guide studs are inside the part, then the second side of the gripper goes next to the part (picture 3 in appendix 4);
- 6) Depending on the part, the sensors on this side of the gripper would now check what's necessary;
- 7) The part is lifted up from the shelf (picture 4 in appendix 4);
- 8) The part is moved away from the shelf.

The pictures that give a better understanding of the gripping operation for each frame's parts are shown in the appendices. Front and rear pillars are shown in appendix 5, the side beams are shown in appendix 6 and the top and bottom beam parts are shown in appendix 7. Also, the top and bottom beam's parts are shown together, because the grabbing shape of those parts is the same. To better show the gripping sequence, one side of the beam is removed. The blue part on all of the pictures in appendices 4 to 7 is a hypothetical gripper to show the size of the gripper compared to the frame parts.

3.6 First draft layout of automated cabinet frame assembly workstation

Besides all the devices that are needed for the new automated cabinet frame assembly, the workstation itself also needs to be designed. On figure 3.29 below is the first draft of the new layout for the workstation. Everything that is visible on the drawing is also explained after the figure.

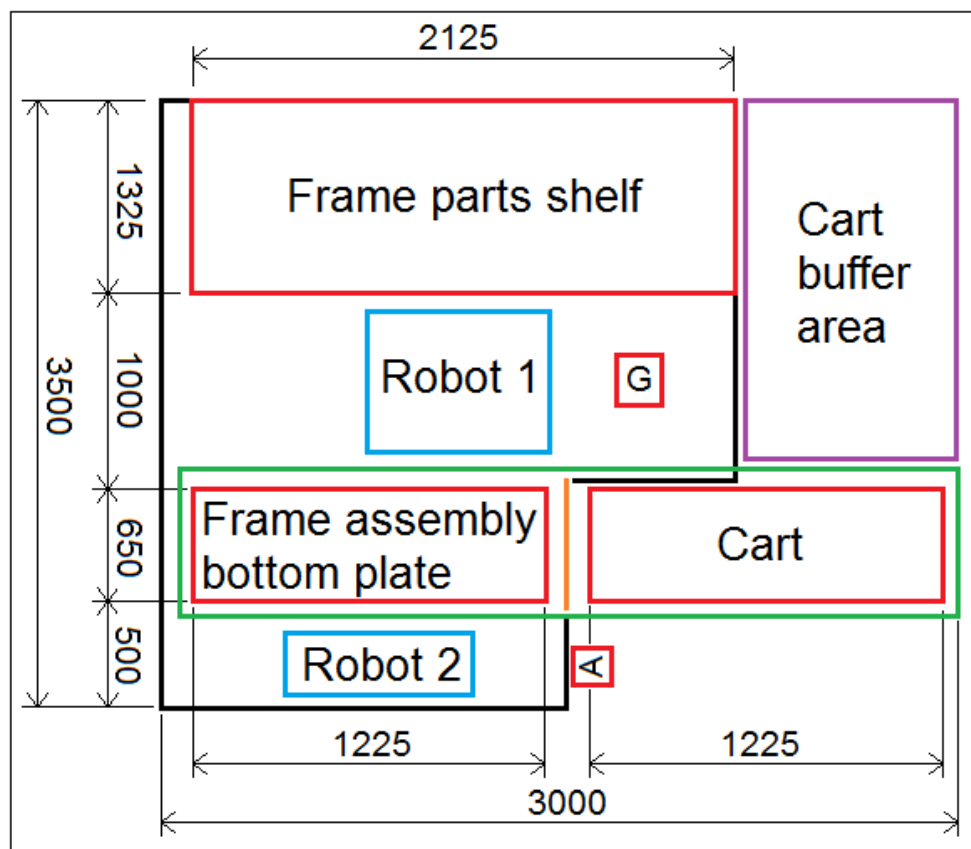


Figure 3.29 Automated cabinet frame assembly workstation first draft layout

Explanations for the layout seen on figure 3.29:

- The frame parts shelf, frame assembly bottom plate and cart dimensions are the only ones that are defined above and known at this stage. They are marked with red on the layout;
- The „A“ on the layout that is marked with red, is where the computer would be located at. A computer is needed to tell the system what needs to be assembled and also from there the situation of the frame parts on the shelves is seen;

- c) The „G“ on the layout that is marked with red, is where the grippers would be located at, which need to be changed;
- d) Robot 1 is for moving the frame parts and robot 2 is for assembling the screws. The dimensions of the robots 1 and 2 are not known at this stage, because they have not been chosen yet. Although the exact dimensions are not known, the room that is needed for them to operate has been estimated;
- e) Next to the cart is also the cart's buffer area. The correct cart would be taken from there by the assembler;
- f) The green box that is around the frame assembly's bottom plate and cart is the area where the lifting device would move at;
- g) Lastly, the orange line that is between the frame assembly's bottom plate and cart is meant for the door.

3.7 Automated cabinet frame assembly working sequence

In sections 3.1 to 3.5, different parts of the automated robot assembly system were explained separately. One thing that was explained for the different robots and the lifting device was the assembly sequence of them and how they work, but those sequences were made separately for each robot and lifting device. In this section, those assembly sequences are combined. Some new smaller things are also added to the sequences, which were not added before, but were explained in the first draft layout in section 3.6. For example, the computer from which the assembly system gets to know what should be assembled. The automated cabinet frame assembly working sequence is described below:

- 1) The cabinet width needs to be chosen from the computer. When the width is chosen, the system knows what needs to be assembled and from which shelves to take the correct parts from;
- 2) The system checks that all of the robots, lifting device and the door are in their starting position. The system also checks that all of the necessary parts are available from the shelves. If something is wrong, the assembly sequence will not start;
- 3) Firstly, the frame's bottom side is assembled. The robots for moving the frame parts and assembling the screws work together to assemble everything in the correct sequence. For more information, see sub-section 3.1.3 for moving the frame parts around and sub-

- section 3.3.2 for assembly of the screws;
- 4) Secondly, the frame's top side is assembled. Besides the robots for moving the frame parts and assembling the screws working in collaboration, the lifting device is now also needed. The lifting device is needed to hold the top beams in place during the frame assembly. For more information, see sub-section 3.4.1 for holding the top beams;
 - 5) Thirdly, the left side pillars are assembled. During the pillars' assembly, the sensors, which are described in sub-section 3.1.2, are in use. If the sensors find out that a wrong part is on the shelf, then;
 - 5.1) That part is left on the shelf, but there will be an error shown on the computer with the exact location of the error;
 - 5.2) The assembly sequence will continue, and the robot will try to pick the same part from another location on the shelf;
 - 5.2.1) If the same error does not happen in the second location again, the assembly sequence continues as normally;
 - 5.2.2) If the same error happens again, for example 3 times in a row, then the assembly sequence will stop completely, because there are wrong parts added on the shelves, which need to be corrected. After the shelves are corrected, the sequence starts over from point 5.2;
 - 6) Fourthly, the right side pillars are assembled. The same sequence, that is described above in step 5, applies also to this step;
 - 7) When the frame assembly is finished, the system gets notified about it and checks if the cart has been placed in the correct place. Before the lifting device can start its second sequence, the cart is needed. The person who chooses the cabinet width from the computer, also needs to bring the cart on which the frame will be lifted to and place it in the correct spot. After the cart is placed, the person needs to notify the system that the cart is available. This step can be done during the frame assembly sequence;
 - 7.1) If there is no cart, the system will wait until the cart has been brought;
 - 7.2) If there is a cart, the sequence can continue;
 - 8) The door that is between the robot workstation area and the cart opens. In its starting position, the door is closed;
 - 9) After the door is opened, the completed frame is moved onto the cart. For more information about moving the completed frame, see sub-section 3.4.2;
 - 10) When the completed frame is moved onto the cart, the person that brought the cart now has to tell the system if the frame is placed on the cart. The person has to tell the system

- to make sure that the frame is placed correctly on the cart;
- 10.1) Before the system has gotten a command that the frame is placed on the cart, the grippers on the lifting device will not open;
 - 10.2) After a person gives a command to the system that the frame is placed on the cart, the grippers on the lifting device will open and the lifting device goes back to its starting position;
- 11) The door closes. Now the automated cabinet frame assembly sequence is finished and all of the robots and lifting devices within the system are back in their starting positions.

3.8 Cabinet summary

All the frame parts and screw types that are going to be needed in the automated cabinet frame assembly were listed. The grippers that are needed to move the parts had their first drafts designed and their working logic explained. A frame assembly's bottom plate and special shelves were also designed to make the new assembly system work smoother. Also, the assembly sequence of both robots and the lifting device were explained separately and together. And finally, a first draft layout for the automated cabinet frame assembly was made.

4. NEW DEVICES

There are several new devices needed for the new automated frame assembly system, for example:

- 1) Robots for moving the frame parts;
- 2) Gripping tool for the frame parts;
- 3) Robot for tightening the screws;
- 4) Screwdriver tool for the screws;
- 5) Lifting device for the completed frame and for holding the top frame section;
- 6) Sensors for the frame parts and new shelves;
- 7) Industrial controller to control all of the devices.

All the new devices are chosen in this chapter and they are chosen in the same order as they are described above.

There are two parameters that need to be researched before the robot for moving the frame parts around and tightening the screws can be chosen. These are:

- 1) Gripping range;
- 2) Weights:
 - 2.1) Weight of the gripper and frame parts that the robot needs to move around;
 - 2.2) Weight of the screwdriver that the robot needs to move around.

The necessary gripping range can be found out based on the automated cabinet frame assembly first draft layout, which is shown in section 3.7. The gripping ranges and necessary weights are calculated in the next sections. Also, the robots are chosen for this thesis from ABB's robots.

4.1 Robot for moving the frame parts

Pythagorean theorem is used to calculate the maximum gripping ranges. The formula is shown below.

$$c^2 = a^2 + b^2 \Rightarrow c = \sqrt{a^2 + b^2}, \quad (4.1)$$

where a – dimension, mm,

b – dimension, mm,

c – dimension, mm.

Because the theorem is used only for one surface, the theorem is used twice to find out the maximum gripping range, which will be dimension e in the calculations below. The first calculation is made based on the floor level and the second one is made based on the height of the frame.

The maximum gripping range on the floor level is shown on the figure 4.1 below, which is based on the figure 3.29 shown in section 3.6.

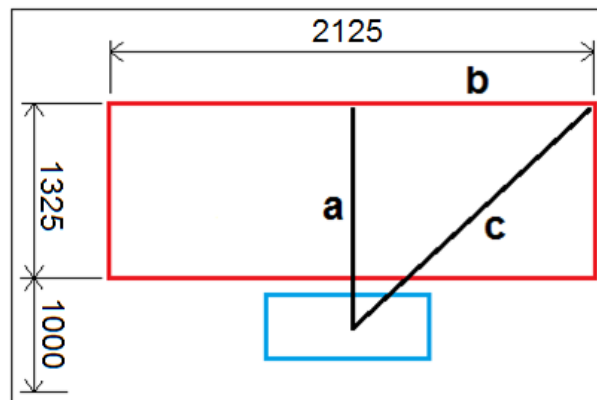


Figure 4.1 Gripping range for moving the frame parts around robot, floor level a, b and c - dimensions

The dimension c is calculated according to formula 4.1. Dimension 1000 mm is divided in half, because the point where dimension a starts from is in the middle of that dimension. The dimension 2125 mm is also divided in half, because the point where dimension b starts from is in the middle of that dimension.

$$c = \sqrt{\left(1,325 + \frac{1}{2}\right)^2 + \left(\frac{2,125}{2}\right)^2} = \sqrt{3,33 + 1,13} = \sqrt{4,46} = 2,11 \text{ m}$$

Now that dimension c is available, dimension e can be calculated. The maximum gripping range, also known as dimension e, for the height is shown on figure 4.2 below.

