TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Mechanical and Industrial Engineering

DEVELOPMENT OF A WORKSTATION FOR DOUBLE-SIDED WELDING OF T-BEAMS IN MARKETEX MARINE OÜ

T-TALADE KAHEPOOLSEKS KEEVITUSEKS TÖÖJAAMA VÄLJATÖÖTAMINE ETTEVÕTTES MARKETEX MARINE OÜ

MASTER THESIS

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Tallinn 2022

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THESIS TASK

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Thesis topic:

(in English) Development of a workstation for double-sided welding of T-beams in Marketex Marine OÜ

(in Estonian) T-talade kahepoolseks keevituseks tööjaama väljatöötamine ettevõttes Marketex Marine OÜ

Thesis main objectives:

1. To design a specialised workstation for double-sided welding of T-beams
2. To choose the components and calculate the cost
3. To familiarise with the implementation requirements

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Consultation with production department, definition of needs	31.10.22
2.	Definition of design requirements	06.11.22
3.	3D models of main sub-assemblies	25.11.22
4.	3D model of a complete workstation	30.11.22
5.	Design process and component choice description	11.12.22
6.	BOM compilation and cost calculation	19.12.22
7.	Summary and conclusions	23.12.22

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CONTENTS

PREFACE

The topic of the following research work was derived from the need of production department of Marketex Marine OÜ – a company that specializes in small shipbuilding – to improve one of the welding processes. Within the framework of the project a development of a station for welding of T-beams used in ship construction is carried out.

Having worked for 3+ years as a project engineer in the technical department of the aforementioned shipbuilding company, my personal goal of this research was to get a deeper hands-on understanding of the processes that transform my technical drawings into the final product. I wish to express my gratitude to my colleagues from technical, production, management departments and my supervisor professor Igor Penkov for assisting me in writing of the present thesis as well as achieving a personal goal of mine.

Keywords: shipbuilding, T-beam, welding, workstation, master thesis

List of abbreviations and symbols

AB – angle bar

EMC – Electromagnetic compatibility (directive)

GMAW – Gas metal arc welding

MIG – Metal inert gas (welding)

MM – Marketex Marine OÜ

FB – flat bar

PU - polyurethane

RB – round bar

RoHS – Restriction of the use of certain hazardous substances (directive)

SB – square bar

SHS – square hollow section

WPS – Welding Procedure Specification

1. INTRODUCTION

The aim of this thesis is to develop a workstation that is going to simplify the manufacturing process of T-beams and significantly reduce the time required for their production in Marketex Marine OÜ. T-beams are one of the main types of profiles that are used in shipbuilding. Together with other profiles, such as bulb flats, they are used in construction of frames that give the ship's hull its rigidity. It is necessary to mention that these T-beams are not standard rolled profiles, but rather are assembled and welded from separate plate parts – vertical webs and horizontal flanges.

With the introduction of new projects into the portfolio of MM there has been a drastic increase in the number of T-beams to be produced due to construction peculiarities of certain types of barges. That increase in the manufacturing volume, in turn, raised the question – how could the production of T-beams be improved? Standard production process of a T-beam consists of assembly, tack-welding of parts, two opposed welding passes and final straightening. Currently, T-beams are assembled directly on the shop floor, similarly to hull's flat sections, and welding solutions that are in place at MM imply two separate consecutive welding passes along the beam, which comprise the majority of production time of a beam.

Thus, the goal is to develop a workstation that would allow assembly in convenient position and would reduce the welding time of a T-beam. The station will consist of a workbench that would be used to assemble and rigidly fix the parts of a beam; and machinery necessary to partially automate and decrease the overall time of welding operation. The most logical solution to decrease welding operation time is to apply a machinery that would perform welding of a beam from both sides simultaneously. The budget for the project is fairly limited; and it is suggested to use as many off-the-shelf components as possible and parts that can be fairly easily manufactured inside the company or with the help of other subsidiaries of BLRT Grupp.

The following research is comprised of several main parts:

- Short overview of the company
- Analysis of T-beam welding methods and comparison of solutions
- Product design requirements
- Product design development and component choice
- Cost and payback calculation
- CE marking of the product

After a short introduction to a company and its field of operation, the conventional methods of T-beam welding and potential alternatives are analysed, then on their basis the design requirements are established. Next, the product development process is described. When the design is finalised, the components are selected, a complete bill of materials is compiled, the total cost of a project is estimated and the payback is calculated. Finally, a short overview of legislative requirements for the product implementation is given. In the course of present work specialised software, such as SolidWorks and AutoCAD, is used to assist in design process and technical documentation compilation.

2. MARKETEX MARINE OÜ

Marketex Marine OÜ is a part of BLRT Grupp AS and is a company that specialises in small shipbuilding. Main type of vessels produced by MM are the fish feeding barges used in fish farming industry. The company acts as a contractor to the Norwegian aquaculture companies, such as AKVA group and ScaleAQ, and produces turn-key barges that are deployed across the world. An example of a barge currently being in construction is ScaleAQ's Aasgard 900 barge (Figure 2.1) [1].

These barges are non-motorized vessels that are towed and then anchored on a stationary location. Their main task is to provide feed storage and act as a feed distribution platform. The storage is comprised of internal silo bunkers and the feeding capacities of produced barges range anywhere from 100 to 850 tonnes [2]. Most of the barges are equipped with living quarters, that can accommodate 4 to 8 people, and come with all of the necessary equipment and systems to monitor and control the feeding operation.

Majority of technical documentation necessary to build the barge is usually provided by the client in the form of certification drawings, which then have to be developed by the company's technical department into the work documentation and be provided to the production department. Construction of the barges entirely – from the ground up to the completely finished state – takes place in Tallinn, Estonia and is performed in close collaboration with other subsidiary companies of BLRT Grupp.

Figure 2.1 ScaleAQ Aasgard 900 [1]

3. INPUTS

In this chapter the methods that are used to weld T-beams are listed i.e., welding techniques, then the solutions that are currently applied in the company are described and compared with other alternative solutions. Based on their pros and cons the design requirements for a developed product are formulated.

3.1 T-beam welding methods

As mentioned previously in the introduction, the beam consists of two separate plate parts – a web and a flange – that first have to be assembled and tack-welded (Figure 3.1), then welded together from both sides and finally, if necessary, straightened to remove any residual deformation.

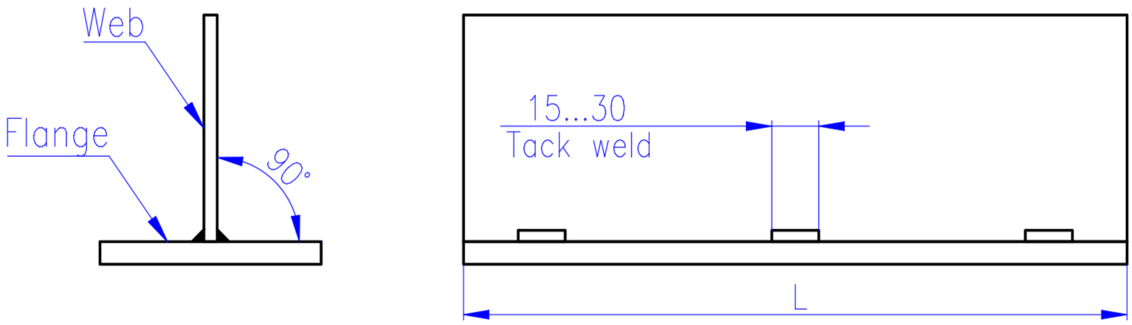

Figure 3.1 T-beam before main welding operation

Majority of the production time is taken up by two longitudinal opposed welding passes and this welding operation can be performed with several different methods or a combination of those.

Method 1 is one of the easiest and the beam is welded in a free state without any clamping. First, one longitudinal welding pass is made and the material is let to cool off. Then, a second opposite weld pass is made. During the welding operation the parts of the beam are free to jointly deform. This method leads to the most amount of residual deformation that then has to be corrected.

Method 2 same as in the case of Method 1 is performed without any clamping of the parts. The welding operation is however performed with two longitudinal welding passes being made simultaneously, where welding arcs travel in parallel to one another. This method also leads to a measurable deformation of the beam.

Method 3 is similar to Method 1, but the main difference is that the flange of the beam is rigidly fixed, preventing the significant amount of deformation in longitudinal and transverse direction of the beam. This method requires much less final straightening than Method 1 and 2.

Method 4 is used to completely remove the need for straightening operation of residual deformations. Both parts of the beam are preliminarily bent in direction opposite to the direction of contraction and are rigidly fixed, in order to compensate for any residual deformations. Two consecutive welding passes are made.

Method 5 is another way to greatly minimize the need for straightening operation of a welded beam. The beam is welded without any clamping and the operation is performed with the use of back step welding technique. First, a longitudinal seam is made in steps from one side, then the beam is let to cool off and after that a second seam is made in steps. This method does not require much straightening, if any at all, but takes much more time due to its welding technique. [3]

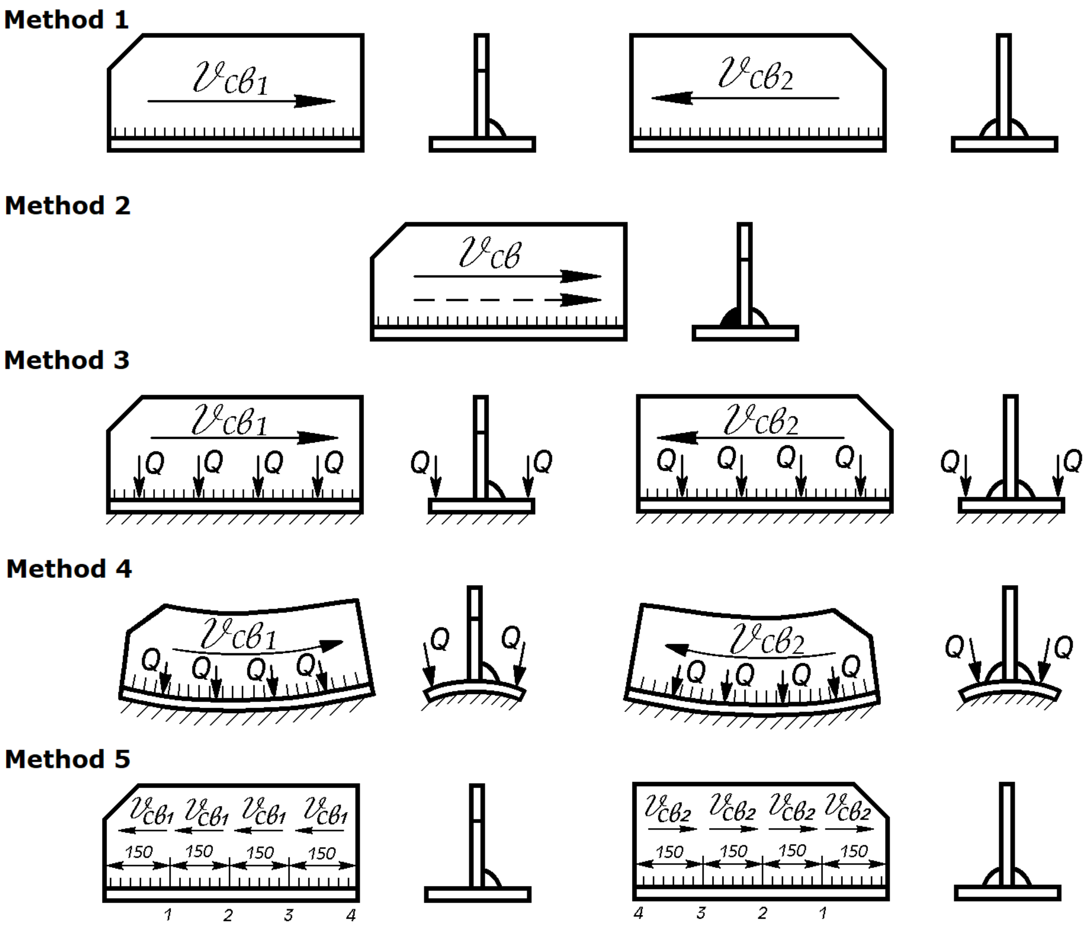

Figure 3.2 T-beam welding methods [3]
Vcb – direction of the weld, Q – clamping force, 1-4 – welding step sequence

3.2 T-beam welding solutions in Marketex Marine OÜ

3.2.1 Manual MIG welding

There are currently two solutions of T-beam welding applied in the company. The first and the one that is used in majority of cases is the manual welding in conjunction with the previously described Method 1. The beams are assembled with the flange lying on the shop assembly floor and welded manually in non-fixed state by the welders using GMAW machines, specifically MIG welding machines. As mentioned previously, application of this method leads to the most amount of residual deformation after a beam has cooled off. The material around welding seam contracts and leads to a deformation of a beam, which then has to be straightened. A method used to straighten these deformations is called wedge heating. Depending on the length of a beam and a deformation magnitude, a number of zones along the beam are heated, with the use of an acetylene torch, in a form of a wedge to get rid of longitudinal deformation (Figure 3.3).

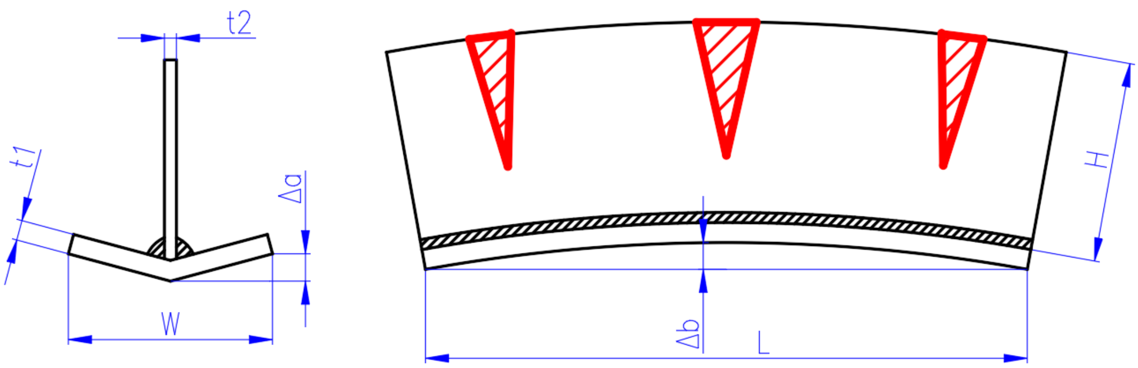

Figure 3.3 T-beam deformation and wedge heating

L – beam length, W – flange width, H – web height, t1 – flange thickness, t2 – web thickness, Δa – flange transverse deflection, Δb – flange longitudinal deflection

According to the experience of production department the transverse deformation is usually negligible due to sufficient thickness of the flange (common flange thicknesses *t1* = 15…20 mm) and only longitudinal deformation has to be dealt with using the wedge heating method. In case of a manual welding operation, Method 1 has proven to be the least time demanding, as the straightening process takes less time than the clamping of the beam, which has to be done if other welding methods are used.