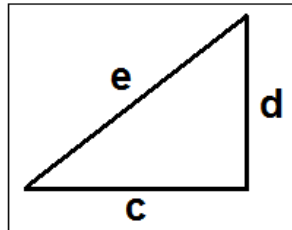


Figure 4.2 Gripping range for moving the frame parts around robot, height of shelf

c, d and e - dimensions

The dimension e is calculated according to formula 4.1. Although the formula is still the same, the symbols are changed. Dimension c = 2,11 m, which was calculated earlier and dimension d = 1,41 m, which is the maximum height of the shelf, from where the gripper could need to grab the parts from.

$$e = \sqrt{c^2 + d^2} = \sqrt{2,11^2 + 1,41^2} = \sqrt{4,45 + 2} = \sqrt{6,45} \approx 2,54 \text{ m}$$

Because there can be changes in the automated cabinet frame assembly layout, for example because the room needed for robot might actually be bigger, an additional 10 % is added for the maximum gripping range. So the final maximum gripping range for moving the frame parts around robot is $2,54 \times 1,1 = 2,79 \text{ m}$.

The actual grippers need to be chosen to know the weight of the grippers and frame parts that the robot needs to be able to move around. This is done in the next sub-section.

4.1.1 Gripper

In the section 3.2, the first draft of grippers was made. Based on the first drafts, the gripper's type will be a parallel-gripper. Based on the solution in sub-item 3.2.2, the same gripper version will be used for all the frame parts. Although the same gripper version will be used, there are still two

different grippers needed, because the grippers' hands need to be different. And because it is faster to change the grippers, rather than the gripper's hands, a quick-tool changing system for the grippers also needs to be chosen.

The gripper's choice is made based on the maximum weight of the frame parts. From the table 3.1 in item 3.1.1, the heaviest frame part weighs 5,26 kg.

Based on the information above, the gripper that is needed, is:

- a) A parallel gripper;
- b) Workpiece gripping surface width difference of the widest and narrowest part is 25 mm;
- c) With maximum workpiece weight of 5,26 kg.

Although there are a lot of different companies providing gripping systems, the gripper in this thesis is chosen from the Schunk company. There are 34 different types of parallel grippers, but only three of them, EGA, LEG and PGN-plus-P variants, were researched more thoroughly, because of the maximum workpiece weight. The other parallel grippers are too small [8].

The final gripper's choice is made from PNG-plus-P variant. Although the EGA and LEG variants' maximum workpiece weights are sufficient, the overall size of the EGA and LEG variants is bigger and heavier [9][10][11].

The PNG-plus-P variant also has seven different sizes available, which are PNG-plus-P 40, PNG-plus-P 50, PNG-plus-P 64, PNG-plus-P 80, PNG-plus-P 100, PNG-plus-P 125 and PNG-plus-P 200. Because the difference of the workpiece's gripping surface width of the widest and narrowest part is 25 mm, only the PNG-plus-P 125 and PNG-plus-P 200 versions are researched more thoroughly. The stroke per jaw for these versions is either 13 mm or 25 mm, while for the other versions, the stroke per jaw is less than 10 mm. [9]

The PNG-plus-P 125 and PNG-plus-P 200 versions also both have two different sizes available, which are the PNG-plus-P 125-1, PNG-plus-P 125-2, PNG-plus-P 200-1 and PNG-plus-P 200-2. Because the maximum weight of the workpiece is 5,26 kg, the PNG-plus-P 125-1 version is chosen, because the recommended workpiece weight for this version is 7 kg, which is enough. The other versions recommended workpiece weight is either 15 kg, 19 kg or 32,5 kg, but those are not needed. [9]

The PNG-plus-P 125-1 itself also has different versions. From those versions, the final gripper is chosen, which is PNG-plus-P 125-1. This version is chosen, because it is the most basic version of the PNG-plus-P 125-1 series. The chosen gripper is shown below on figure 4.3.



Figure 4.3 Schunk PNG-plus-P 125-1 [12]

Below is the table 4.1 which shows the most basic PNG-plus-P 125-1, PNG-plus-P 125-2, PNG-plus-P 200-1 and PNG-plus-P 200-2 versions with also the one chosen.

Table 4.1 Schunk PGN-plus-P parallel gripper versions [9]

Description of PNG-plus-P parallel gripper	Stroke per jaw, mm	Recommended workpiece weight, kg	Weight of gripper, kg	Length X, mm	Width Y, mm	Height Z, mm
PNG-plus-P 125-1	13	7	1,4	151	60	69,5
PNG-plus-P 125-2	6	15	1,4	151	60	69,5
PNG-plus-P 200-1	25	19	5,4	234	100	99,5
PNG-plus-P 200-2	14	32,5	5,4	234	100	99,5

The final gripper, which is chosen, is the PNG-plus-P 125-1 parallel gripper and the weight of it is 1,4 kg. To find out the maximum weight of the gripper and frame part that the robot needs to be able to move around, a quick tool changing system needs to be chosen.

4.1.2 Quick tool changing system

A quick-tool changing system for the grippers needs to be chosen. The quick-tool changing system's choice is made based on the gripper chosen in sub-section 4.1.1, which is the PGN+P 125-1 gripper. And as with the gripper, the quick-tool changing system is also chosen from the Schunk company.

Based on the gripper chosen in sub-section 4.1.1, the quick-tool changing system that is chosen, is SWK-160-000-000-SM as the head on robot side and SWA-160-000-000 as the adapter on tool side. Because there are two grippers in the system, two adapters on the tool's side are needed. This quick-tool changing system is chosen, because it was recommended by Schunk and the parameters are sufficient for the automated cabinet frame assembly system, for example the handling weight of 300 kg and nine pieces of air connection thread pneumatic feed-throughs. Below on figures 4.4 and 4.5 is shown how the quick-tool changing system that is chosen looks like and its technical data [13].



Figure 4.4 Schunk SWS 160 [13]

Technical data

Description		SWK-160-000-000-SM	SWA-160-000-000
		Quick-change head	Quick-change adapter
ID		0302440	0302441
Recommended handling weight	[kg]	300	300
Piston stroke monitoring		integrated	
Locking force	[N]	31000	31000
Repeat accuracy	[mm]	0.015	0.015
Weight	[kg]	6.44	2.86
Max. distance when locking	[mm]	2.54	2.54
Air connection thread pneumatic feed-through		5x G3/8"	5x G3/8"
Air connection thread pneumatic feed-through		4x G1/2"	4x G1/2"
Lock/unlock main connection		G1/8"	
Max. permissible XY-axis offset	[mm]	±2	±2
Max. permissible angular offset	[°]	±1	±1
Robot-side connection		ISO 9409-1-125-10-M10	ISO 9409-1-125-10-M10
Min./max. ambient temperature	[°C]	5/60	5/60
Min./max. operating pressure	[bar]	4.5/6.9	4.5/6.9
Dimensions Ø D x Z	[mm]	217 x 55.5	217 x 37.6

Figure 4.5 SWS 160 technical data [14]

The weight of SWK-160-000-000-SM is 6,44 kg and the weight of SWA-160-000-000 is 2,86 kg. In total the quick-tool changing system weight is 9,3 kg, which is needed for choosing the final robot.

The maximum weight that is applied to the robot head can now also be calculated. The maximum weight is necessary to know for choosing the robot. So the weights are:

- a) Maximum frame part weight is 5,26 kg, which is taken from table 3.1 in sub-section 3.1.1;
- b) Gripper weight without the gripping heads is 1,4 kg;
- c) Quick-tool changing system weight is 9,3 kg.

In total the maximum weight that is applied to the robot head is 15,96 kg. The overall weight is doubled, because there are different wires, hoses and gripper heads also attached. The final weight for the robot chosen is $15,96 \times 2 = 31,92$ kg.

4.1.3 Final choice of the robot for moving the frame parts

The robot for moving the frame parts around can now be chosen, because the necessary parameters are known. The maximum weight of the robot head is 31,92 kg and the maximum gripping range is 2,79 m. Although there are a lot of different robots available, there is a search engine on ABB's site which helps to choose the correct robot [15]. From the search engine, the option of parameter "reach" was chosen and set to „over 2.55 (m)“. The payload option wasn't chosen, because all of the robots, which are within the necessary gripping range, have the payload much higher than needed anyway. From the search, robots IRB 660 and IRB 6700 are

chosen for more research. Although there are other robots with enough reach as well, they aren't researched more thoroughly for different reasons, for example being designed for other purposes than needed.

Robots IRB 660 and IRB 6700 robot bases are compared. The table 4.2 for comparing robots IRB 660 and IRB 6700 base dimensions is below [16][17].

Table 4.2 Robot IRB 660 and IRB 6700 base dimensions

Robot name	Robot base dimensions, mm
IRB 660	1136 x 850
IRB 6700	1004 x 720

Based on the robot's base dimension, the IRB 6700 series is chosen, because the robot base is smaller. The IRB 6700 robot also has different versions with for example different reaches and weights. Different versions and their weights are shown on figure 4.6 below.

IRB 6700-200/2.60	1250 kg
IRB 6700-155/2.85	1260 kg
IRB 6700-235/2.65	1205 kg
IRB 6700-205/2.80	1270 kg
IRB 6700-175/3.05	1220 kg
IRB 6700-150/3.20	1280 kg
IRB 6700-300/2.70	1525 kg
IRB 6700-245/3.00	1540 kg
IRB 6700 Inv-300/2.60	1690 kg
IRB 6700 Inv-245/2.90	1705 kg

Figure 4.6 IRB 6700 versions with their weights [18]

From the different robot versions, the final robot version chosen is IRB 6700-205/2.80, which is also shown on figure 4.7 below with its working range. This robot version is chosen for one reason:

- 1) If a larger version is chosen, then the free space area needed for the robot to move around, gets bigger. The free space is needed on the back side of the robot and it is marked on figure 4.7 below with a red box.

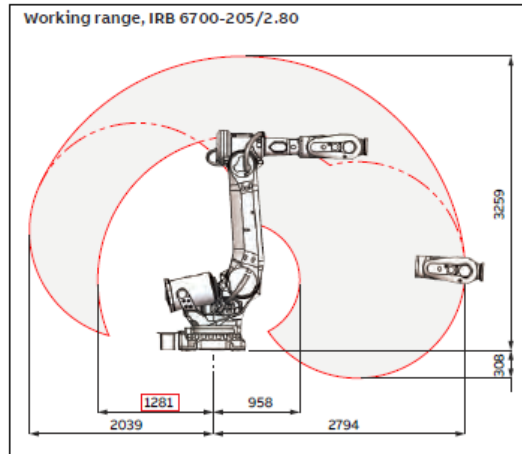


Figure 4.7 IRB 6700-205/2.80 working range [18]

4.2 Robot for tightening the screws

Pythagorean theorem is used to calculate the maximum gripping ranges. Because the theorem is used only for one surface, the theorem is used twice to find out the maximum gripping range, which will be dimension e in the calculations below. The first calculation is made based on the floor level and the second one is made based on the height of the frame.

The maximum gripping range on the floor level is shown on the figure 4.8 below, which is based on the figure 3.29 shown in section 3.6.

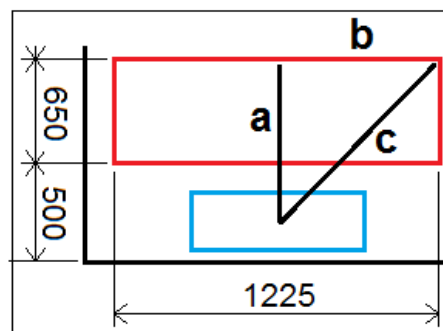


Figure 4.8 Gripping range for tighttening the screws robot, floor level

a, b and c - dimensions

The dimension c is calculated according to formula 4.1. Also, the dimension 500 mm is divided in half, because the point where dimension a starts from is in the middle of that dimension. The dimension 1225 mm is also divided in half, because the point where dimension b starts from is in the middle of that dimension.

$$c = \sqrt{a^2 + b^2} = \sqrt{\left(0,65 + \frac{0,5}{2}\right)^2 + \left(\frac{1,225}{2}\right)^2} = \sqrt{0,81 + 0,37} = \sqrt{1,18} \approx 1,09 \text{ m}$$

Now that dimension c is available, dimension e can be calculated. The maximum gripping range, also known as dimension e, for the height is shown on figure 4.9 below.

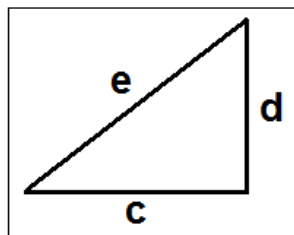


Figure 4.9 Gripping range for tightening the screws robot, height of frame

c, d and e - dimensions

The dimension e is calculated according to formula 4.1. Although the formula is still the same, the symbols are changed. Dimension c = 1,09 m, which was calculated earlier and dimension d = 2 m, which is the maximum height of the frame, where the screwdriver could need to reach to.

$$e = \sqrt{c^2 + d^2} = \sqrt{1,1^2 + 2^2} = \sqrt{1,21 + 4} = \sqrt{5,21} \approx 2,28 \text{ m}$$

The maximum gripping range for tightening the screws robot is now known, which is 2,28 m.

Because there can be changes in the automated cabinet frame assembly layout, for example because the room needed for the robot might actually be bigger, an additional 10 % is added for the maximum gripping range. So the final maximum gripping range for tightening the screws robot is $2,28 \times 1,1 = 2,51 \text{ m}$.

To know the weight of the screwdriver that the robot needs to move around, the actual screwdriver needs to be chosen, which is done in the next sub-section.

4.2.1 Screwdriver function module

Although there are a lot of different companies that offer screwdriving technologies, the screwdriver in this thesis is chosen from the Deprag company. There are a lot of different screwdriving technologies available, but for automation purposes, there is a special product named screwdriver function module [19]. This module is chosen, because it is easily assembled onto the robot and it fulfills all the necessary parameters that need to be covered, which are:

- a) Maximum tightening torque of 5 Nm;
- b) Two different screws can be fed to the screwdriver head.

There are different stroke variants available for this module. For this thesis, the version which is meant for robotic applications with automatic screwfeeding through a feedhose is chosen. On the figure 4.10 below, the screwdriving base and operating positions are shown.

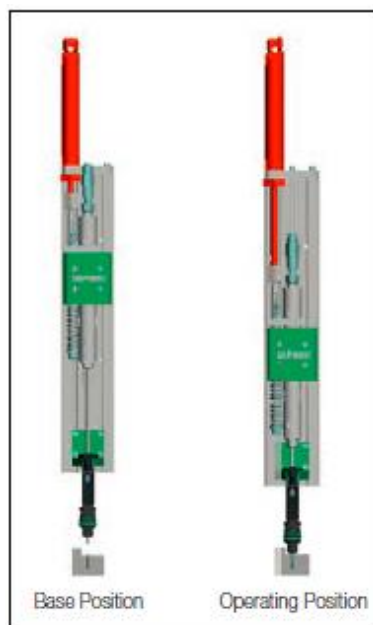


Figure 4.10 Screwdriving base and operating positions [20]

There are six different standard modular designs available. From those six, the second version, which is for limited space access, is chosen. It is chosen, because the space available within the automation area is small. The different designs are shown on figure 4.11 below.

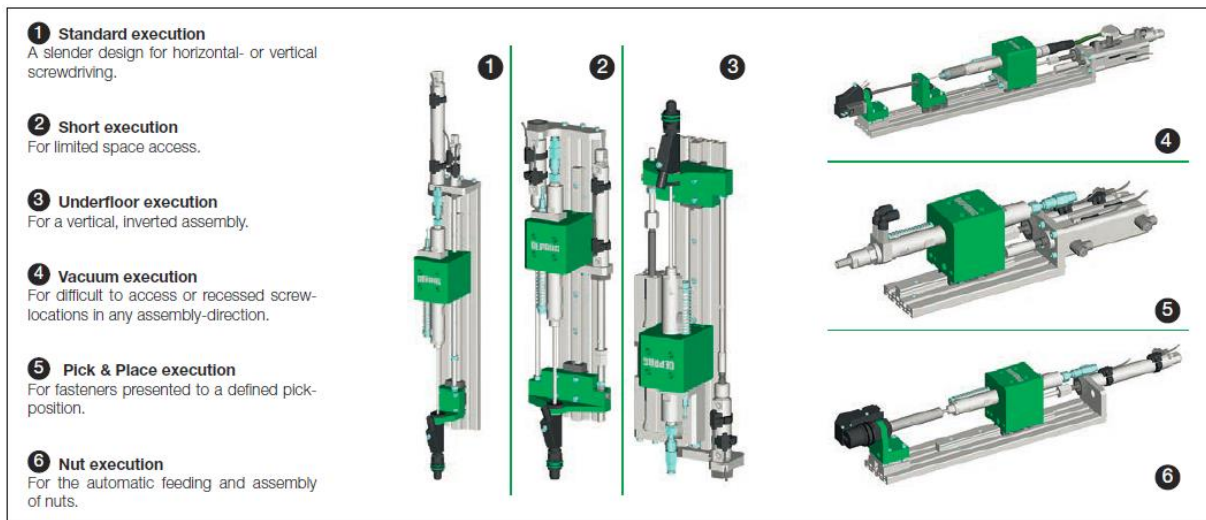


Figure 4.11 Different standard modular designs [20]

Finally, there are three different module sizes, named execution SFM-L, execution SFM-N and execution SFM-S. The main differences are shown in the table 4.3 below and the specifications are taken from the technical data [20].

Table 4.3 Execution SFM main differences [20]

Screwdriver types	Torque range, Nm	Screw head diameter, mm
SFM-L	0,008 – 0,8	Up to 10
SFM-N	0,06 - 20	Up to 14
SFM-S	Depends on application	Up to 10

The final screwdriver function module, that is chosen, is the SFM-N type. It is chosen, because the 5 Nm torque, that is necessary, is within the range of this screwdriver types torque. The technical data of the SFM-N type is shown on the figure 4.12 below.

Screwdriver Function Module SFM-N - Single-Spindle Execution			
		Without Feeding	With Feeding
Max. screw head-Ø	mm / in.	no limit	14 / 0.55
Max. number of screwdriver spindles		1	1
Torque	Nm / in.lbs	0.06 - 20 / 0.53 - 177	0.06 - 20 / 0.53 - 177
Mouthpiece stroke	mm / in.	-	25, 80 / 0.98, 3.1
Spindle stroke	mm / in.	50, 100 / 1.95, 3.9	depends on mouthpiece stroke
Stroke vacuum finder (only with vacuum execution)	mm / in.	-	50, 100 / 1.95, 3.9
Stroke socket (only with nut execution)	mm / in.	-	50, 100 / 1.95, 3.9
Split-jaw nosepiece / ball-type nosepiece length	mm / in.	-	40, 80 / 1.56, 3.1
Operating modes		pneumatic electric	pneumatic electric
Possible stroke variants		A / B	C / D / E
Distance from mounting surface to screw axis (a)	mm / in.	94 / 3.67	94 / 3.67
Weight	kg / lbs.	5 / 11	8 / 17.6

Figure 4.12 Technical data of SFM-N type [20]

Because the module needs to have the feeding system attached as well, the weight of the SFM-N type is 8 kg. The overall screwdriver weight is doubled, because there are actually different wires and hoses also attached. The final screwdriver weight for the robot chosen is $8 \times 2 = 16$ kg.

4.2.2 Final choice of the robot for tightening the screws

The robot for the screwdriver can now be chosen, because the necessary parameters are known. The weight of the screwdriver is 16 kg and the maximum gripping range is 2,51 m. The same search engine is used again as was used in item 4.1.3. From the search engine, the option for parameter “reach” was chosen and set to „1.8 – 2.55 (m)“. The payload option was again not chosen. From the search, robots IRB 460 and IRB 4600 are chosen for more research. Although there are other robots with enough reach as well, they aren’t researched more thoroughly because for example they have been designed for other purposes.

Robots IRB 460 and IRB 4600 robot bases are compared. The table 4.4 for comparing robots IRB 460 and IRB 4600 base dimensions is below [21][22].

Table 4.4 Robot IRB 460 and IRB 4600 base dimensions [21][22]

Robot name	Robot base dimensions, mm
IRB 460	1007 x 720
IRB 4600	512 x 676

Based on the robots’ base dimension, the IRB 4600 series is chosen, because the robot’s base is smaller.

Robot IRB 4600 also has different versions with for example different reaches and weights. Different versions with their reach, payload and armload are shown on figure 4.13 below.

Robot version	Reach (m)	Payload (kg)	Armload (kg)
IRB 4600-60/2.05	2.05	60	20
IRB 4600-45/2.05	2.05	45	20
IRB 4600-40/2.55	2.55	40	20
IRB 4600-20/2.50	2.51	20	11

Figure 4.13 IRB 4600 versions with their reach, payload and armload [23]

From the different robot versions, the final robot version chosen is IRB 4600-40/2.55. This robot version is chosen, because the reach and armload are sufficient. Below is the IRB 4600-40/2.55 working range, on figure 4.14.