3.2.2 MIG welding with the use of a welding tractor

Another solution that is occasionally applied is MIG welding with the use of a welding tractor. A welding tractor is a fairly unsophisticated motorised carriage that is used to drive the welding torch along the seam at a desired velocity. A couple of welding tractors are used on the production floor of the company with the main model being ESAB Miggytrac B501 (Figure 3.4).

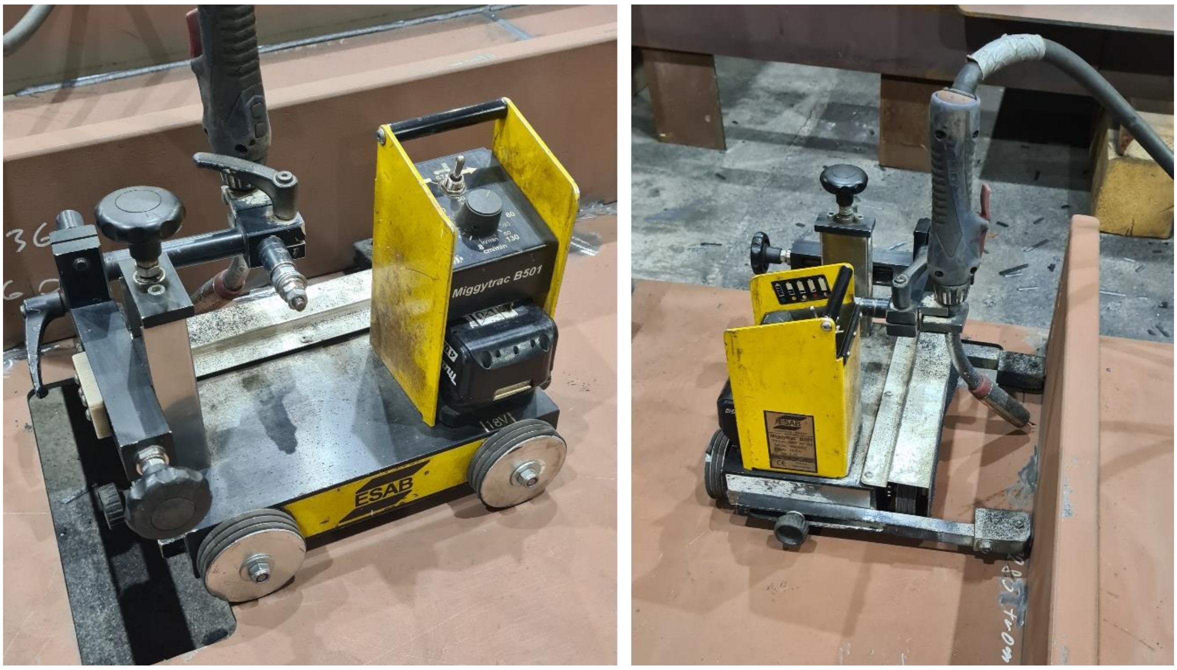

Figure 3.4 ESAB Miggytrac B501

Miggytrac B501 is a battery powered or, in case of older models, powered from 220 V grid welding tractor that is driven by a stepper motor. It has only two simple controls – a direction control switch and a potentiometer to select the velocity. The tractor is equipped with a XYZ-adjustable clamp that is capable of holding one MIG welding torch.

A method of T-beam welding that is used in conjunction with a welding tractor is the previously described Method 3. Already during a welding pass a deformation in the beam starts to occur, which causes the beam to move quite a bit in transverse direction. While a welder, who welds manually, can compensate for this movement; a welding tractor might drive off its trajectory due to these contractions, which is why rigid fixation of the beam to the shop floor is required. Overall, welding with a tractor takes measurably less time than welding manually, but still requires two separate welding passes and might not always be applicable due to construction of tractor’s guiding rollers making it impossible to place a welding torch close enough to the seam.

3.3 Comparison of T-beam welding solutions

Apart from solutions that are currently applied in the company there are obviously other ones that make use of different types of specialised machinery. Three main types of machinery available on the market that could be applied for welding of T-beams are further outlined.

Fillet carriage is a type of welding tractor that travels along the upper edge of the beam's web. The carriage that can hold two welding torches does not require any rails, is equipped with magnets that hold the carriage on the welded part and drive wheels that push the carriage along the beam. An example of fillet carriage is Koweld CS-251 (Figure 3.5) [4].

Figure 3.5 Koweld CS-251 [4]

Double-sided welding tractor is a welding tractor that is similar to the aforementioned Miggytrac welding tractor, but is equipped with clamps for two welding torches. An example of double-side welding tractor is Huawei HK-6A-II (Figure 3.6) [5].

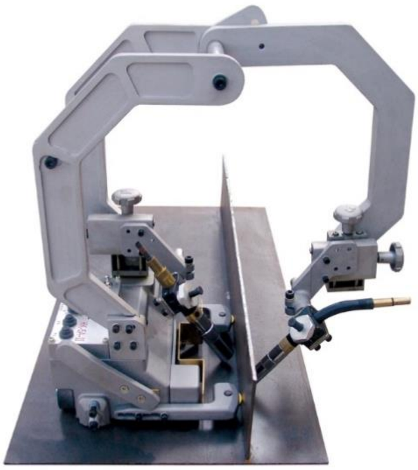

Figure 3.6 Huawei HK-6A-II [5]

Welding gantry is a mobile portal frame that moves along the floor mounted rails. A gantry could be used to weld different types of profiles and can be used not only with welding equipment, but also cutting equipment. An example of a gantry is ESAB MechTrac 1730 (Figure 3.7) [6].

Figure 3.7 ESAB MechTrac [6]

All of the outlined types of solutions come with a big advantage over the currently applied Miggytrac B501 as well as manual welding method – they provide the ability to simultaneously weld the beam from both sides, thus greatly reducing the overall time of the welding operation. But each of them has its own drawbacks that make those solutions unreasonable or simply impossible to apply in our case. Which is why next, a table is compiled, where the pros and cons of the currently used methods and alternative solutions are listed. Based on the data compiled in this table, shortcomings of the named solutions that make them unsuitable for the application will be explained and as many advantages as possible will be adopted in development of an own solution. Then, in the next section, the product design requirements will be established.

Table 3.1 T-beam welding solutions

Solution type	**Advantages**	**Disadvantages**	**Approximate cost**
		Currently applied	
Manual MIG welding	• Constant control of the welder over the welding seam • No need for rigid fixation of the beam	• Highest total operation time • Single-sided welding	N/A
Single-sided welding tractor	• Higher uniformity of the seam over manual operation • Uses conventional MIG welding equipment	• Single-sided welding • Limited seam reachability	~ 2300 € (ESAB Miggytrac B501)
		Alternatives	
Fillet carriage	• Double-sided welding • Uses conventional MIG welding equipment • Good seam reachability and uniformity	• Requires continuous edge to drive on • Max T-beam web height of ~ 200 mm	~ 3500 € (Koweld CS-251)
Double-sided welding tractor	• Double-sided welding • Uses conventional MIG welding equipment • Max T-beam web height of ~ 450 mm	• Limited seam reachability	~ 1700 € (Huawei HK-6A-II)
Welding gantry	• Double-sided welding • High degree of adjustability and seam reachability • Ability to use other equipment e.g., for metal cutting	• High cost • Requires purchase of specialised welding equipment	~ 8000 € + welding equipment (ESAB MechTrac 1700)

Now, it is necessary to explain some of the disadvantages of the alternative solutions that make them unsuitable for our application. In case of single-sided and double-sided welding tractors, one of the disadvantages listed is "limited seam reachability". What is meant by that, is that in case of specific widths and thicknesses of a beam's flange, a tractor will not be able to drive along the seam. Either its guiding roller has to fit above the flange, which is not possible at higher flange thicknesses ($t1$ = 15…20 mm), or the tractor's carriage has to fit completely width-wise atop the flange (Figure 3.8).

Unfortunately, it is not always possible with the currently used tractor and will definitely restrict the use of a double-sided welding tractor in an analogous manner.

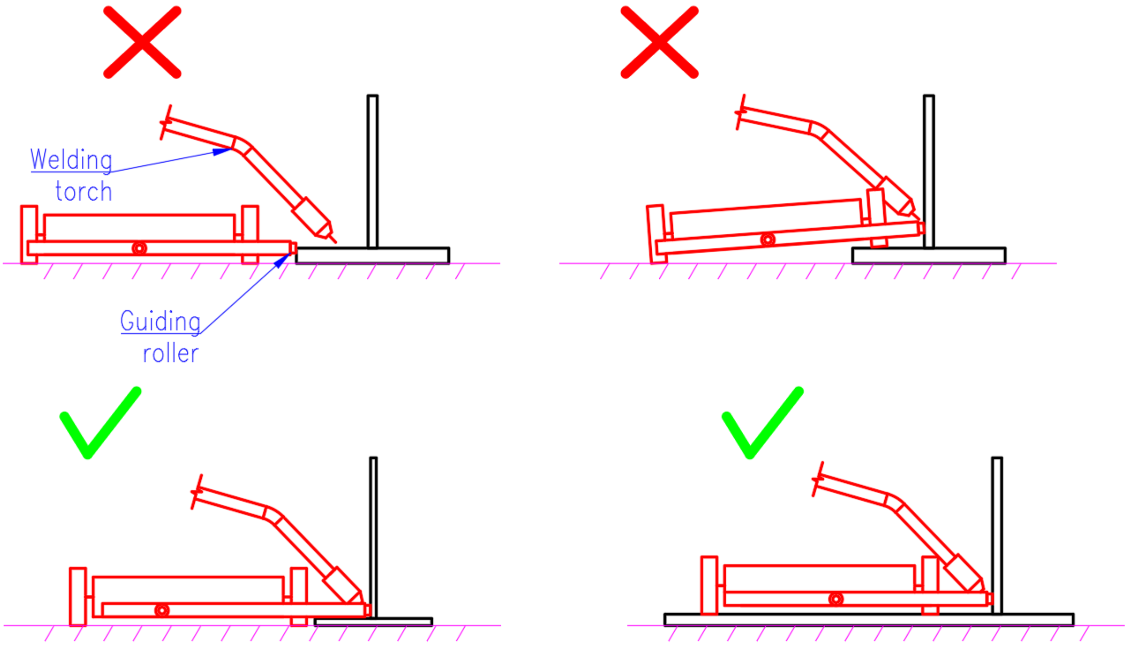

Figure 3.8 Seam reachability of a welding tractor

In case of a fillet carriage, one of the listed disadvantages is "requires continuous edge to drive on". A fillet carriage is very well applicable if the web of a beam is a solid plate piece. In case of T-beams used in shipbuilding, they usually act as transverse or longitudinal stiffeners that are crossed perpendicularly by other hull frame profiles, for example bulb flats. These punctures will prevent the carriage from driving along a full length of a beam. A common example of a T-beam used in shipbuilding looks like this:

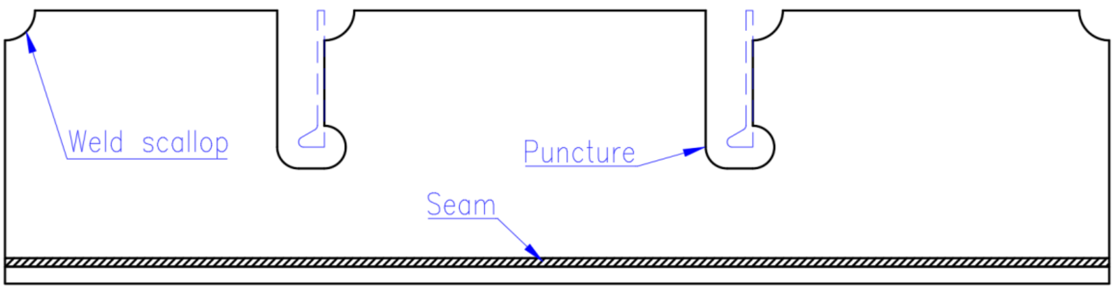

Figure 3.9 Common T-beam

Finally, a welding gantry. An inherent advantage of this solution is its high degree of flexibility in terms of reach and adjustability, but at the same time it is the most complicated piece of machinery out of the listed ones. First of all, the gantry requires dedicated shop floor space to install its guiding rails. Then comes the price - not only the basic cost of the gantry itself is much higher than that of other listed solutions, but also it requires separate specific welding equipment, making it in total a very hefty investment.

3.4 Product design requirements

Having assessed the pros and cons of the abovementioned solutions and taking into account production specific parameters, the product design requirements were formulated.

The first requirement that has to be taken into consideration is maximal dimensions of a T-beam that could be produced. These dimensions depend on 2 main factors – maximal dimensions of plate parts provided by our metal supplier and barge's type specific dimensions of T-beams. Some T-beams can span the whole length of the ship's hull, but they are almost always made out of sections that are welded together. The length of a T-beam section is then limited by the plate parts that are cut and supplied to MM by Elme Metall OÜ – another subsidiary of BLRT Grupp. While there are steel plates available in sizes up to 12000x2500 mm, the material that is cut and supplied to MM is predominantly of 6000x2000 mm in size. When the plate parts are cut from these sheets, some margin for cutting operation has to be taken into consideration, which is why the maximal plate part dimensions are agreed to be 5980x1980 mm. This is where the maximal length of a beam section comes from. Depending on the barge project and its size, T-beams come in a variety of different thicknesses and sizes. Previously mentioned ScaleAQ Aasgard 900 is currently one of the largest barges in portfolio of MM and the maximal dimensions of T-beams that would be produced on the developed workstation will be derived from this barge's largest T-beams:

- Length L = 5980 mm
- Flange width W = 200 mm
- Flange thickness $t1$ = 20 mm
- Web height H = 300 mm
- Web thickness $t2$ = 15 mm

Having figured out the maximal dimensions of a T-beam to be produced and taking into account the remarks of a production department, we have agreed upon the design requirements for a custom welding carriage and a workbench for assembly and welding operations. These requirements are listed below.