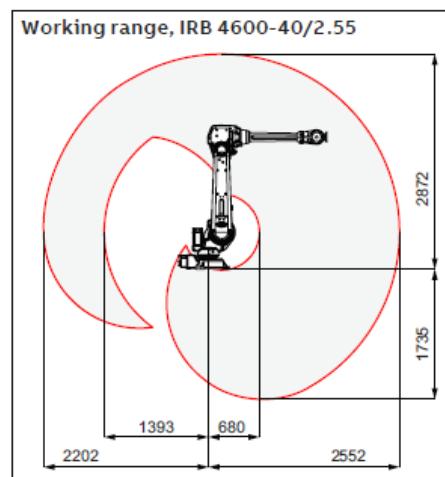


Figure 4.14 IRB 4600-40/2.55 working range [23]

4.3 Lifting device

For the lifting device, grippers are also needed. The gripper chosen is PNG-plus-P 200-2. This gripper is chosen, because although the maximum workpiece weight can be up to 40,65 kg with the 1200 mm wide frame, the recommended workpiece weight of the grippers should actually be divided between two grippers. And in this case, the chosen gripper would withstand the

maximum weight. Also, the same gripper type is chosen for moving the frame parts as well, chosen in sub-section 4.1.1. The PNG-plus-P 200-2 gripper is shown on figure 4.15 and also the main parameters are shown below [24]:

- a) Stroke per jaw – 14 mm;
- b) Recommended workpiece weight – 32,5 kg;
- c) Weight of gripper – 5,4 kg;
- d) Length – 234 mm;
- e) Width – 100 mm;
- f) Height – 99,5 mm.



Figure 4.15 Schunk PNG-plus-P 200-2 [24]

Because there are two grippers needed, the maximum weight that the lifting device has to withstand is $5,4 \times 2 + 40,65 = 51,45$ kg.

Because only the gripper's hands will move and either hold the top beams or not, the gripper itself can always be in the same position. This means that the lifting device only needs to move in two directions, which will be named X and Z axis. X axis is the movement direction between the frame assembly bottom plate and the cart. Z axis is the movement when the completed frame will be either lifted up or lowered. Now that the movement's directions are explained and the maximum weight to be lifted is known, the parameters that the lifting device has to fulfil are listed. The X axis movement dimension is taken from sub-section 3.6 figure X and the Z axis movement dimension is taken from sub-section 3.4.2 assembly sequence:

- 1) Maximum weight – 51,45 kg;
- 2) X axis movement – 2000 mm;
- 3) Z axis movement – 10 mm.

The X axis dimension is 2000 mm, because when doing the first draft layout in section 3.6, the room needed for the robot to move the frame parts around was not considered sufficiently. Therefore, the distance between the frame assembly's bottom plate and the cart must be bigger than shown on figure 3.29 in section 3.6.

The lifting device in this thesis is searched for from Deprag and Festo companies, because both of them have standard lifting solutions that could work for this thesis [25][26]. Unfortunately, the final lifting device is not chosen in this thesis, because there isn't one available as a standard application right now. Therefore, a customized system needs to be done that fulfils the parameters shown above. For example, the movement could be accomplished with a Deprag LPE line gantry system, but the recommended maximum workpiece weight is only 20 kg [27]. Although the final lifting device is not chosen, the lifting device itself would look like shown on figure 4.16 below.



Figure 4.16 Schunk 2D linear gantry [28]

4.4 Sensors

Although there are lots of sensors needed, there are only two different locations where the sensors are needed. One location is on the side beam and pillar grippers, which are needed to detect if either there are holes on frame parts or not. The other location is on the shelves, which

are needed to detect if either there are frame parts on the shelves or not. All of the sensors needed in this thesis are inductive proximity sensors.

A proximity sensor detects using light, sound and electromagnetic fields the absence or presence of an object. If the configuration of the sensor is normally open, the output is an „on“ signal when a object enters the sensing zone. The configuration can also be normally closed, which means that the output is an „off“ signal with the object present. The output itself is read by an external control unit, for example a motion controller [29].

For the grippers, the inductive proximity sensor chosen for this thesis is PY3-AN-1A. Its sensing range is 0,6 mm and the output state is normally open. Because the sensors are on the gripper’s hand, which goes in contact with the frame parts, the sensor must be protected from mechanical damage. The sensor chosen is shown on figure 4.17 below [30].



Figure 4.17 PY3-AN-1A inductive proximity sensor [31]

For the shelves, the inductive proximity sensor chosen for this thesis is DW-AD-501-04. Its sensing range is 2,5 mm and the output state is normally open. The sensor chosen is shown on figure 4.18 below [32].



Figure 4.18 DW-AD-501-04 inductive proximity sensor [33]

4.5 Industrial controller

An industrial controller is needed to control all of the devices chosen in paragraph 4. But a separate controller does not have to be chosen, because the ABB robots chosen in sections 4.1 and 4.2 already include industrial robot controllers, which are named IRC5. More specifically, they are named single cabinet controllers and are shown on figure 4.19 below [34].



Figure 4.19 IRC5 Single cabinet controller [35]

And besides using this controller for the robots movement, other devices can also be connected with the same controller. So for the new automated frame assembly system, only one controller is needed.

4.6 New devices layout in RobotStudio

Now that all of the new devices have been chosen, the new layout can be made. The new layout is made with RobotStudio program and is shown on figure 4.20 below. The new layout is also shown from another angle in appendix 8 and the overall dimensions of the new system are shown in appendix 9.

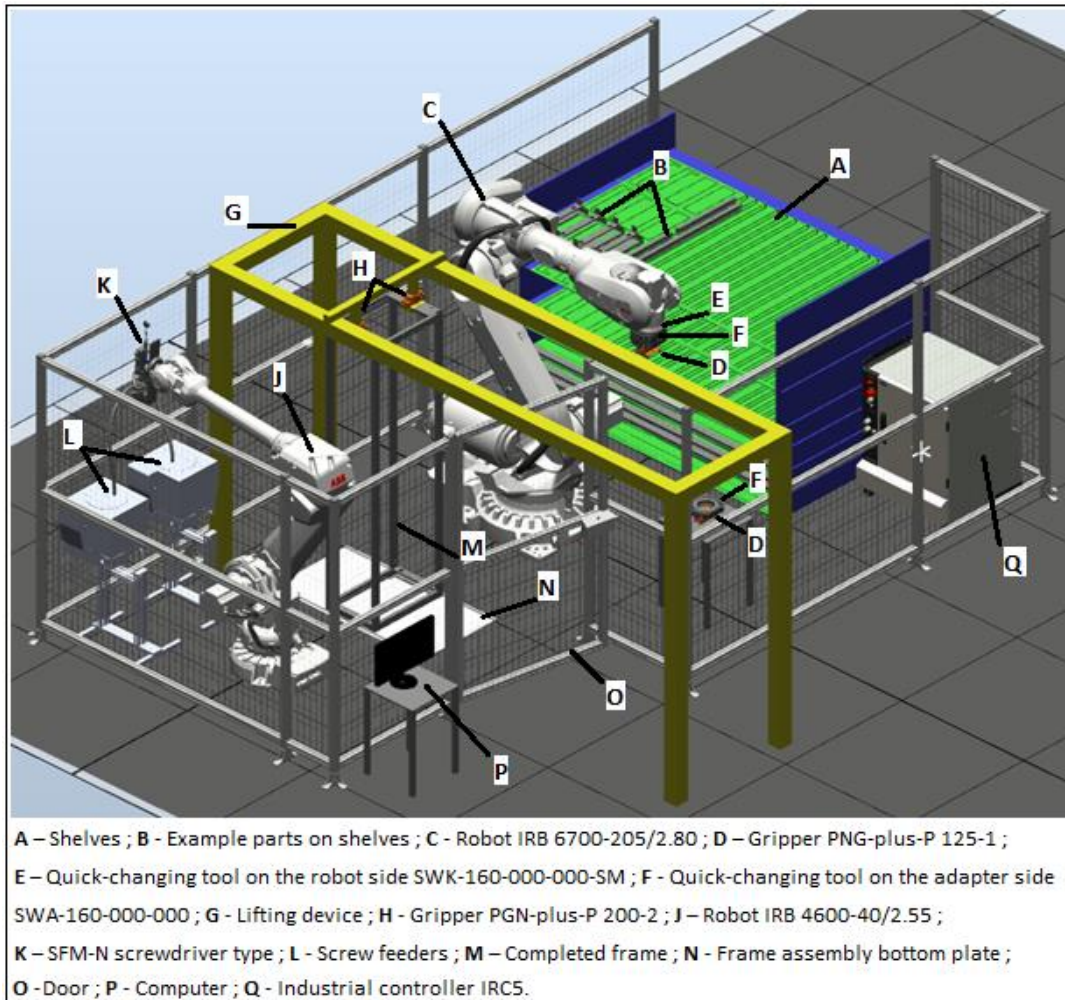


Figure 4.20 Automated cabinet frame assembly workstation layout

4.7 New devices summary

All of the new devices that were chosen for the new automated frame assembly system are shown below:

- 1) Robot for moving the frame parts - IRB 6700-205/2.80;
- 2) Gripping tool for the frame parts;
 - 2.1) Gripper - PNG-plus-P 125-1;
 - 2.2) Quick-changing tool system - SWK-160-000-000-SM as the head on robot side and SWA-160-000-000 as the adapter on tool side;
- 3) Robot for tightening the screws - IRB 4600-40/2.55;

- 4) Screwdriver tool for the screws - SFM-N screwdriver type;
- 5) Lifting device – not chosen;
- 6) Gripper for lifting device - PNG-plus-P 200-2;
- 7) Sensors:
 - 7.1) For the grippers - PY3-AN-1A;
 - 7.2) For the shelves - DW-AD-501-04;
- 8) Industrial controller - IRC5 Single cabinet controller.

5. CURRENT HAND-MADE ASSEMBLY VS AUTOMATED ROBOT CELL ASSEMBLY

The current hand-made and automated robot cell assembly times are compared in this chapter to find out if and how much faster the new assembly times are. Also, the return of investment is calculated to find out how long it would take for the new system to pay back.

5.1 Assembly times

To compare the current hand-made assembly times versus the new automated robot cell assembly times, some research is needed. First, the current hand-made assembly times must be found out. Secondly, the automated robot cell assembly times are needed, which are going to be hypothetical, because accurate assembly times for the new system cannot be known at this point.

5.1.1 Current hand-made assembly times

A camera was used in the factory to record actual and accurate assembly times for the frame sub-assembly. Different frame sizes and assemblers were used over the course of 5 measurings that were made for the current frame assembly times. In the table 5.1 below is a list of the most important and different steps that the assemblers did, how many times those steps were made during the assembly time, the average time it took them to do those steps and the total frame assembly time. Also, because most of the videos had some glitches during the recording, some estimated additional time is added for the total frame assembly time. The estimated time added is made based on the other recording.

Table 5.1 Current hand-made assembly times

Description of steps that the assemblers did	Amount of different times this step was made	Average total time min:sec
Picking frame parts from trolley	8	01:53
Taking the screwdriver	6	00:24
Taking screws from shelves	6	00:36
Assembling frame parts	12	09:47
Non-value adding steps	Depends on assembler	03:03
IP plug assembly to pillars	4	1:28
Total frame assembly time		17:11
Total frame assembly time without IP plugs		15:43

There are different steps that are summarized under the non-value adding steps and a list of them is below:

- a) Reading and re-checking the manuals more than once;
- b) Checking something from the computer;
- c) Finding the correct tool size for the screwdriver;
- d) Taking more screws during the assembly, because the assembler didn't take enough before;
- e) Moving the frame around.