Welding carriage:

- The carriage to have a capacity to hold two welding torches
- A standard MIG welding equipment that is present in the company to be applied with the carriage
- Gantry-type frame to be applied to ensure compatibility with varying dimensions of a T-beam section
- Electric motor drive with direction and speed controls to be used, similar to currently used welding tractors
- Relatively low weight to be able to lift the carriage by hand

Workbench:

- The workbench to have a capacity, in terms of weight and size, to support the produced beams
- To be compatible with the developed carriage in terms of size, clearances, etc.
- To have fixtures for part clamping
- To be designed with work ergonomic principles in mind

Overall project requirements:

- Project budget limit – 4500 €
- Use of components that are fairly easily supplied – either readily available from catalogues, or could be manufactured inside the company, or with the help of other BLRT Grupp subsidiaries (Elme Metall OÜ, AS ELME, BLRT Masinaehitus etc.)

4. WELDING CARRIAGE DEVELOPMENT

In this chapter the process of designing a custom welding carriage on the sub-assembly basis is described.

4.1 Frame sub-assembly

First sub-assembly that was designed is the frame sub-assembly. The design of the frame was built on several main requirements – it has to be light, of a gantry type and it has to be flexible in terms of fixing other sub-assemblies to the frame. One profile type suitable for this application immediately came to mind – an aluminium extrusion profile. These profiles are light and come in variety of different sizes and forms. Due to their slotted shape, they are often used in industrial applications to construct different kinds of workbenches, trolleys, storage structures etc. Moreover, there is a huge variety of fasteners available on the market that are compatible with these profiles.

Based on the estimated dimensions of an assembled carriage, a T-slot 40x40 aluminium extrusion was chosen (Figure 4.1). This profile has the best ratio of cost to weight, has shown great versatility and already found its application areas in the company. Having slots from all 4 sides makes it especially convenient when something has to be fixed to it.

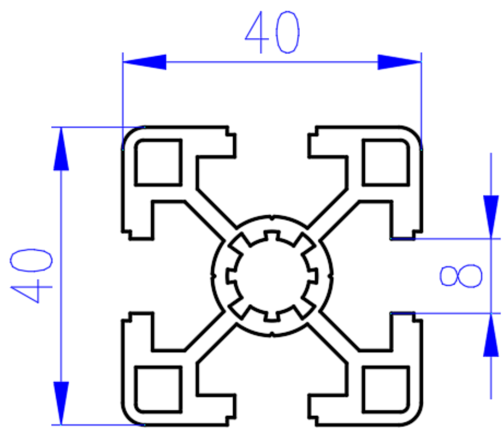

Figure 4.1 T-slot 40x40 aluminium extrusion

To assemble the frame, the extrusions have to be cut to length and fastened together with the use of corner brackets and hardware in the form of T-nuts and bolts. A complete bill of materials for the frame can be found in Appendix 1. This is what a final version of the frame looks like (Figure 4.2):

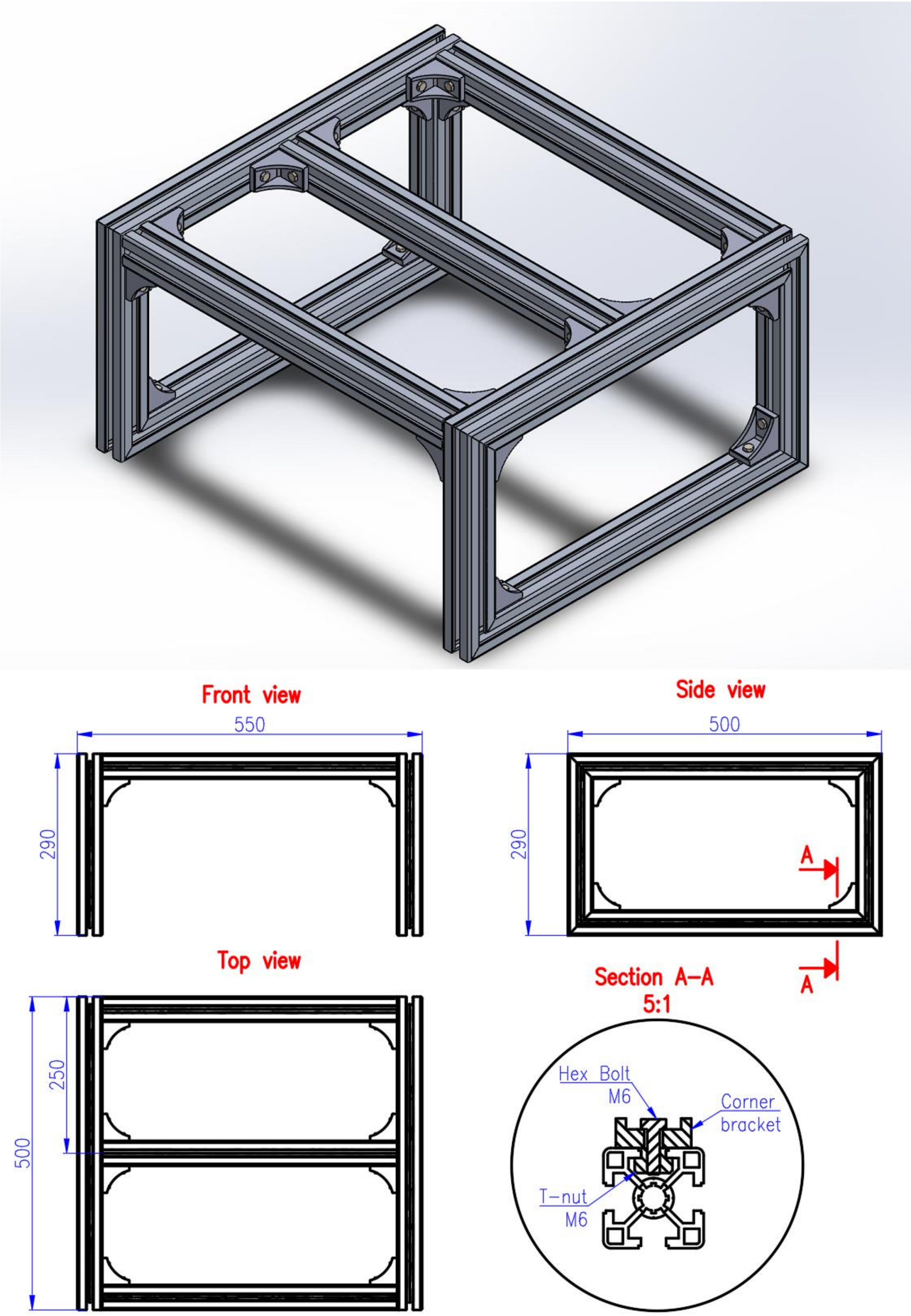

Figure 4.2 Frame sub-assembly

4.2 Wheel hub sub-assemblies

When there was a clear idea of what a frame should look like, it was necessary to design a chassis for the carriage. To make the solution compact and to stay away from the additional complexity of a guiding rail system of a conventional gantry, it was decided to use wheels, similar to those used in welding tractors. Currently applied Miggytrac B501 welding tractor can work on inclines of up to 45 degrees and comes with a four-wheel drive system, where torque from the motor is transferred to all wheels by a roller chain. In case of a gantry type frame, at least two motors would be required to drive all four wheels – one on each side of the frame. Since the developed carriage is supposed to be used in horizontal plane only, atop the workbench, it was decided that only one side of the carriage powered by the motor would be sufficient; and a roller chain would likewise be used to drive the wheels.

First step was to choose the wheels. On the non-drive side of the carriage everything was clear with the choice of wheels – a wheel would need to have a bearing to freely spin around the fixed axle. On the drive side it is different – a torque from the motor has to be transferred from the motor to the wheel. One way is to use keyed drive rollers, like those used to drive conveyors. But unfortunately, it has proven to be very difficult to find a suitable roller that is readily available – they are usually made to order and are fairly expensive. Because of this and also to standardise the components, it was decided to use plain plastic/rubber wheels with roller bearing meant for casters on all corners of the carriage.

4.2.1 Non-drive side wheel hub

With the selected type of wheel in mind, the design of a non-drive side hub was very straightforward. The selected wheel has an outer diameter D = 80 mm with a bore diameter d = 12 mm and has an integrated roller bearing. A shoulder bolt – bolt with a threadless middle section – is used as a shaft. To prevent any axial movement of the wheel – two set collars with set screws are fastened on both sides of the wheel. To mount the wheel to the frame a hub housing is made. A hub housing is welded of two side plates, a bent back plate and a fixture bracket that are made out of 3 mm thick steel. Two hub housings are welded and assembled in a mirrored way. A complete bill of materials for non-drive side wheel hub assembly can be found in Appendix 1. This is what a final version of a non-drive side wheel hub assembly looks like (Figure 4.3):

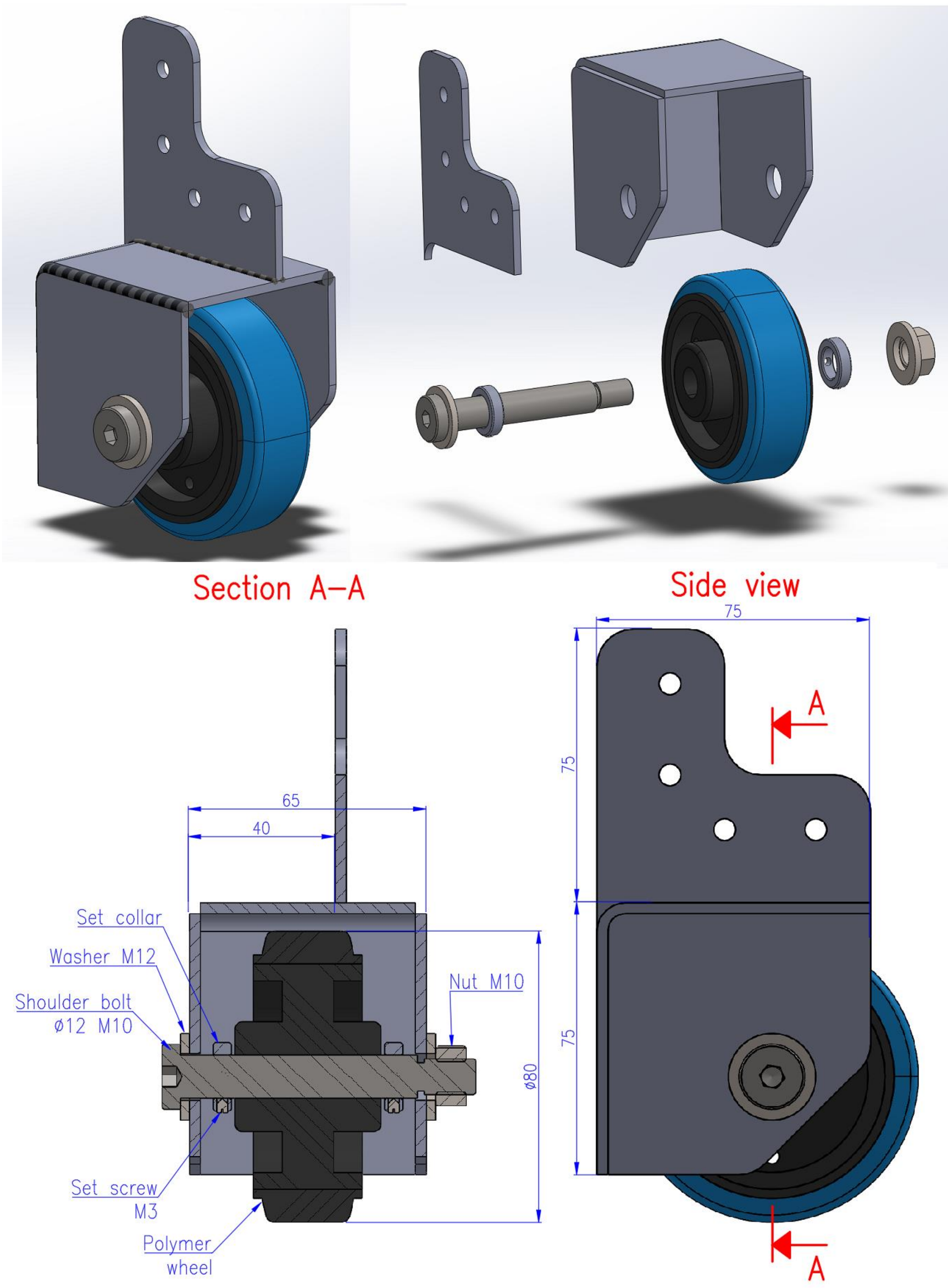

Figure 4.3 Non-drive side wheel hub sub-assembly

4.2.2 Drive side wheel hub

While the non-drive side assembly was fairly straightforward, it was necessary to figure out, how the torque from the motor could be transferred to the wheels on the drive side of the carriage. Previously it was decided that the carriage will make use of a roller chain to drive its wheels. To transfer then the torque from a motor to a wheel with a use of a roller chain the following components are required – gear sprockets, axle shaft and shaft bearing supports.

Three gear sprockets in total are required for the developed carriage. One driving gear sprocket is located on the drive shaft of the motor and each of two drive-side wheels is paired with a driven sprocket. Based on the overall dimensions of the chosen wheel, its bore diameter and wheel hub housing dimensions, a suitable sprocket was selected from the catalogue. The chosen sprocket is of 06B-1 type – the smallest type that was possible to find with a keyway and a bore diameter d = 12 mm. A keyway for a parallel key in a sprocket bore is required to prevent rotation around the axle shaft. To prevent any axial movement of the sprocket along the axle, two holes for set screws are tapped in the body of a sprocket. Chosen driven sprocket has 15 teeth.

An axle shaft with a diameter d = 12 mm is machined out of steel round bar RB12 and has a slot for a parallel key. To support the axle and ensure its free rotation, two flanged ball bearings are used. To prevent any lateral motion of the axle inside the bearing, bearing's inner race has two tapped holes for set screws that pinch the axle in place.

Main question that was left was how to couple a sprocket with a wheel. Since the wheel has a roller bearing inside, it would freely spin around the axle, but it has to be locked to the axle. Two variants were considered – either fix it to the axle or to the sprocket. The solution that was applied was to bend a bracket out of 1,5 mm steel, weld it to the face of a sprocket and drill two holes through the body of a wheel to fasten them together.

The housing for a drive side hub assembly has essentially the same construction and dimensions as non-drive side, but has an opening in side plates to be able to install the wheel with shaft, sprocket and bearing as one unit. Two hub housings are assembled and welded in a mirrored way. A complete bill of materials for the drive side wheel hub assembly can be found in Appendix 1. This is what a final version of the drive side wheel hub assembly looks like (Figure 4.4):

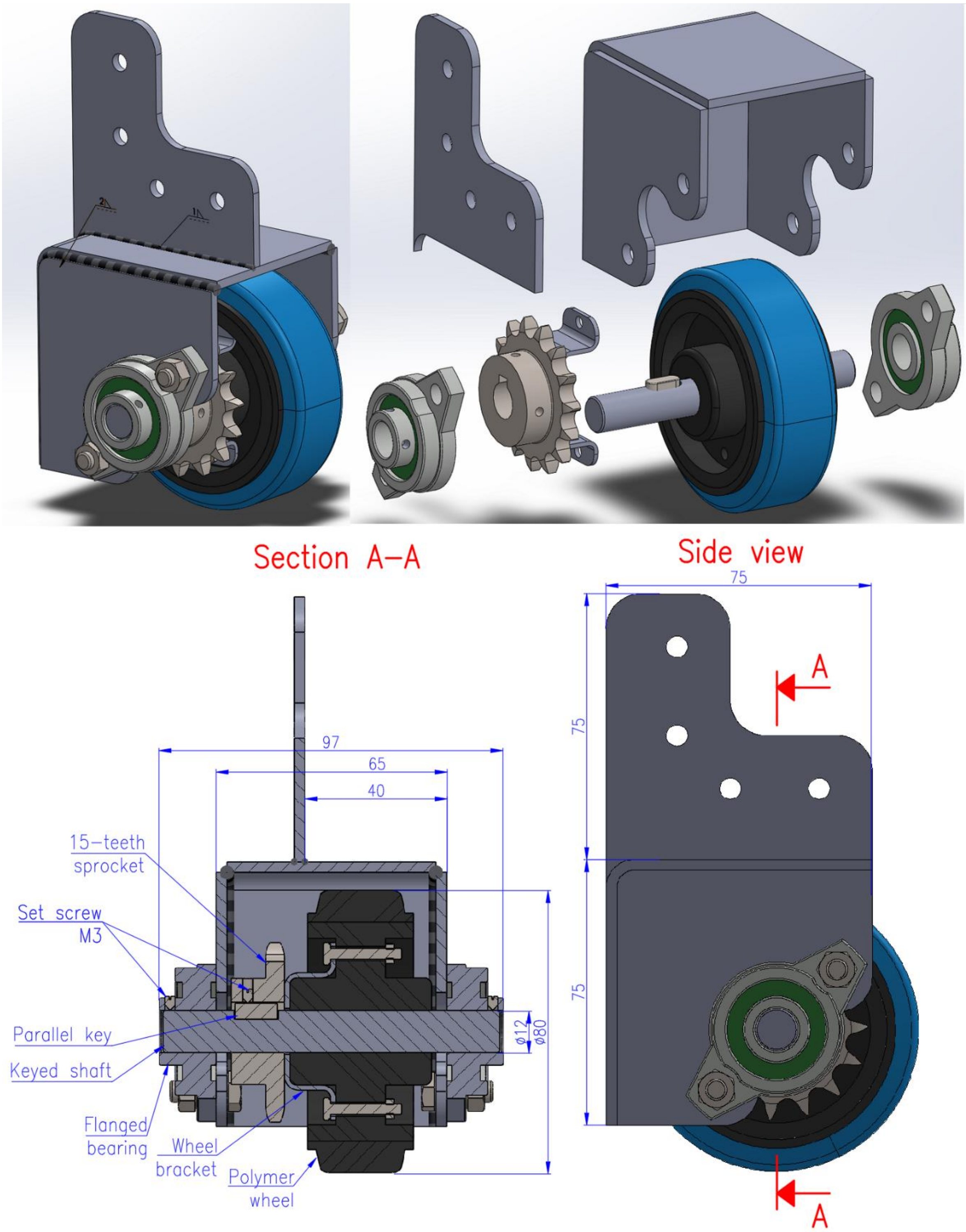

Figure 4.4 Drive side wheel hub sub-assembly

4.3 Guiding roller sub-assembly

When it was decided to put a gantry carriage on regular wheels without any auxiliary guiding rails, a necessity of a guiding assembly arose. All types of welding carriages follow the same principle - they have some sort of guides that assist the carriage in driving along the profile, precisely following the seam. It was necessary to make an adjustable guiding assembly that would be compatible with different T-beams regardless of their dimensions and whether there are punctures in the web part of a beam.

The upper part of a guiding assembly is a housing that slides along the middle member of a carriage’s frame and is locked in desired position with a threaded knob and a T-nut. Plate parts of the housing are made out 3 mm thick steel. On the inner side of a bent part there are welded two plate parts in the form of a T-nut that act as supporting guides. On both sides of a housing there are slotted shaft pinch blocks that are machined out of FB20x10 flat bar with tapped holes for clamping levers.

In the lower part there are two bearings with threaded shafts that roll along the profile’s web. Bearings are held by the support bracket that is made out of same 3 mm steel and is suspended on two round bars RB12 that are clamped in the upper part of assembly.

Two such guiding assemblies are installed on the frame and are pushed against the vertical web plate of a T-beam. Depending on thickness and height of a T-beam’s flange the guides can be easily adjusted without any tools. A complete bill of materials for the guiding roller assembly can be found in Appendix 1. This is what a final version of the guiding roller assembly looks like (Figure 4.5):

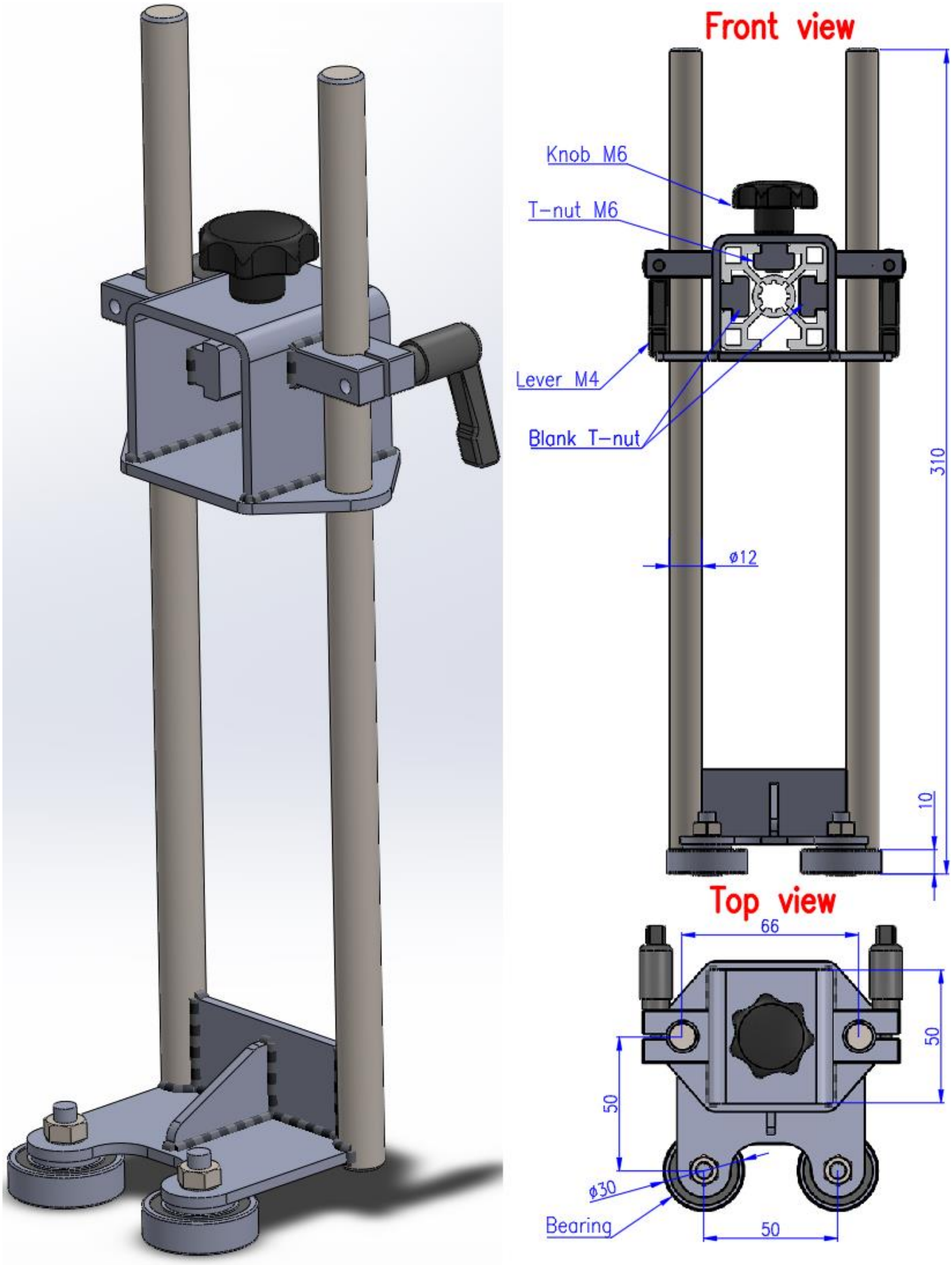

Figure 4.5 Guiding roller sub-assembly

4.4 Gripping jig sub-assembly

Next step was to design a jig that would allow to attach the welding torches to the carriage. To ensure an excellent range of reach and adjustability, it was decided to design a gripping clamp that would be attached to a jig capable of XYZ-movement.

The overall concept was borrowed from the currently used Miggytrac welding tractor. Two manual linear slides are assembled together to allow positioning in YZ-plane (movement of the carriage is considered to be in X-direction). The frame of each of the slides is made out of SHS30x30x3 mm square tube with one of the side walls cut off. There are two main mounting points to the carriage's frame – the end cap of the vertical slide has a mounting hole and a mounting bracket is welded to the side of a vertical slide. End caps and a bracket are cut out of 3 mm thick steel. A threaded rod M6 passes through the whole length of each slide's frame. The rod is fastened on one end using a jam nut method and can be freely rotated with a knob on that end. Two of these frames are held together with a sliding block that is machined out of SB24 - 24x24 mm square bar. The block has two holes tapped with M6 thread that are perpendicular to one another. By rotating a knob, the frames move laterally to one another. Some grease is applied to the inner sides of the tubes to ensure smooth motion.

On the end of a secondary slide there is a pinch block with a clamping lever that supports the shaft that slides in X-direction and also provides the adjustability of an angle, at which a welding torch is clamped. On the end of a shaft there is a clamping jaw meant for a standard MIG welding torches' neck that is fastened with a threaded through-knob.

In total there are four gripping jig assemblies used, one on each corner of the carriage, to remove the need to turn around the carriage when it is on either side of the workbench. Two identical gripping jigs are assembled and other two are assembled in a mirrored way. A complete bill of materials for the gripping jig assembly can be found in Appendix 1. This is what a final version of the gripping jig assembly looks like (Figure 4.6):

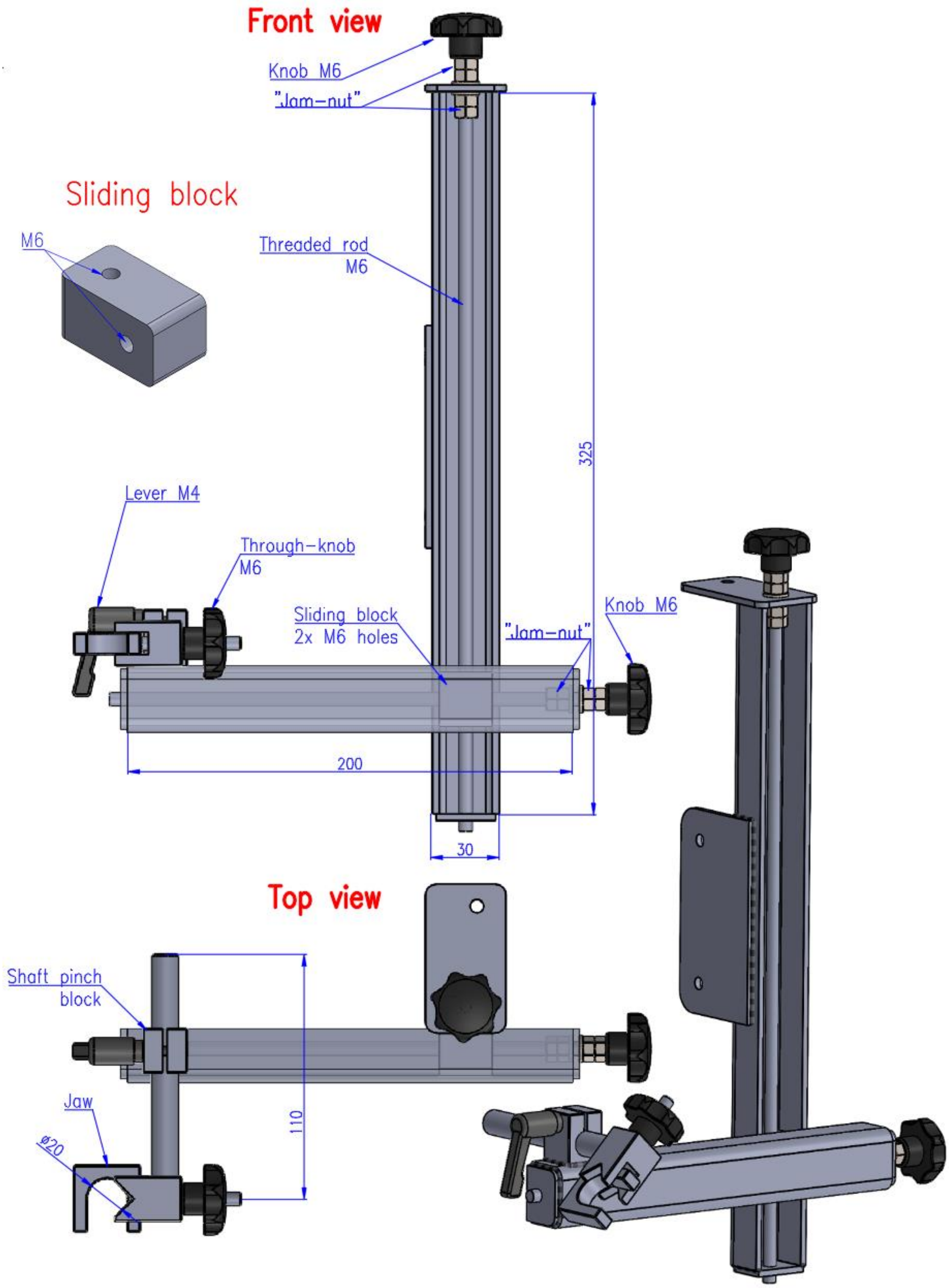

Figure 4.6 Gripping jig sub-assembly

4.5 Powertrain

When all of the main structural sub-assemblies were finalised, it was necessary to choose the components that would put the carriage in motion. A powertrain of the carriage consists of a drivetrain sub-assembly and electronic components that would provide the drivetrain with power and would control it.