5.1.2 Hypothetical automated robot cell assembly times

The hypothetical automated robot cell assembly times are estimated based on the assembly videos. The list of steps and the estimated time they take are listed below:

- a) Robot for moving the frame parts around:
 - a.1) Moving from shelves to frame assembly bottom plate or the other way - 6 seconds;
 - a.2) Moving the gripper head closer to the frame parts or the other way – 0,5 seconds;
 - a.3) Moving to the quick-tool changing system location or the other way – 3 seconds.
- b) Grippers for frame parts:
 - b.1) First gripper's head going closer to frame part – 1 second;
 - b.2) Second gripper's head going closer to frame part – 1 second;
 - b.3) Sensors on second gripper's head checking for holes if necessary – 1 second;
 - b.4) Both grippers' heads moving away from frame part at the same time – 1 second.
- c) Lifting device:
 - c.1) Moving higher or lower – 2 seconds;
 - c.2) Moving from frame assembly bottom plate to cart location or the other way –

- 6 seconds.
- d) Screwdriver:
 - d.1) Assembling and tightening the screws – 3 seconds.
- e) Quick-tool changing system:
 - e.1) Changing the grippers – 5 seconds.

In table 5.2 below are shown the total assembly times of different sections and the overall whole automated robot cell assembly sequence assembly time. For the overall whole automated robot cell assembly sequence, it is assumed that there are no stops in the sequence, which means that the cart must be placed in the correct place before the system checks if the cart has been placed.

Table 5.2 Hypothetical automated robot cell assembly times

Frame sections	Assembly time min:sec
Frame bottom side	1:14
Frame top side	1:42
Frame left side	1:14
Frame right side	1:14
Whole frame	5:24
Overall whole automated robot cell assembly sequence	5:44

5.1.3 Assembly time comparisons

In conclusion, the current assembly time is 15 minutes and 43 seconds and the estimated automated robot cell assembly time is 5 minutes 44 seconds. This means that the newer system would be 9 minutes and 59 seconds faster, which is about 63,5 % faster than the current assembly time.

5.2 Return on Investment

Return on investment is necessary to know if the automated cabinet frame assembly solution, which is currently chosen and made in this thesis, is beneficial for ABB. And for that, the time in which the investment would pay back must be calculated. The formula for the calculation is shown below.

$$A = \frac{\text{capital expenses}}{(\text{annual profit} - \text{annual costs})}, \quad (5.1)$$

where A – payback time, year,

- capital expenses – total sum of expenses, €,
- annual profit – assembly savings, € per year,
- annual costs – maintenance costs, € per year.

Capital expenses consists of the overall cost for the new system development. The new system itself consists of the price of the new devices chosen in this thesis and some other costs which are not exactly known, for example the programming cost of the new system. Because the other costs are not known at this point, they are estimated based on other workstations where robots within ABB are used. Based on the estimations, the other costs are 200 000 €. The new devices with the prices for the new system are listed below:

- 1) Robot IRB 6700-205/2.80 – 40 000 €;
- 2) Grippers PNG-plus-P 125-1 and PNG-plus-P 200 – 750 € each;
- 3) Quick-changing tool system SWK-160-000-000-SM and SWA-160-000-000 – 6200 €;
- 4) Robot IRB 4600-40/2.55 – 25 000 €;
- 5) SFM-N screwdriver tool type – 50 000 €;
- 6) Lifting device was not chosen, but the price is estimated to be 45 000 €;
- 7) Sensors:
 - 7.1) PY3-AN-1A – 73 € each;
 - 7.2) DW-AD-501-04 – 87 € each;
- 8) IRC5 Single cabinet controller – 0 € (included in the robot price).

In total all of the new devices cost 180 000 € and the total sum of capital expenses is 380 000 €.

Annual profit consists of the assembly savings. Because the frame assembly is now done 9 minutes and 59 seconds faster, the assembly savings per year are 11 707 €.

Annual costs are the new maintenance costs per year. Because the maintenance costs are not known at this point, they are estimated based on other workstations where robots within ABB are used. Based on the estimations, the maintenance costs per year are 1000 €.

The payback time can now be calculated according to formula 5.1.

$$A = \frac{380000}{11707 - 1000} \approx 35,5 \text{ years}$$

The payback time with the new system which has been chosen within this thesis is 35,5 years, which is a very long time. If we presume that the amounts of cabinets assembled in Estonian factory will be higher in the future (for example cabinets currently built in Finland would be also built in here), then the payback time would also be lower. The new system could become profitable if amounts of cabinets assembled would be higher, the capital expenses could be lowered, or some other assemblies could be assembled with the same system. For example, if some additional sub-assemblies could be assembled with the same setup and the assembly is finished 1 hour faster, the payback time would be about 5,9 years. There are of course other things that are also better with the new system (for example safety), but those cannot be put into numbers. With the new system, assemblers would not have to lift the heavy completed frames onto the carts like they have to right now.

SUMMARY

The subject of this thesis was automation study of the cabinet frame assembly for ABB AS. The subject was chosen, because the cabinet assembly automation had not been studied very much earlier and because these cabinets are assembled in Estonian factory. And also, because the amount of cabinets assembled in Estonian factory is likely to rise in the near future.

In this thesis, only the cabinet frame assembly was studied more thoroughly, because the cabinet assembly in whole is very big and complex. In the beginning, other sub-assemblies were studied as well, and they are listed in section 2.3 with the frame sub-assembly. The frame sub-assembly was chosen for more thorough research for different reasons, but two of them were that frames are always needed for every cabinet and they have the least variables during assembly.

In the first chapter, the portfolio in which the cabinets studied in this thesis are offered at is explained more thoroughly. The cabinets are part of the ACS880 single drives portfolio, which itself is part of the Industrial drives' portfolio. This portfolio is part of the Low voltage AC portfolio, which itself is part of the Drives portfolio. This in turn is part of the Motion business, which lastly is one of the five main businesses that are in ABB globally.

In the second chapter the cabinets in overall were explained. In more detail, the different cabinet versions and sizes were listed with the overall amount of cabinets that were produced in Estonian factory in 2018 and how big percentage of those cabinets were single cabinets. Also, the different sub-assemblies which were studied are listed with the final frame sub-assembly.

In the third chapter, the frame sub-assembly was studied more thoroughly. All of the different frame parts that were needed for this thesis were listed and first drafts of the grippers for these parts were made. Also, the new devices which should be needed were listed. In the end, there should be one robot to move around the frame parts, one robot to assemble the screws, a lifting device to move the completed frame and some smaller things, for example grippers and sensors. Also, the assembly sequence for the new automated system was made for each new device which

would be needed in the new automated system and a first draft of the new workstation layout was made.

In the fourth chapter, the new necessary devices were researched. To move the frame parts around, the IRB 6700-205/2.80 robot was chosen, together with two different grippers of PGN-plus-P 125-1 and a quick-changing tool system for these grippers, which is SWK-160-000-000-SM as the head on robot's side and SWA-160-000-000 as the adapter on robot's side. To assemble the screws, the IRB 4600-40/2.55 robot was chosen, together with a SFM-N screwdriver type. The final lifting device was not chosen, because there was not a standard solution available, a special solution should be ordered. But for the lifting device, the gripper was chosen, which is PGN-plus-P 200-2. The sensors were chosen as well, which for the grippers is PY3-AN-1A and for the shelves is DW-AD-501-04. Finally, the industrial controller for the new system is IRC5 single cabinet controller, which is included with the robots chosen.

In the fifth chapter, the current and hypothetical new assembly times were compared and also the return of investment calculation was made. The new hypothetical assembly would be 63,5 % faster than the current assembly, but the payback time of the new system would be 35,5 years.

SUMMARY IN ESTONIAN

Lõputöö teema oli kabineti raami automatiseeritult koostamise uuring ettevõttele ABB AS. See teema sai valitud, kuna kabineti automatiseeritult koostamist ei olnud varem väga palju uuritud ja kuna neid kabinette koostatakse Eesti tehases. Ja lisaks, kuna Eestis tehases koostatud kabinettide hulk suureneb arvatavasti lähiajal.

Selles lõputöös uuriti kabineti raami koostamist põhjalikumalt, kuna kabineti koostamine üldiselt on väga mahukas ja keeruline. Alguses uuriti ka teisi alam-kooste ning need on loetletud alapeatükis 2.3 koos raami alamkoostuga. Raami alakoost sai valitud põhjalikumaks uurimiseks mitmel põhjusel, kuid kaks nendest olid, et raame on alati vaja iga kabineti jaoks ning neil on koostamise ajal kõige vähem variatsioone.

Esimeses peatükis on seletatud täpsemalt, millises tootegrupis uuritavad kabinetid asuvad. Kabinetid on osa *ACS880 single drives* tootegrupist, mis omakorda on osa *Industrial drives'* tootegrupist. See tootegrupp on osa *Low voltage AC* tootegrupist, mis omakorda on osa *Drives* tootegrupist. See omakorda on osa *Motion*-i ärist, mis on üks osa viiest ABB põhilisest ärist globaalselt.

Teises peatükis on kabinette üldisemalt kirjeldatud. Erinevad kabineti versioonid ja nende suurused on nimetatud koos kõigi Eesti tehases 2018 aastal toodetud kabinettide arvuga ning välja on toodud, kui suur protsent nendest kõikidest kabinettidest olid üksikud kabinetid. Kõik erinevad uuritud alamkoostud on loetletud koos raami alamkoostuga.

Kolmandas peatükis uuriti raami alamkoostu täpsemalt. Kõik erinevad raami detailid, mis olid vajalikud selle lõputöö jaoks, on loetletud selles peatükis. Samuti on loetletud esimesed näidised haaratsitest, mis on nende detailide jaoks vajalikud. Lisaks sai nimetatud ka kõik uued seadmed, mida võib vaja minna. Töö raames uuritud kabineti koostamiseks on vaja ühte robotit, mis liigutab raami detaile ringi; ühte robotit, mis paigutab kruvisi; tõsteseadet, et liigutada valmis raami ja muid väiksemaid asju, näiteks haaratseid ja andureid. Lisaks valmis ka uue süsteemi koostamise järjekord iga seadme jaoks eraldi ning esimene näidis uuest töökoha asetusest.

Neljandas peatükis uuriti uusi vajalikke seadmeid. Raami detailide liigutamiseks valiti IRB 6700-205/2.80 robot, koos kahe haaratsiga PGN-plus-P 125-1 ja kiirvahetus lahenduse süsteem nende haaratsite jaoks, milleks on SWK-160-000-000-SM ja SWA-160-000-000. Kruvide keeramiseks valiti IRB 4600-40/2.55 robot koos SFM-N kruvikeeramise tüübi lahendusega. Viimast tösteseadet ei valitud, kuna standardset lahendust ei ole olemas, vaid see tuleb eraldi tellida. Kuid tösteseadme jaoks valiti haarats, milleks on PGN-plus-P 200-2. Lisaks valiti ka andurid, millest PY3-AN-1A on haaratsite jaoks ja DW-AD-501-04 on riiulite jaoks. Viimasena valiti tööstuslik kontrolleri uue süsteemi jaoks, milleks on IRC5 üksiku kabineti kontrolleri, mis on olemas koos valitud robotitega.

Viiendas peatükis võrreldi hetke koostamise aega ja oletatavat uut aega. Lisaks tehti investeeringu tasuvusarvutused. Uus oletatav koostamise aeg oleks 63,5 % kiirem hetkeajast, kuid uus süsteem tasuks ennast ära alles 35,5 aasta pärast.

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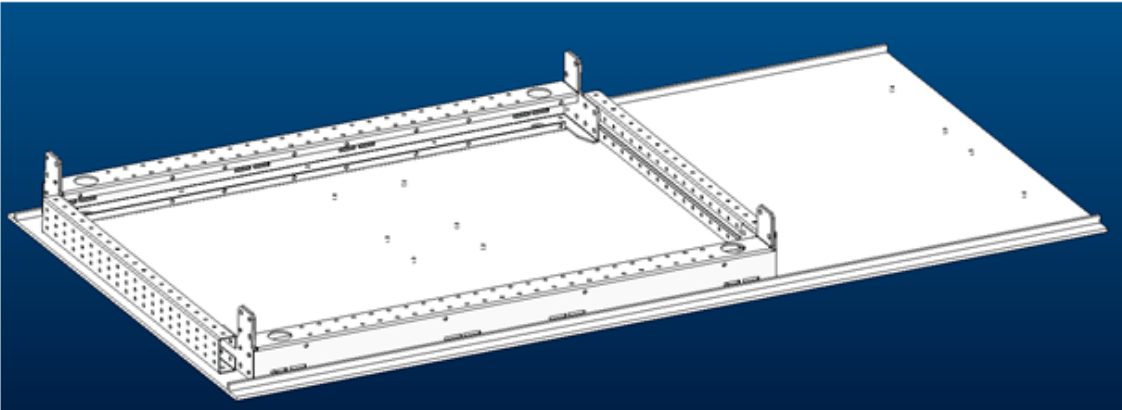
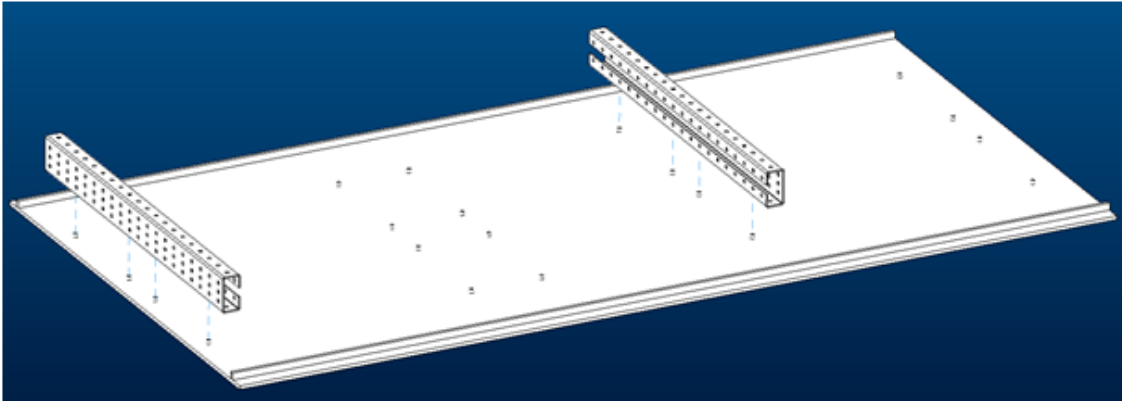
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APPENDICES:

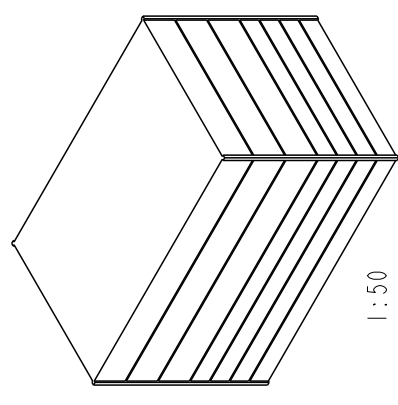
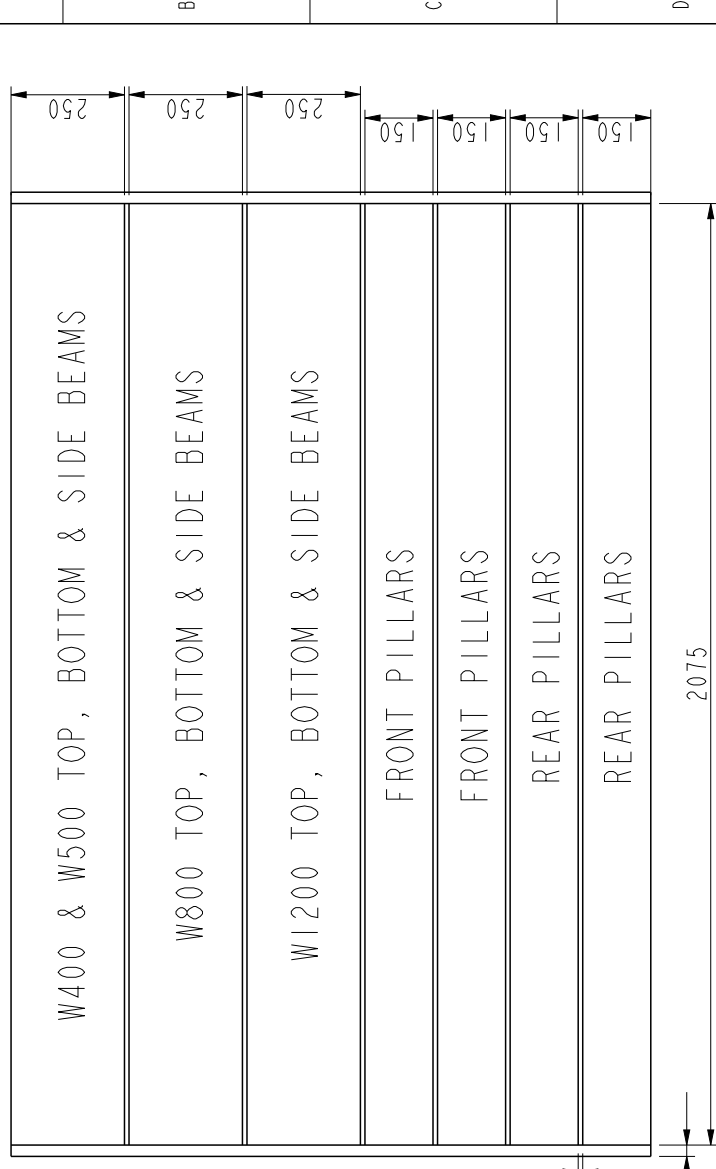
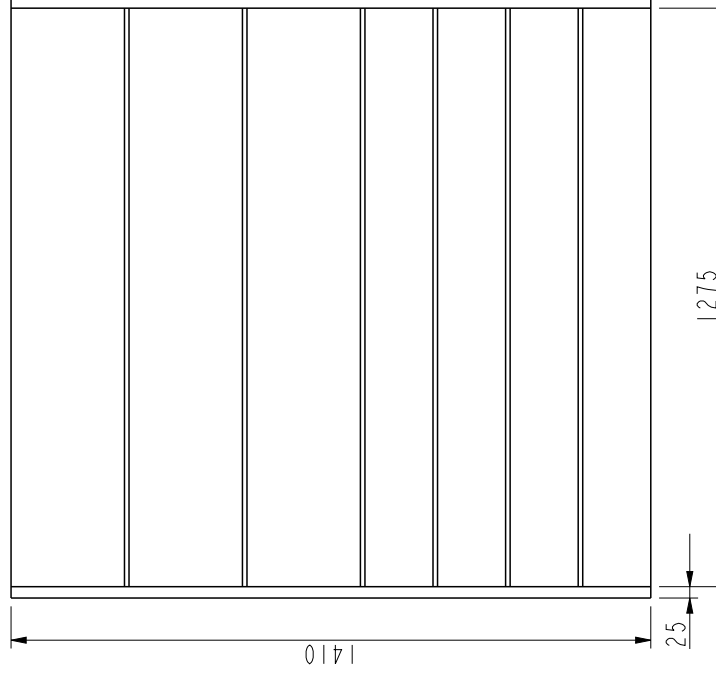
APPENDIX 1 FRAME ASSEMBLY'S BOTTOM PLATE DIMENSIONS

APPENDIX 2 EXAMPLE OF FRAME PARTS ASSEMBLY ONTO FRAME
ASSEMBLY BOTTOM PLATE



APPENDIX 3 FIRST DRAFT OF SHELF'S DIMENSIONS AND LAYOUT

1	2	3	4	5	6	7	8
First angle projection. Original drawing made with 3D CAD. Set the correct scale factor when adding dimensions after DWG/DXF conversion.							
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B							
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E							
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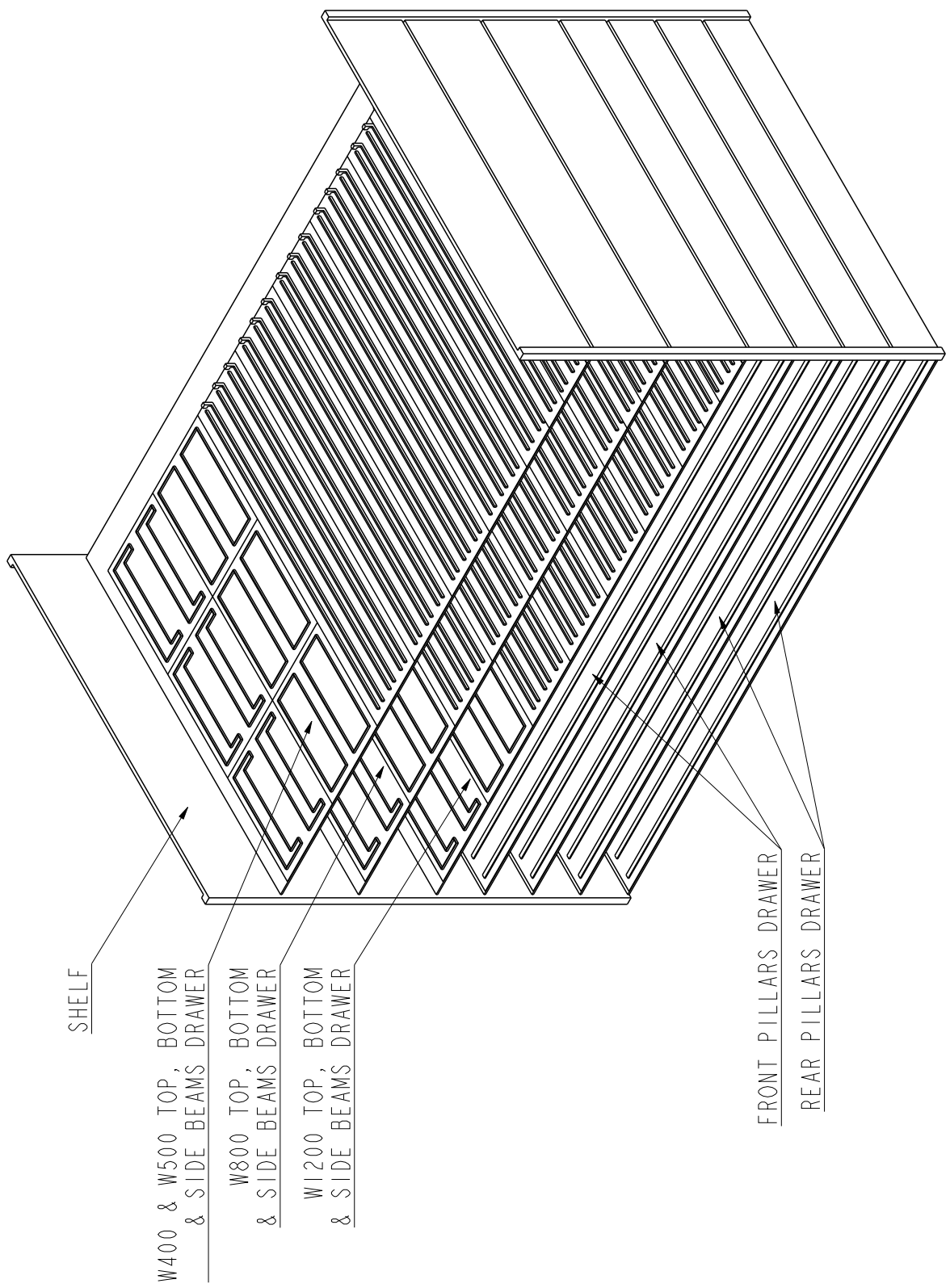


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First angle projection. Original drawing made with 3D CAD. Set the correct scale factor when adding dimensions after DWG/DXF conversion.