4.5.1 Calculations for motor choice

To select a motor, several input parameters have to be known – mass of the carriage, speed at which it has to move, forces that have to be applied to the carriage to put it into motion. Having put all of the previously described sub-assemblies together, the mass of the carriage comes out to exactly 20 kg. To that we have to add the mass of welding torches, that will be driven by the carriage, and an estimated mass of a drivetrain and electronic components that are being selected. Each of two welding torches, that would be clamped to the carriage, comes with a 5 m cable and weighs at 2,5 kg. Assuming that some portion of that cable will be on the ground at any time, we estimate the mass of each torch, that the carriage has to move, to be 2 kg. Then come the drivetrain components – an electric motor, driver for the motor, power supply, drive sprocket and a roller chain. The mass of these components was roughly estimated to be around 2 kg, which in the end has proven to be fairly accurate. Thus, having summed up all of the parts, the total mass of the carriage comes out to:

- m = 26 kg – total operating mass of the carriage

The speed, at which the carriage has to travel, is defined by WPS – a Welding Procedure Specification. WPS establishes the procedure requirements and norms for different types of welding operations, that are applied in the company, and is developed by the certified authority. In table 4.1 the conforming norms for T-beam welding operation in flat position are presented. These, however, are listed for a single-sided welding operation only.

Table 4.1 T-beam welding norms in flat position

Equipment	**Welding process**	**Welding seam, mm**	**Welding speed, m/min**	**Arc burning time, hour/m**	**Total welding time, hour/m**
Manual MIG	135	a4	0,3	0,06	0,12
Miggytrac	135	a4	0,35	0,05	0,07

As we can see from the table, the welding speed for a Miggytrac welding tractor is listed as 0,35 m/min. However, after consultation with the production department it was found out that in reality, they are able to achieve a comparable quality of the seam at a slightly higher welding speed. This is the actual welding speed used in the production, that will be referred to in the calculations:

- v = 0,45 m/min = 0,0075 m/s – reference speed of carriage during welding

Now the forces required to put our carriage into motion have to be calculated. First one is the force required to accelerate the mass of the carriage, which is derived from the Newton's second law of motion. Another force, that has to be overcome, is rolling resistance force. It is the friction force that acts between the wheels and the surface; and resists the forward motion. There is also a drag caused by the air resistance, but since the velocity in question is so low, the air resistance in the following calculation will be neglected. Thus, the sum of the forces that have to be applied to the carriage to put it into motion can be expressed as:

$$F_{\Sigma} = F_a + F_{rr} \ , \tag{4.1}$$

where F_{Σ} – sum of forces to be applied to the carriage, N,

F_a – accelerating force, N,

F_{rr} – total rolling resistance force, N.

Accelerating force is the first component that will be calculate. We know the mass of the carriage and the velocity at which it has to move. To calculate the aforementioned force, we have to decide how quickly our carriage should achieve this velocity. Assuming that the carriage is put into motion almost simultaneously with welding torches being turned on, the carriage has to achieve the running velocity fairly quickly, to ensure the quality of the weld. We will assume, that the carriage has to achieve its selected velocity in 0,5 seconds. Thus, the accelerating force is calculated according to Newton's second law:

$$F_a = m * a = m * \frac{v}{t} \ , \tag{4.2}$$

where F_a – accelerating force, N,

m – mass of the carriage, kg,

a – accelerationn, $a = \frac{v}{t}$, m/s²

$$F_a = 26 * \frac{0,0075}{0,5} = 0,4 \text{ N}$$

Rolling resistance force in our case has two main components. First of all, we have rolling resistance in the medium between carriage wheels and the table top of a workbench. Secondly, we have rolling resistance between guiding rollers and the web of a T-beam.

$$F_{rr} = F_1 + F_2 \ , \tag{4.3}$$

where F_{rr} – total rolling resistance force, N

F_1 – force required to start wheel motion from rest, N

F_2 – rolling resistance of guiding rollers, N.

First, we will find the rolling resistance force acting on our wheels. Some force $F_1{}'$ has to be applied to the carriage to overcome the rolling resistance. Here we assume that our carriage is already in motion. We can derive this force $F_1{}'$ by balancing the moments (Figure 4.7):

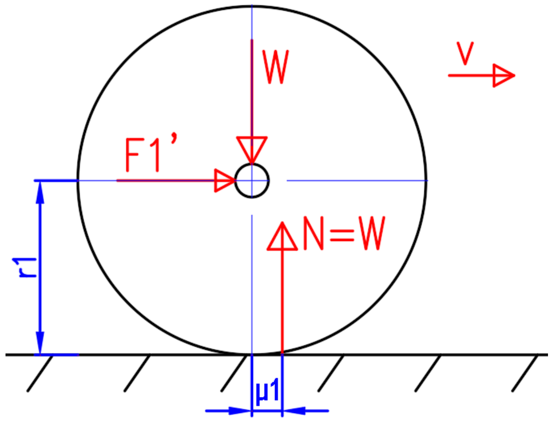

Figure 4.7 Forces acting on carriage wheels

$$F_1{}' * r_1 =* \mu_1 * W => F_1{}' = \mu_1 * \frac{W}{r_1} \ , \tag{4.4}$$

where $F_1{}'$ – rolling resistance force acting on carriage wheels, N,

μ_1 – rolling resistance coefficient of carriage wheels, cm,

W – weight of the carriage $W = m * g$, N,

r – radius of the wheel, cm.

In order to calculate it, we have to know the rolling resistance coefficient associated with our conditions. This coefficient depends on the material of the wheel, material of the contact surface and the load. Usually, this coefficient is found experimentally. In our case, the wheel material is polyurethane and the contact surface is steel. Since the load on our wheels is comparatively low and they will not deform as much, a lower value of rolling resistance coefficient found for polyurethane caster wheels on steel surface will be taken and the rolling resistance force will be calculated:

- μ_1 = 0,03 in ≈ 0,076 cm – rolling resistance coefficient of PU wheels [7]
- r_1 = 4 cm – radius of carriage wheels

$$F_1{}' = 0{,}076 * \frac{26*9{,}81}{4} = 4{,}8 \text{ N}$$

This force will be enough to sustain the motion of the carriage that is already rolling. However, we have to consider that our carriage is starting the motion from rest, which introduces another component – static friction. According to empirical data, the force that is required to initiate the motion is about 2 times higher, than the force required to sustain the motion [7]. Thus, we will calculate the force, that is required to set the wheels in motion from rest:

$$F_1 = 2F_1{}' \,, \tag{4.5}$$

where F_1 – force required to start wheel motion from rest, N.

$$F_1 = 2 * 4{,}8 = 9{,}6 \text{ N}$$

Now we have to calculate the rolling resistance force acting on the guiding rollers of the carriage. Since we have two driving wheels on one side of the carriage and the tractive force is evenly distributed between these wheels, the carriage tries to steer to the centre and pushes two diagonally opposed guiding rollers into the T-beam's web. Thus, a rolling resistance force occurs between guiding rollers and the beam (Figure 4.8):

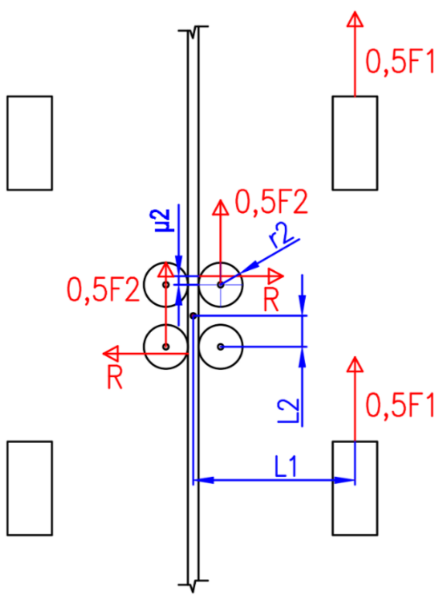

Figure 4.8 Forces acting on guiding rollers

To find force F_2, we first have to find reaction force R. This is again done by balancing the produced moments:

$$2 * 0{,}5F_1 * l_1 = 2 * R * l_2 => R = \frac{0{,}5F_1 * l_1}{l_2}\ , \qquad (4.6)$$

where R – reaction force at the contact point of a roller and a beam, N,

l_1 - lever arm of the force applied to the wheel, mm,

l_2 - lever arm of the force applied to the guiding roller, mm.

$$R = \frac{0{,}5*9{,}6*250}{25} = 48 \text{ N}$$

Now we apply equation 4.4 to find force F_2:

- μ_2 = 0,02 in = 0,05 cm – rolling resistance coefficient of a forged steel roller [7]
- r_2 = 1,5 cm – radius of guiding rollers

$$0{,}5F_2 = 0{,}05 * \frac{48}{1{,}5} => F_2 = 2 * 0{,}05 * \frac{48}{1{,}5} = 3{,}2 \text{ N}$$

Then we can finally calculate the total rolling resistance force (4.3) and the sum of forces, that have to be applied to the carriage, to put it into motion (4.1):

$$F_{rr} = 9{,}6 + 3{,}2 = 12{,}8 \text{ N}$$

$$F_{\Sigma} = 0{,}4 + 12{,}8 = 13{,}2 \text{ N}$$

Knowing the sum of forces required to set the carriage in motion, we can calculate the torque that the motor has to produce. Each component of the drivetrain has its efficiency index, so we have to account for the losses that occur in those components to calculate the required torque.

$$T = F_{\Sigma} * r * \frac{1}{\eta_1} * \frac{1}{\eta_2} * \frac{1}{\eta_3}\ , \qquad (4.7)$$

where T – torque from the motor, Nm,

F_{Σ} – sum of forces to be applied to the carriage, N,

r – radius of the carriage wheel, m,

η_1 – efficiency of motor reductor,

η_2 – efficiency of wheel bearings,

η_3 – efficiency of chain drive.

$$T = 13{,}2 * 0{,}04 * \frac{1}{0{,}75} * \frac{1}{0{,}99} * \frac{1}{0{,}92} \approx 0{,}8 \text{ Nm}$$

Since the speed characteristic of a motor is expressed by its rotational speed, the linear speed of a carriage will be converted into rotational speed of its wheels. This is the rotational speed that the wheels should achieve after all of the gear reductions in the drive train:

$$\omega = \frac{v}{2\pi r}\,, \tag{4.8}$$

where ω – rotational speed of wheels, s^{-1},

v – linear speed of the carriage, m/s,

r – radius of the wheel, m.

$$\omega = \frac{0{,}0075}{2\pi * 0{,}04} \approx 0{,}03 \text{ s}^{-1} = 1{,}8 \text{ rpm}$$

4.5.2 Motor, controller and power supply choice

There are different types of electric motors: DC motors, AC motors, stepper motors, servo motors etc. Different types of motors have different torque profiles and types of control systems. As we have figured out, we will need a motor that has to produce the calculated torque at low rotational speed. Out of all electric motor types, a stepper motor can be distinguished as the one that generally has lower rotational speed, but has the highest torque. One of the other main advantages of a stepper motor is that it is easy to control. It can be used with an open-loop control system, that does not require feedback. As a result, it requires less complex controller and an overall cost of implementation is much lower compared to other types of electric motors [8]. The choice to use a stepper motor is further backed up by the fact that currently applied Miggytrac welding tractor also uses this type of motor.

There are two possible ways to select a stepper motor – either we can choose a bigger motor with higher torque and no gearbox, or we can take a smaller one with lower torque, but with the gearbox. Due to very low required velocity of the carriage, the rotational speed of the motor also has to be low, which is why we will make use of an option with the gearbox. Based on required parameters, the following stepper motor was chosen from the *Stepperonline* catalogue:

Motor:

- Manufacturer Part Number: 17HS15-1684S-PG5
- Motor Type: Bipolar Stepper
- Torque without Gearbox: 0,36 Nm
- Torque with Gearbox: 1,86 Nm
- Rated Current/phase: 1,68 A
- Voltage: 2,8 V
- Frame Size: 42 x 42 mm (Nema 17)

Gearbox:

- Gearbox Type: Planetary
- Gear Ratio: 5,18: 1
- Max. Permissible Torque: 2 Nm
- Shaft Diameter: 8 mm
- Weight: 460 g

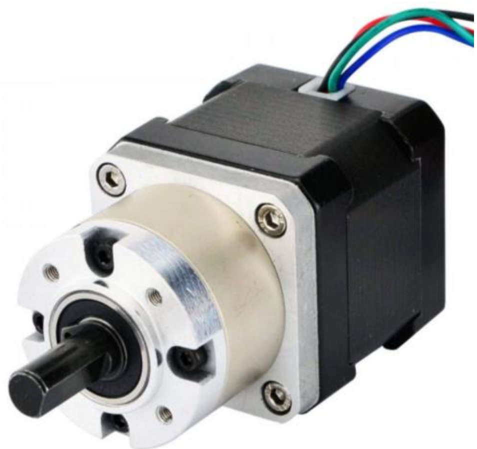

Figure 4.9 Nema 17 type stepper motor with planetary gearbox [9]

In order for this motor to operate, we will need a power supply, a driver and a controller. While looking for a controller, one convenient solution came to light, where a driver and a controller are integrated into one single unit. This unit has an in-built driver that provides the motor with required voltage and current from the power supply; and has the required controls to select the motion direction and the rotational speed.