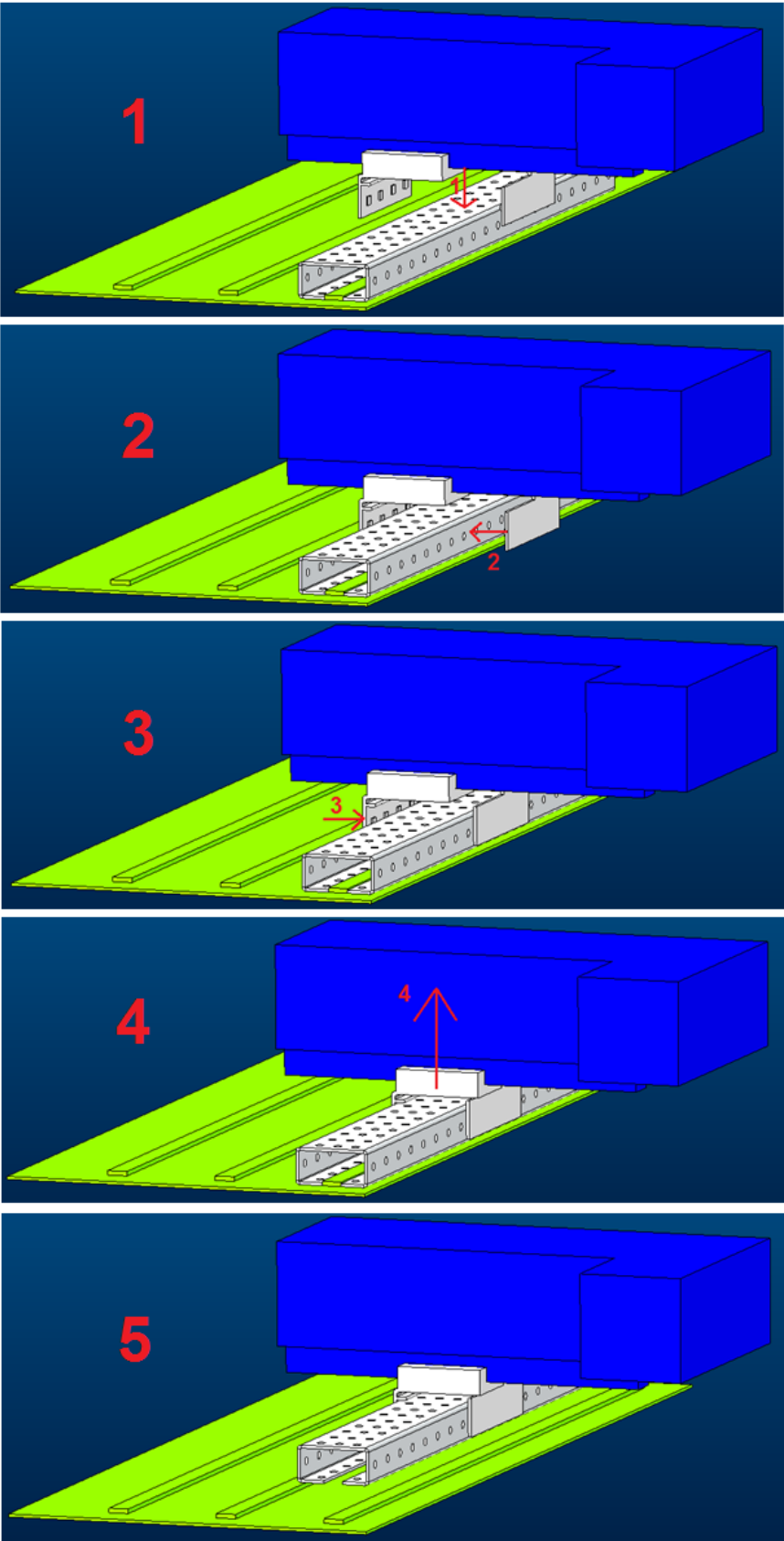


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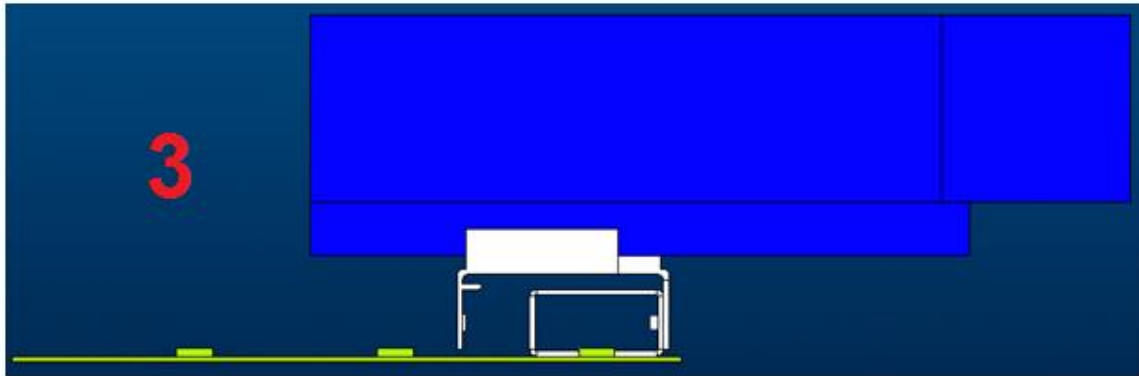
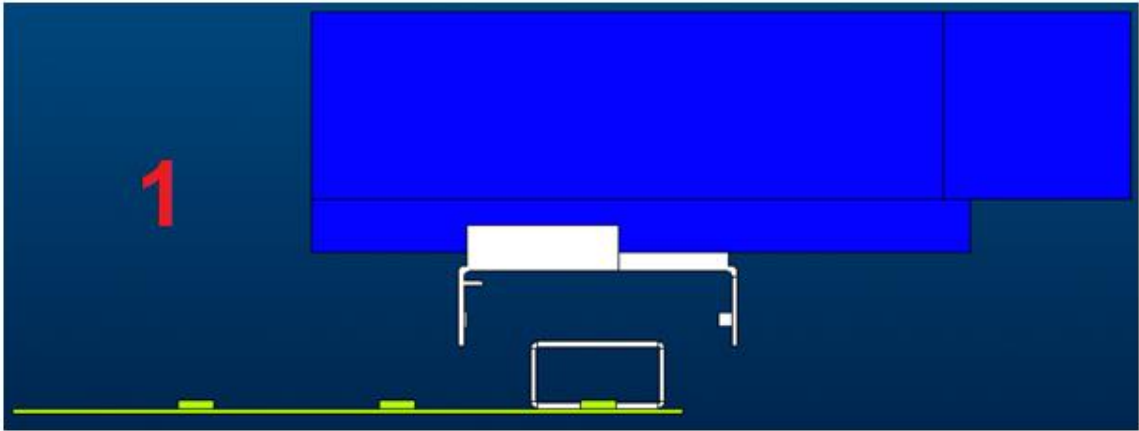
Based on Customer	Prepared I. Meesak Check. Appr.	21-May-19 21-May-19 21-May-19	Title ASSEMBLY DRAWING SHELVES LAYOUT	Scale 3:50	Form A4	Doc. des. ASSEMBLY DRAWING	Rev.ind. -1,2 (DR)	Lang. EN	Sheet 1	Total 1
Cust. Doc. No. DMS Number	Project name	Weight kg	Doc. No.	SHELVES LAYOUT						