Controller + driver:

- Manufacturer Part Number: ZK-SMC02
- Motor Type: Stepper
- Number of control axes: 1
- Power supply range: DC 5-30V
- Driving capacity: 4 A

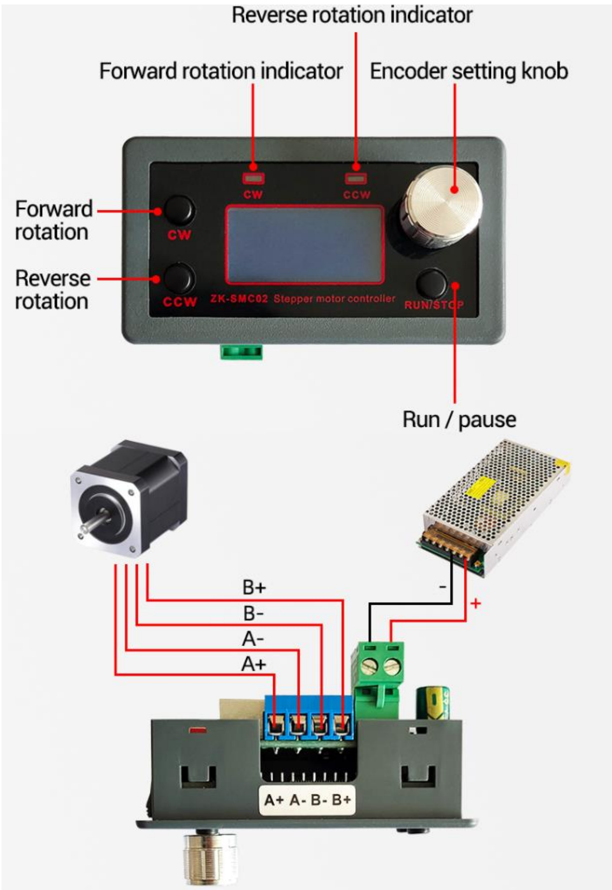

Figure 4.10 SMC02 Stepper motor driver and controller [10]

Finally, we need to select a power supply. For now, it is planned to power the carriage directly from the 220 V electrical grid. A suitable for the application power supply was selected from the *Stepperonline* catalogue:

Power supply:

- Manufacturer Part Number: S-50-12
- Output: 12 V DC 4,2 A
- Input: 85~132V/170~264VAC

Figure 4.11 Switching power supply [11]

4.5.3 Drivetrain sub-assembly

Several other components are required to complete the assembly of a drivetrain. A motor has to be mounted to the carriage's frame, a drive sprocket for the motor has to be selected and a roller chain installed.

An 11-teeth sprocket of 06B-1 type is selected and installed onto the motor shaft and locked with a set screw. This, together with the 15-teeth sprockets in the wheel hubs, gives an additional gear ratio of 1,36:1. Taking into account the 5,18:1 gear ratio of the motor gearbox, we achieve a final gear ratio of 7:1. Thus, the torque of the motor is increased by seven times when it reaches the wheels and the rotational speed is reduced by the same amount.

To attach the motor to a carriage's frame, a motor has to be mounted to its own frame. A motor frame for Nema 17 type motor is also supplied from the *Stepperonline* catalogue. To achieve a required chain wrap angle of 120°, the motor has to be raised in relation to wheel axes. To achieve that, a motor frame is attached to the frame of the carriage with the use of a mounting bracket, that is manufactured out of the 3 mm thick steel.

The assembly is finalised with an installation of 06B-1 simplex roller chain. An appropriate fit and sufficient tension of the chain is achieved through the use of two ball bearing rollers, that act as idler wheels. These are mounted directly to the carriage's frame. A complete bill of materials for the drivetrain assembly can be found in Appendix 1. This is how the drivetrain components of the powertrain are arranged (Figure 4.12):

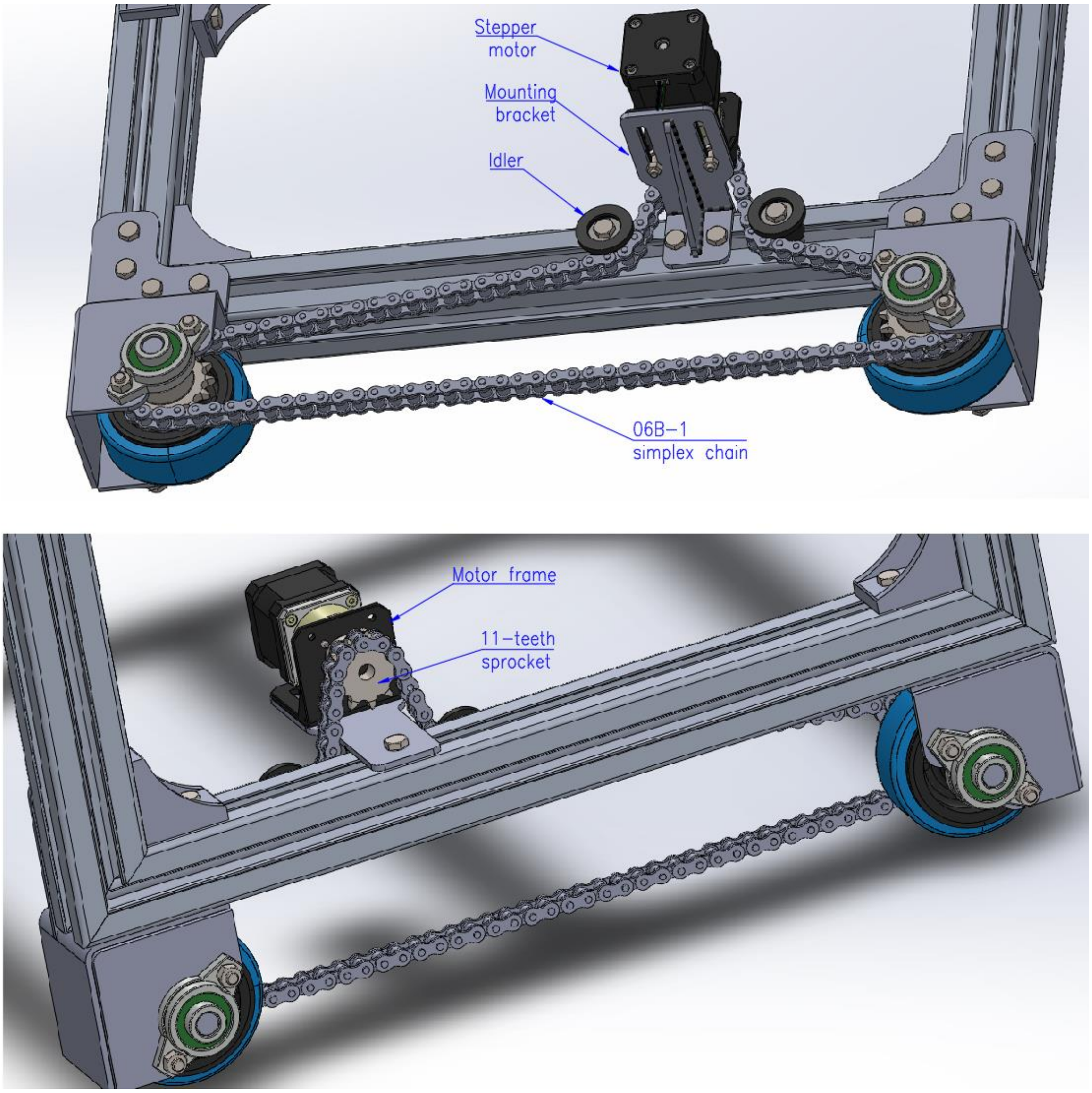

Figure 4.12 Drivetrain components

4.6 Complete assembly of welding carriage

Now, with all of the sub-assemblies complete, a welding carriage could finally be fully assembled. Wheel hubs, guiding roller assemblies and gripping jig sub-assemblies are attached to the frame with the use of T-nuts and M6 fasteners. In the final assembly side panels that are made out of 1 mm thick steel were added. On the non-drive side, a power supply is installed between these panels. On the drive side, the panels serve as safety shrouds that cover the moving components of the carriage. The controller is installed on top of the middle frame member. This is what an assembled welding carriage looks like (Figure 4.13 and Figure 4.14):

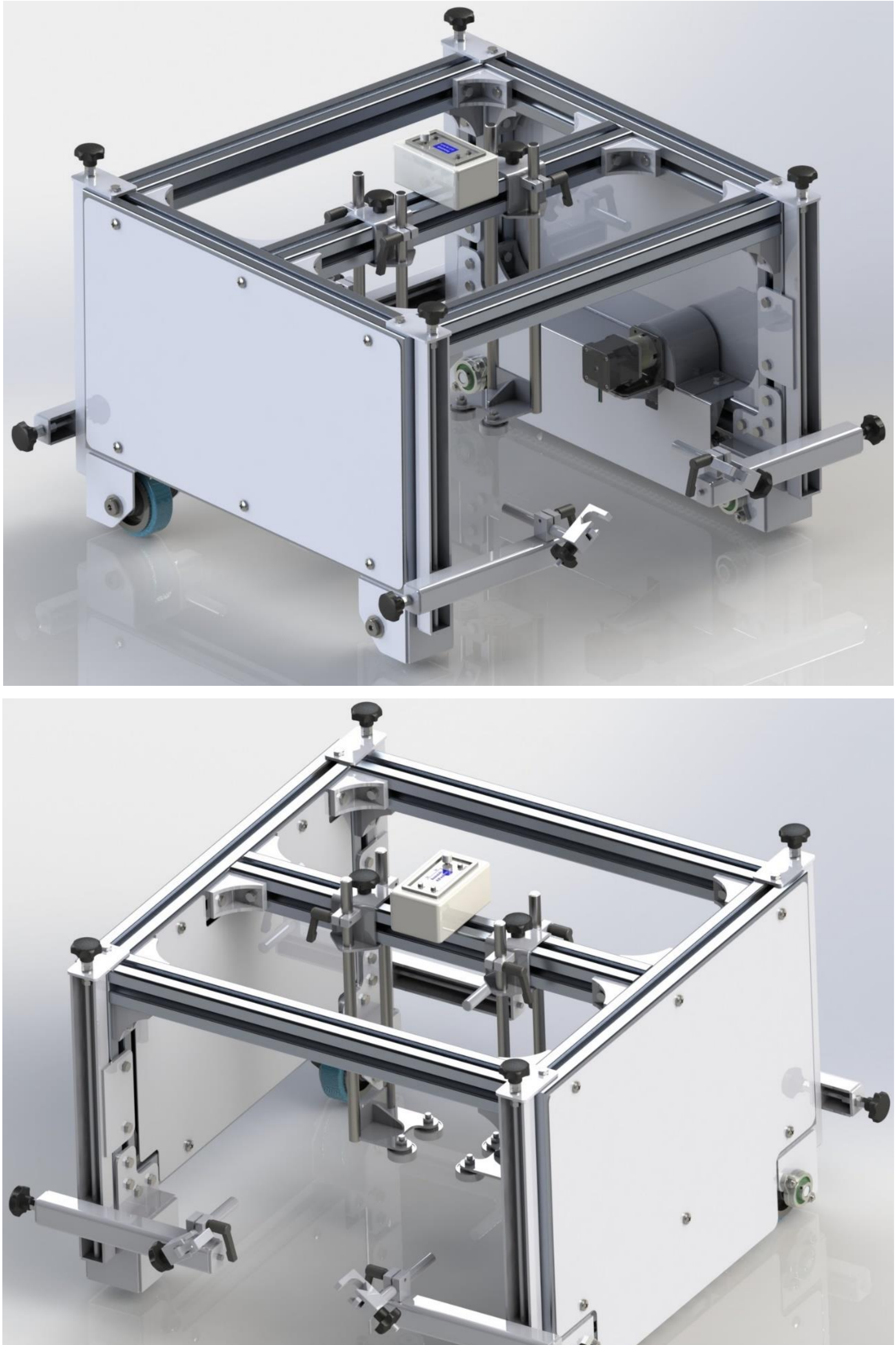

Figure 4.13 Assembled welding carriage

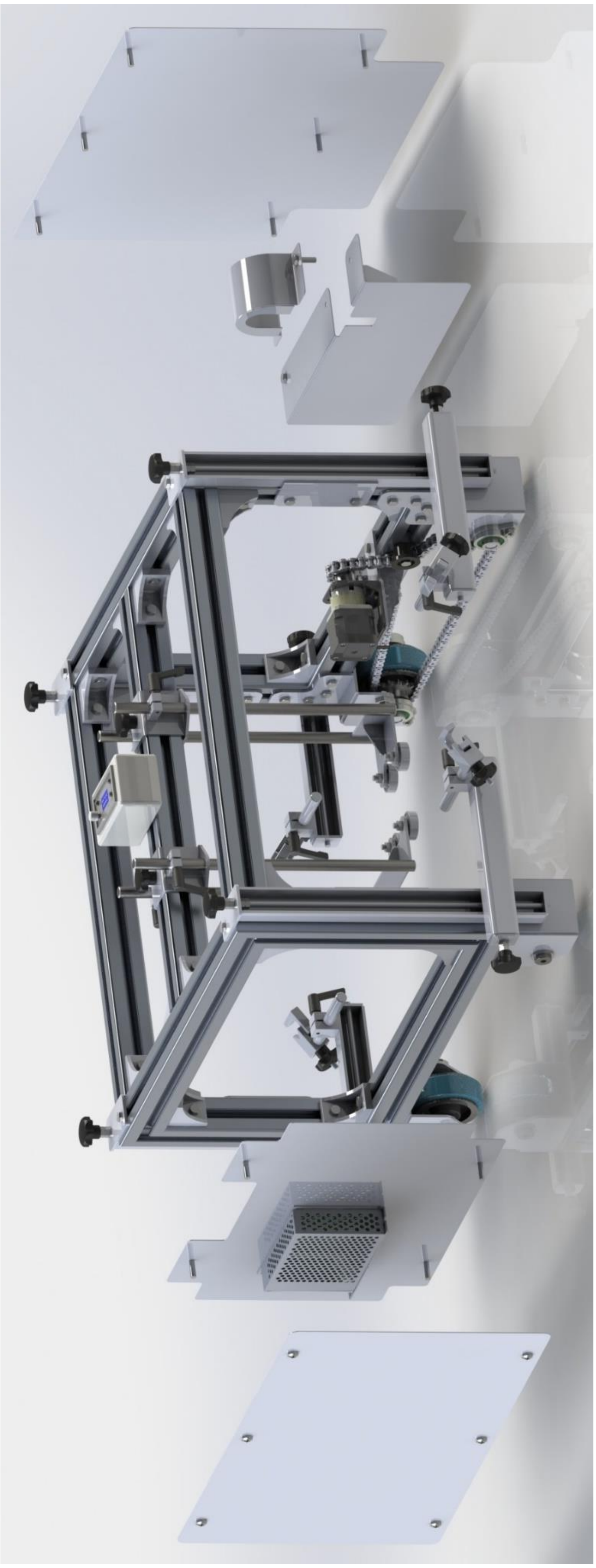

Figure 4.14 Side panels exploded view

5. WORKBENCH DEVELOPMENT

In this chapter a design process of a T-beam welding workbench is described. The design of a workbench was developed in parallel with a welding carriage.

Currently, the process of assembly and welding of T-beams in Marketex Marine OÜ takes place directly on the assembly shop floor. The floor is covered with special tiles, that act as fixture points for the assembled structures. Assembly and welding directly on the floor imply that the workplace ergonomics of the workers performing these tasks are sub-optimal. While this is basically an integral part of production of large flat sections of the hull that are simply impossible to place on some sort of workbench; T-beams are not that big in size, and if they are produced in relatively large quantities, a separate specialised workbench for their assembly and welding could be justified. The established requirements for the developed workbench were that it has to have a capacity to support produced T-beams' sizes, has to provide the possibility for a welding carriage to move lengthwise without obstructions, has to provide fixture points for produced profiles and has to be designed with workplace ergonomics' principles in mind.

Table top of the workbench is made out of 10 mm thick steel and has dimensions of 1000x7300 mm. These dimensions allow to place a T-beam that has a length L = 5980 mm and leave enough spare space for the carriage to drive the complete length of the welding seam in both directions. The underside of the table top is reinforced with transverse and longitudinal stiffeners made out of FB50x10 flat bar. On both ends of the table top there are bolted angle bars AB50x50x5 that act as stoppers and would prevent the carriage from falling off the workbench in case operator does not manage to stop the carriage in time.

T-beam is placed in the centre of the workbench and has to be clamped to prevent any movement due to contraction of metal in the process of welding. To provide clamping of the beam flanges of varying thicknesses, a wedge clamping solution was designed. Offset from one side of the middle of a workbench there are seven equally spaced wedges that are machined out of FB70x30 flat bar and welded to the surface of the table top. From the other side of the middle there are slots cut in the table top and the wedges can be moved along these slots to clamp beams of different widths. These moveable wedges are clamped in place with the M20 bolts and nuts that are welded to the backing flat bar FB80x8. This contraption eliminates the need to hold the nut in place from the underside when tightening the wedge clamp (Figure 5.1).

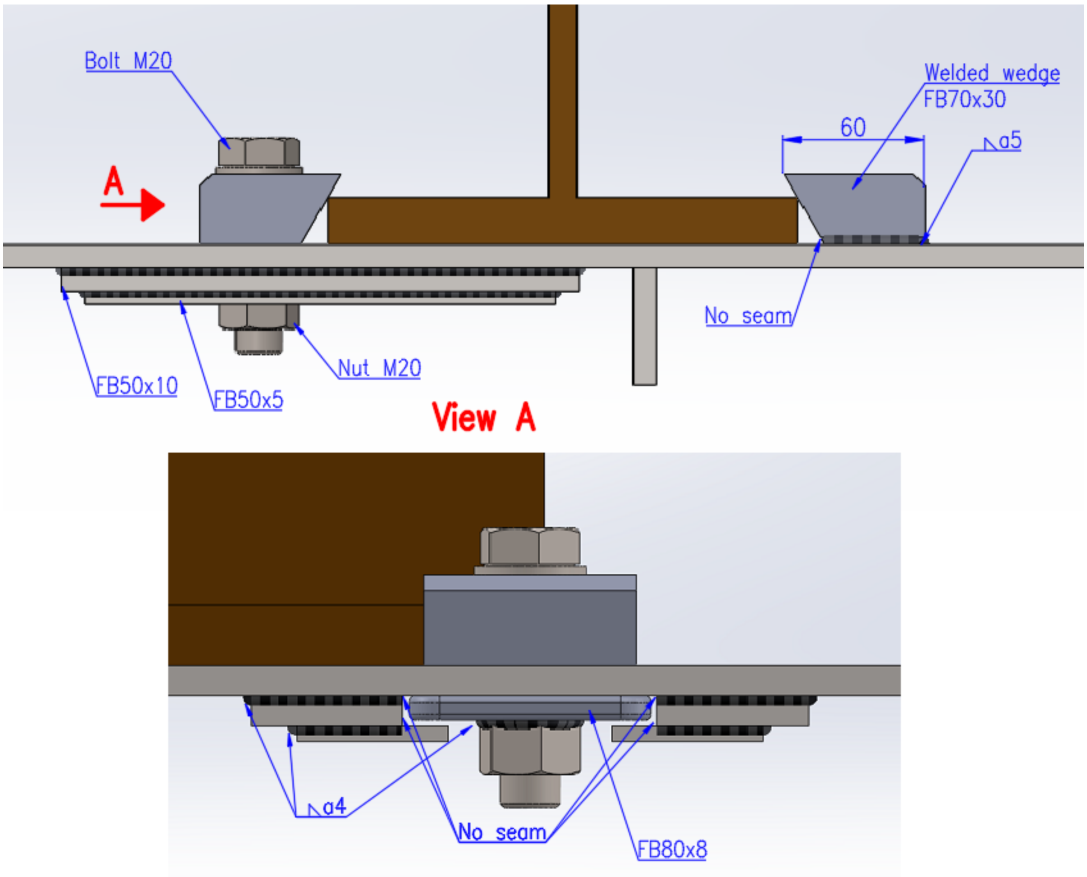

Figure 5.1 Wedge clamping

The workbench stands on eight legs made out of square tube SHS50x50x5 that are braced together with angle bars AB50x50x5. All legs are equipped with adjustable feet that would compensate for any unevenness of the shop floor. When the workbench was developed, the height parameter had to be selected. The goal was to keep to the ergonomic principles of welder's workplace.

Thus, it was decided to turn to occupational safety and health act. Unfortunately, it has proven to be difficult to find any information concerning this topic in the European Union's act, but a suitable graph from the materials of Canadian Centre for Occupational Health and Safety was found. The graph provides advisory information regarding the standing welding workbench design (Figure 5.2) [12]. There are two parameters of interest – minimal work zone height "*d*" and maximal height "*e*". Assuming that the beam's seam that is being worked on is basically on the level of the table top and assuming that average welder's height is around 175 cm, the height of the workbench was taken as an average of minimal and maximal work zone heights. So, the table top of the workbench is at exactly 100 cm or 1 m above the ground. This makes the assembly and welding of the beam much more convenient and will still allow the welder to bend over the beam to control the welding process of both seams by the welding carriage.

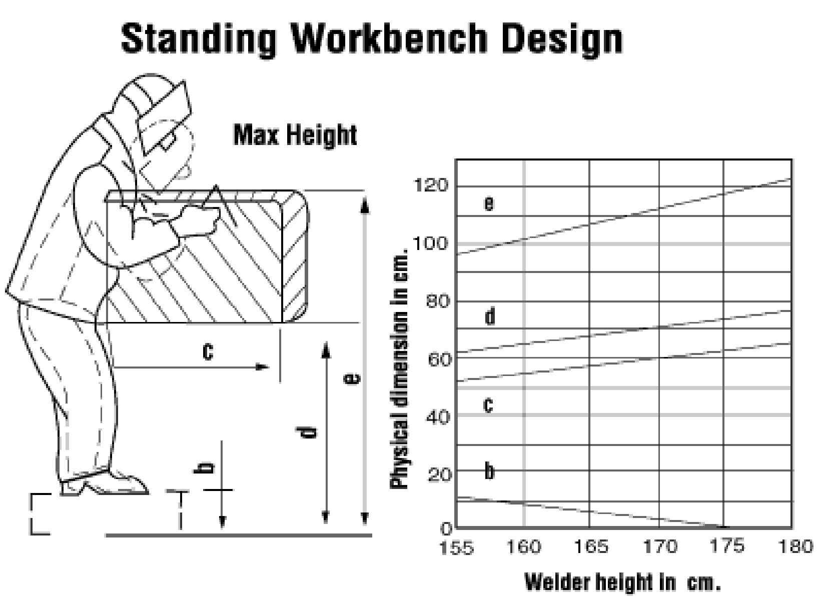

Figure 5.2 Standing workbench design [12]

Finally, to make sure that the designed workbench is safe and would be able to support the weight of the produced parts and other equipment that could be placed on top, a stress analysis of the structure was performed with the help of SolidWorks Simulation. During the simulation a load in the form of distributed mass was applied to the top of the workbench. The mass of the largest possible section of T-beam that could be produced at a time was estimated to be around 350 kg. To that a supposed weight of the carriage and other equipment and tools that could be placed on the workbench was added. Thus, the final applied load was taken as 500 kg.

As a result of the simulation the following parameters were received (Figure 5.3). A value of 26,3 MPa was received in the von Mises stress analysis, which is way below the critical amount of stress. A maximal displacement of 0,748 mm was observed, which is completely acceptable, considering the overall dimensions of the workbench. An axial and bending stress analysis has shown a maximal value of stress equal to 23,7 MPa. All of the received values indicate, that the developed workbench has enough sturdiness to support the supposed loads.

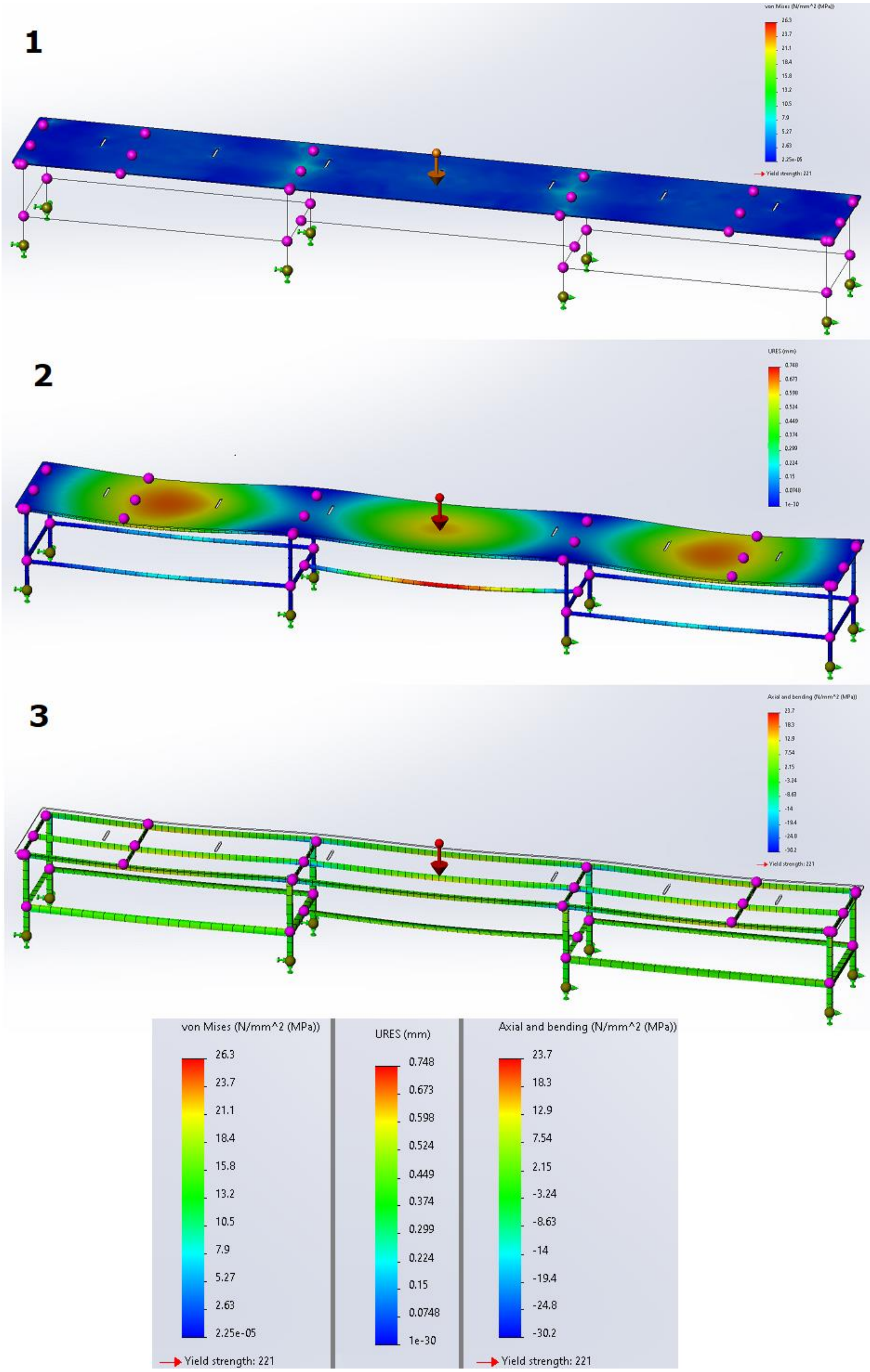

Figure 5.3 SolidWorks Simulation

1 – von Mises, 2 – displacement, 3 – axial and bending

A complete bill of materials for the workbench can be found in Appendix 1. This is what a final version of the workbench looks like (Figure 5.4):