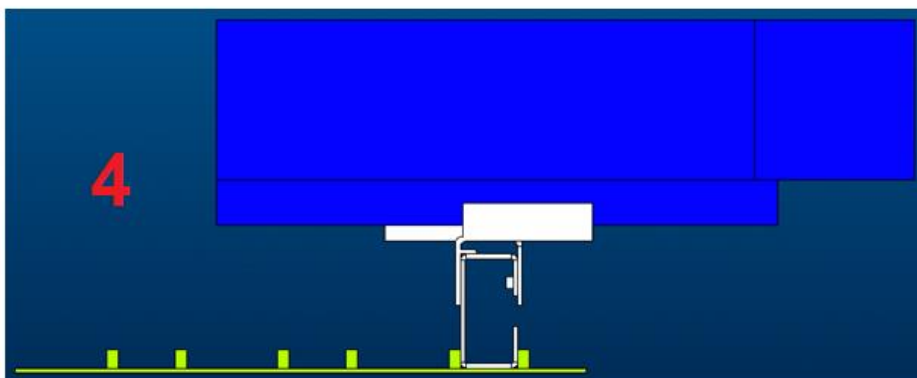
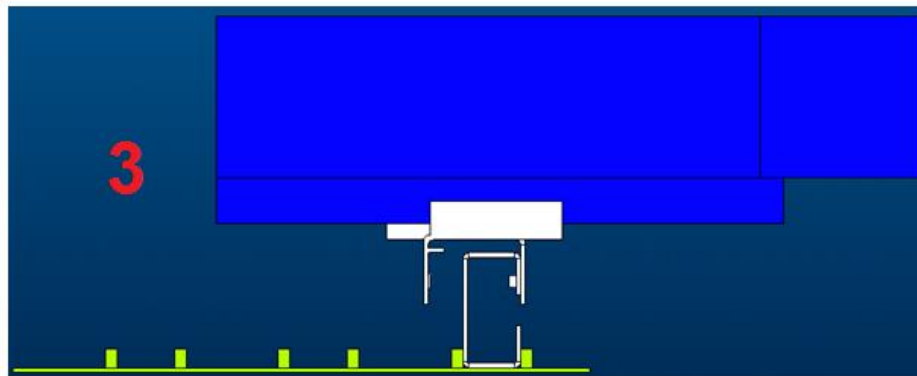
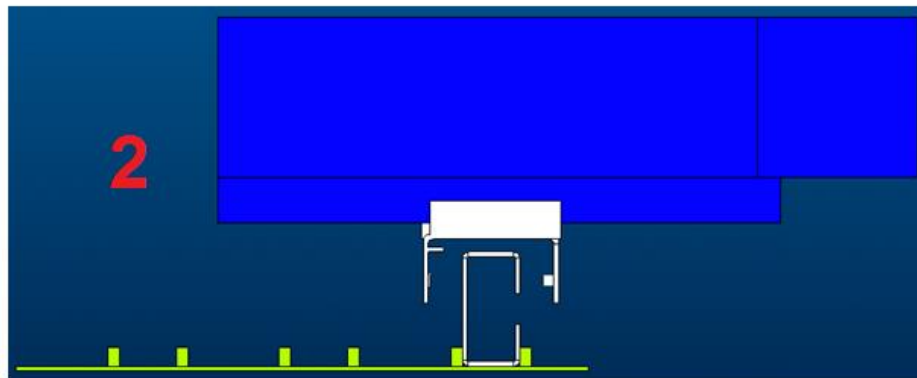
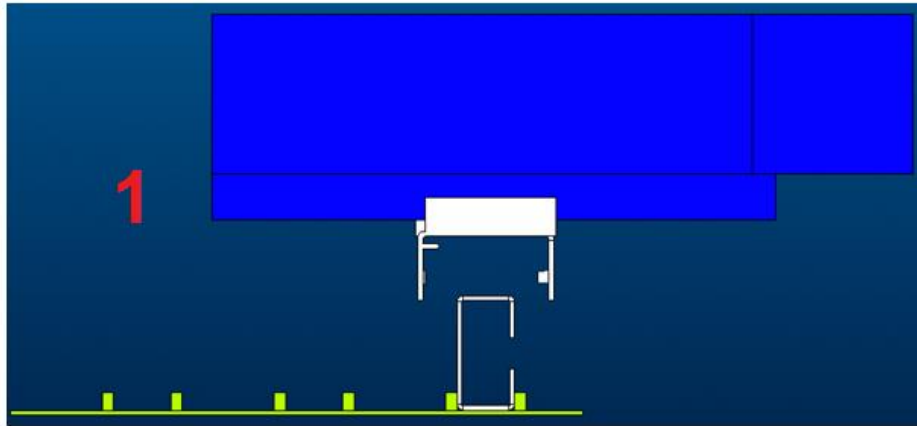
APPENDIX 4 FRAME PARTS GRIPPING OPERATION



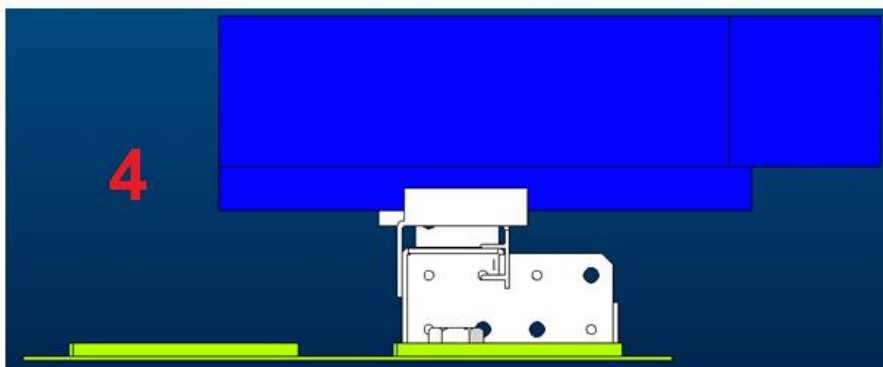
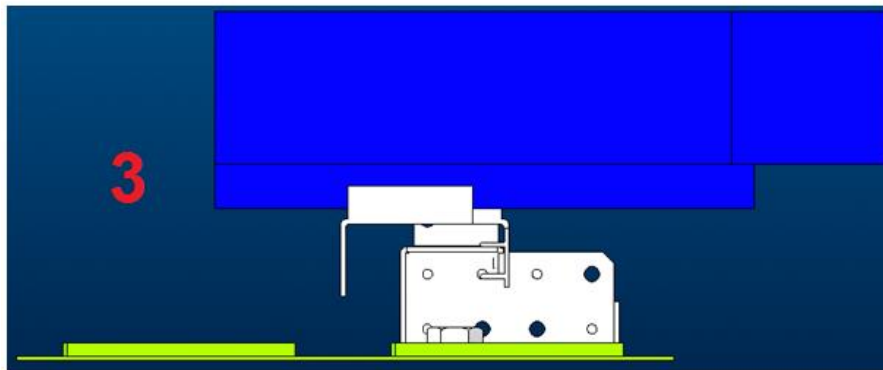
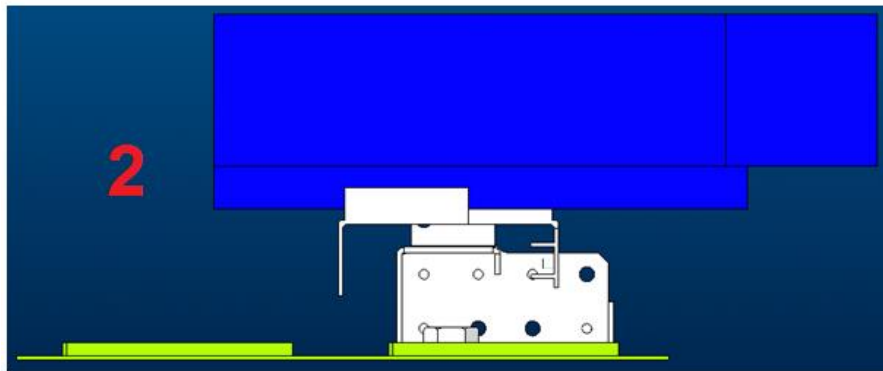
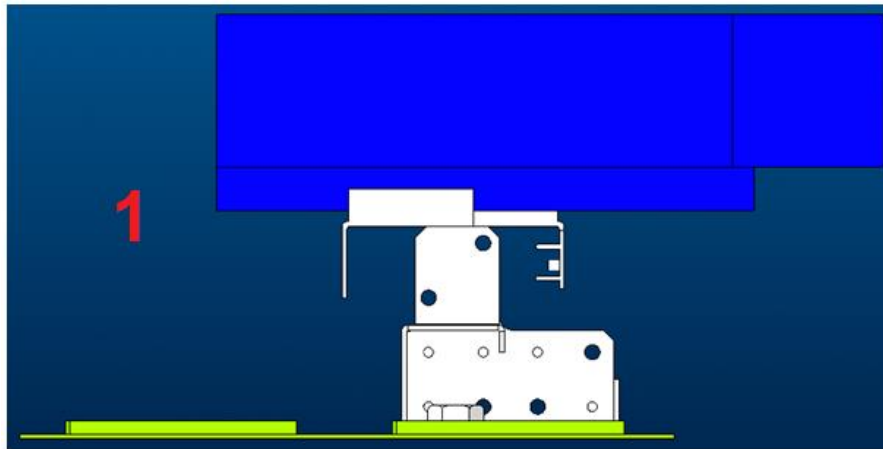
APPENDIX 5 FRONT AND REAR PILLARS' GRIPPING OPERATION



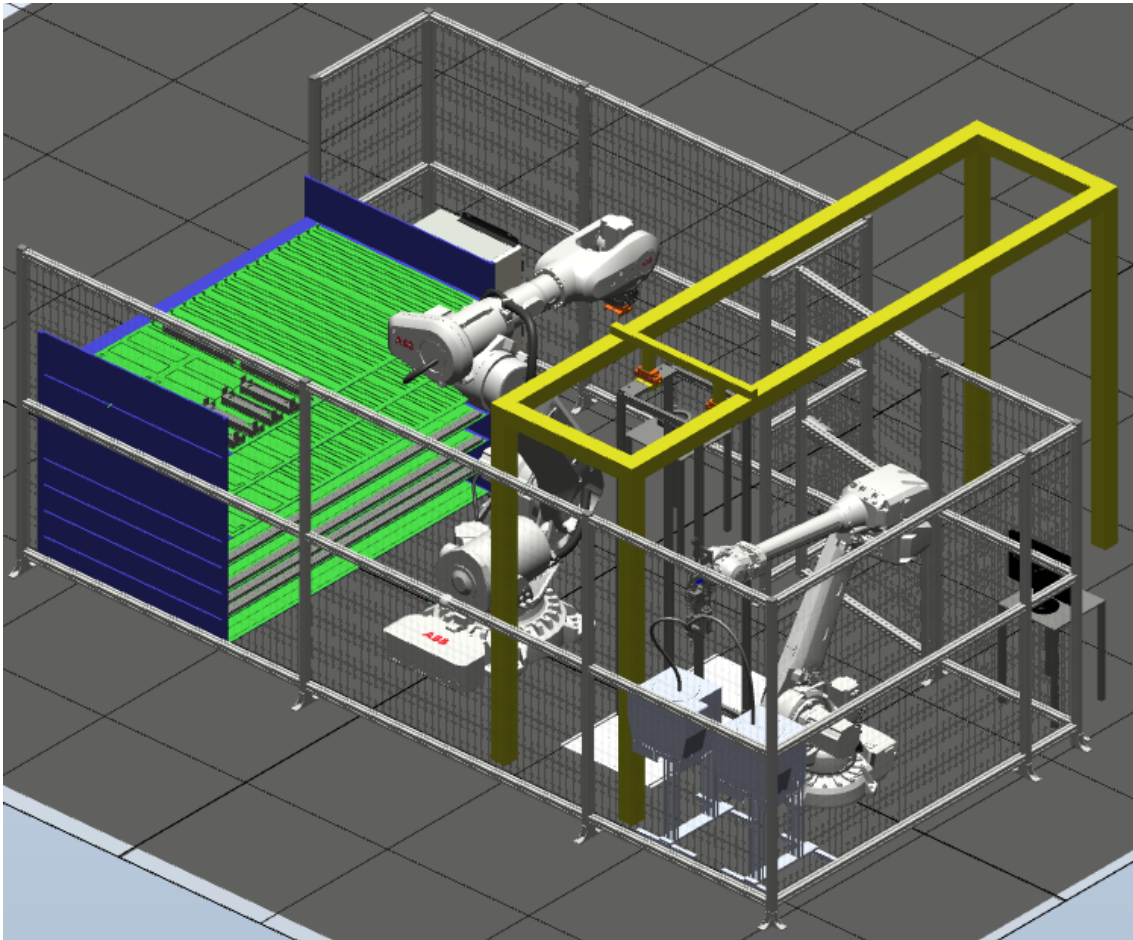
APPENDIX 6 SIDE BEAMS' GRIPPING OPERATION



APPENDIX 7 TOP AND BOTTOM BEAMS' GRIPPING OPERATION



**APPENDIX 8 AUTOMATED CABINET FRAME ASSEMBLY
WORKSTATION LAYOUT, VIEW FROM OTHER SIDE**



**APPENDIX 9 AUTOMATED CABINET FRAME ASSEMBLY
WORKSTATION LAYOUT OVERALL DIMENSIONS**