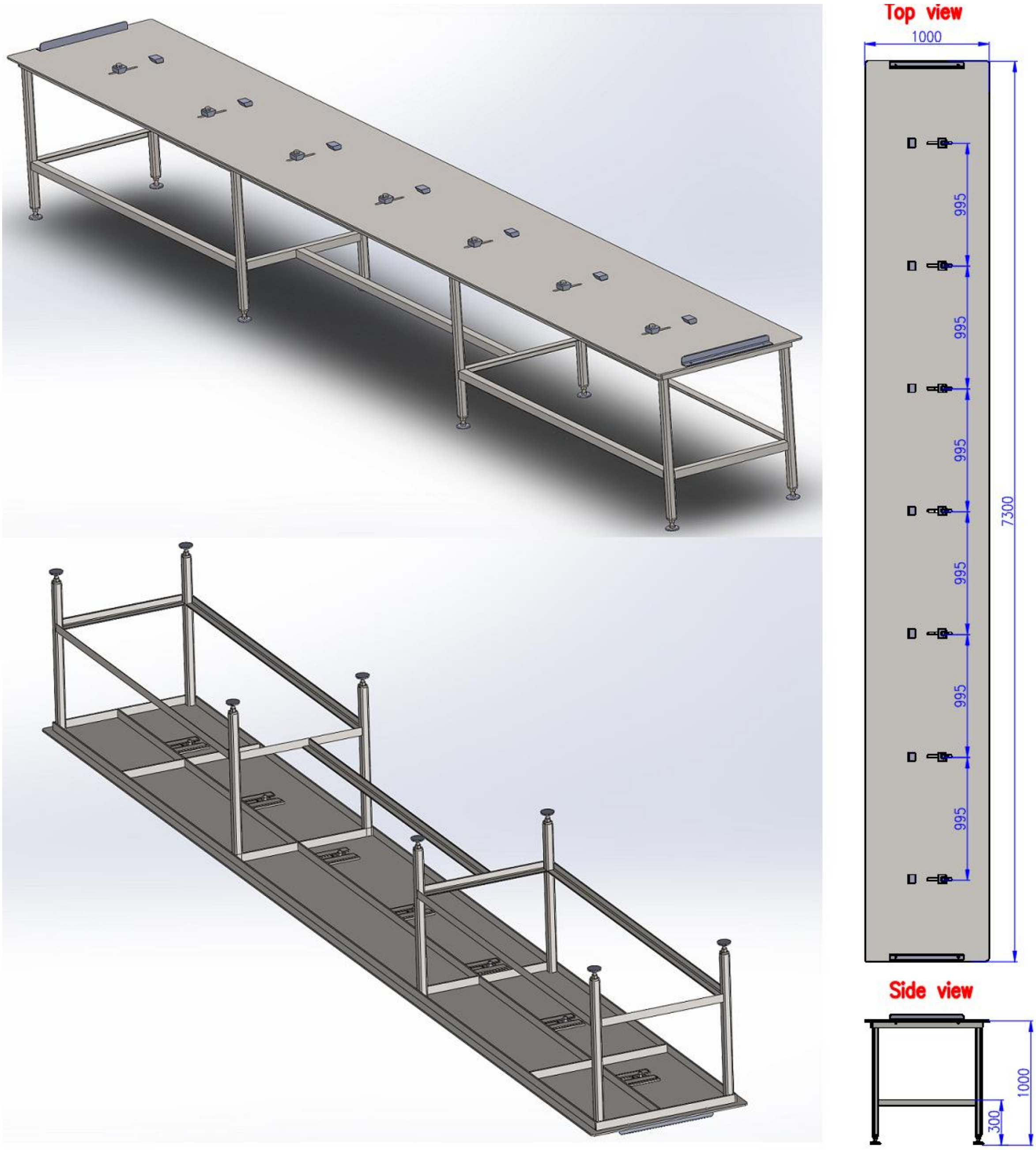

Figure 5.4 Workbench

6. COST CALCULATION

With the design of the carriage and the workbench finalised, it was necessary to calculate the costs associated with building of this complete workstation. The total cost would tell how reasonable such solution would be in the long run and how quickly it could pay off.

As mentioned in the previous chapters, a complete bill of materials for the proposed workstation on the sub-assembly basis was compiled and could be found in Appendix 1. All of the listed parts were divided into four main categories and colour coded: plate parts, profiles, fasteners and ready-made components. As per one of the project requirements, the majority of parts or at least the raw materials for their fabrication are sourced from the partner companies. Cut plate parts and profiles are supplied entirely from Elme Metall OÜ and the cost is mainly agreed between the companies on per kilogram basis. All fasteners are provided by ELME AS and the cost is defined based on the fastener type. Custom drive shafts for the drive-side wheel hubs are machined by BLRT Masinaehitus OÜ. Majority of the remaining ready-made components are purchased from the following product catalogues. All of the corresponding product codes are indicated in the BOM in Appendix 1.

- *Stepperonline* – motor, motor frame, power supply
- *TYMA CZ, s.r.o.* [13] – sprockets, roller chain
- *MISUMI* [14] – wheels, bearings, rollers, knobs, levers, set collars
- *Aliexpress* – motor driver+controller

In the following two tables there are listed the total material costs for the welding carriage and the workbench assemblies.

Table 6.1 Welding carriage material costs

Welding carriage			
	Total amount, kg (m)*	**Price, €/kg (€/m)***	**Cost, €**
Fasteners	N/A	N/A	230,9
Components	N/A	N/A	356,49
Plates	7,30	2,40	17,52
Profiles	6,10	1,40	8,54
Alu. extrusion 40x40*	4,57	19,10	87,29
Total	**as of 15.12.2022**		**700,03**

Table 6.2 Workbench material costs

Workbench			
	Total amount, kg	**Price, €/kg**	**Cost, €**
Fasteners	N/A	N/A	34,05
Plates	577,20	2,40	1385,28
Profiles	230,80	1,40	323,12
Total	**as of 15.12.2022**		**1742,45**

To calculate the total cost, one has to include the work hours required to machine, assemble, weld and paint the components. Each type of operation is calculated according to established norms from reference handbooks and normalised time components are summed up. It is worth noting, that no matter the operation type, the cost price of a work hour is essentially the same for the company. Having normalised the production operations, the total production cost of the project was estimated and presented in the following table.

Table 6.3 Workstation total cost

Workstation				
	Work hours, h	**Cost price, €/h**	**Material cost, €**	**Manufacturing cost, €**
Welding carriage	24	35,00	700,03	1540,03
Workbench	18	35,00	1742,45	2372,45
Total	**as of 15.12.2022**			**3912,48**

This is as close of an estimation as it is possible to do at this stage. Some additional expenses, such as shipping costs, would be later added to the final cost of the project. Overall, it can be declared that the total cost of the project is definitely within the allocated budget of 4500 €.

6.1 Payback calculation

Calculation of the payback is done on the basis of welding norms presented in table 4.1. The norms in the table for manual welding operation and for Miggytrack welding tractor are given for a single-sided welding operation, but since a T-beam has two welding seams, the total welding time will be doubled for those solutions in the following calculation. The total welding time for a developed carriage that performs double-sided welding will be equal to half of a Miggytrac welding tractor's total welding time. Cost price of a work hour is the same in all cases. Knowing the welding time and cost price of a work hour, a welding cost of a running meter of a T-beam is calculated. Then, knowing the difference in cost of a running meter, a meterage required to compensate for the previously found manufacturing cost of a workstation is calculated. And finally, a payback time is calculated. The results are presented in table 6.4.

Table 6.4 Payback calculation

	Total welding time, h/m	**Work hour cost price, €/h**	**Running meter welding cost, €/m**	**Payback meterage, m**	**Payback time, h**
Manual MIG (2 single-sided passes)	0,24	35,00	8,40	657,56	46,02
Miggytrac (2 single-sided passes)	0,14	35,00	4,90	1596,93	111,79
New carriage (1 double-sided pass)	0,07	35,00	2,45	N/A	N/A

What should be noted, is that Marketex Marine OÜ employs project-based production. This means that payback period cannot be accurately expressed in days, months or years. In this case, it is much more convenient to calculate the meterage that a developed carriage would have to weld, in order to pay off its manufacturing cost. If it is assumed that only manual MIG welding method of T-beams is used, it would have to weld a total of around 657 meters to pay off completely. If only Miggytrac welding tractor is used, it would need to weld around 1597 meters of a T-beam to compensate for its manufacturing cost. An actual amount would be somewhere in between, likely closer to the lower value, since majority of T-beams are welded manually after all. To provide a better context for these values, they can be compared with the total length of T-beams used in the previously mentioned ScaleAQ Aasgard 900 barge. The total length of T-beams used in the construction of this type of barge is estimated at around 1200 meters. This means, that the proposed solution would, with a high probability, pay off during the construction of a single analogous project.

7. CE MARKING

Before being able to put the developed product to use, it is necessary to understand and follow the relevant legislation. Manufacturer of the product has to make sure that his product conforms to the EU safety, health and environmental protection requirements. To verify the conformity of the product to these requirements, a manufacturer has to carry out the assessment with all of the required procedures and affix the CE marking to his product. [15] Contrary to broad assumption, products manufactured for own use do require CE marking.

There are six main steps to affix a CE marking to a product [15]:

- Identifying applicable directives and harmonised standards
- Verifying product specific requirements
- Identifying whether conformity assessment by a notified body is necessary
- Testing the product
- Creating a file with the required technical documentation
- Affixing the CE marking and compiling a declaration of conformity

There are three main directives that are applicable to a developed welding carriage:

- Machinery Directive 2006/42/EC
- EMC Directive 2014/30EU
- RoHS Directive 2011/65/EU

When the applicable directives are defined, it is necessary to understand the requirements determined by these directives. These requirements are known as essential requirements. Best way to verify that the essential requirements are met is to follow more technically detailed requirements of applicable harmonised standards. An example of an applicable harmonised standard is EVS-EN ISO12100:2010 [16], which describes the procedures of risk assessment and risk reduction associated with the use of machinery.

Then the conformity to the standards and fulfilment of requirements has to be assessed. This could be done independently by manufacturer or in certain cases with the help of accredited conformity assessment body. For example, since the developed carriage does not fall under categories of machinery specified in Annex IV of Machinery Directive, the conformity assessment to the Machinery Directive could be performed by the manufacturer himself [17].

The following important step is to compile and maintain all the of technical documentation that demonstrates the product's conformity, such as technical drawings, test reports, instructions, BOM etc. This compiled document is called a technical file. Finally, when the product is proven to be conforming to the standards, declaration of conformity to the applicable directives should be created and a CE marking affixed to the product. Only after completing all of these steps, the developed product could be officially put to use.

SUMMARY

The aim of this thesis was to design a custom workstation that would allow to drastically decrease the time of a T-beam welding operation in shipbuilding company Marketex Marine OÜ. The developed workstation has to allow to employ simultaneous double-sided welding, while also being convenient for the operator.

First step of the research was to analyse the existing T-beam welding methods and to describe the solutions, that are currently applied in the company. After that, the alternative solutions were listed and compared with the current ones. Based on the pros and cons, as well as productions department's needs, the product design requirements were established.

Next step was the development a 3D model in CAD software SolidWorks. The proposed workstation consists of two main assemblies – a welding carriage and a workbench. A motorised welding carriage that facilitates partial automation of a welding operation was developed. Two conventional MIG welding torches are attached to the carriage, operator selects the speed and direction of motion, and the carriage drives along the seam. Then, a practical workbench with a clamping system was developed. During the development, required calculations were made and the appropriate materials and components were selected. Majority of components for the workstation are to be manufactured with the help of BLRT Grupp AS subsidiaries, others were chosen from the catalogues.

As a result of a design development, a complete bill of materials was drawn up. The total manufacturing cost was estimated and it has proven to be within the project budget limit. Payback calculation has revealed that the proposed solution could with a high degree of probability pay off within the timeframe of a single project.

Overall, the proposed workstation is almost ready for manufacturing. But before being able to put it to use, the conformity assessment for the CE marking of the product has to be carried out. If the project will in fact prove to be efficient, further development could be proposed. For example, conversion of a carriage to a battery power, analogously to an applied welding tractor, could be explored.

In conclusion, the author feels that the established goals of the thesis were achieved. At the same time, it became clear that a significantly more extensive volume of work has to be done to transform the concept into an actual product.

KOKKUVÕTE

Käesoleva magistritöö eesmärk oli eritööjaama projekteerida, mis võimaldaks tunduvalt vähendada T-tala keevitusoperatsiooni aega Marketex Marine OÜ laevaehitusettevõttes. Projekteeritud tööjaam peab samaaegset kahepoolset keevitust võimaldama, mis omakorda oleks ka operaatorile mugav.

Kõigepealt oli vaja analüüsida T-taladede keevitusmeetodeid ja kirjeldada lahendusi, mida praegu ettevõttes kasutatakse. Need lahendused olid seejärel võrreldutud esitatud alternatiividega. Lähtuvalt eelistest ja puudustest, samuti tootmisosakonna vajadustest, tootekonstruktsiooni nõuded olid kehtestatud.

Sellele järgnes 3D-mudeli arendamine SolidWorks CAD-tarkvaras. Kavandatud tööjaam koosneb kahest põhikomponendist – keevitustraktorist ja töölauast. Mootoriga keevitustraktor, mis võimaldab keevitusoperatsiooni osaliselt automatiseerida, oli välja töötatud. Traktorile on kinnitatud kaks tavalist MIG-keevituspõletit. Operaator valib kiiruse ja liikumissuuna, ning traktor sõidab piki keevisõmblust. Selleks oli projekteeritud otstarbekas töölaud koos kinnitusseadmega. Planeerimise käigus olid läbi viidud vajalikud arvutused ning valitud sobivad materjalid ja komponendid. Enamik tööjaama komponentidest tuleb valmistada BLRT Grupp ASi tütarettevõtete abil, ülejäänud komponendid on valitud kataloogidest.

Projekti koostamise tulemuseks oli täielik materjalide loetelu. Tootmise kogumaksumus oli kalkuleeritud – see jäi projekti eelarvesse. Tasuvusarvutus näitas, et pakutud lahendus võib suure tõenäosusega tasuda end ära ühe projekti raames.

Üldiselt on kavandatav tööjaam peaaegu valmis tootmiseks. Kuid enne selle kasutusele võtmist, esiteks on vaja toote vastavushindamine läbi viia CE-märgise saamiseks. Kui projekt tõestab oma tõhusust, võib teha ettepaneku edasiseks arendamiseks. Näiteks võiks uurida traktori ümberehitamist akutoitele, analoogselt rakendatud keevitustraktorile.

Kokkuvõttes autor tunneb, et magistritöö eesmärgid on saavutatud. Samal ajal on selgunud, et selleks, et kontseptsioonist saaks tegelik toode, tuleb teha veel palju lisatööd.

LIST OF REFERENCES

[1] Scale Aquaculture AS. *Aasgard 900*. [Online]. Available: https://scaleaq.com/product/aasgard-900/?xdomain_data=EgkjJimkbtVL14GOhC%2B5XKVWAYhdhYwwIkH4lrNXKUgFgHrVYDjpJLl1zuPMdlbR. [Accessed 22 Dec 2022].

[2] Marketex Marine OÜ. *About us*. [Online]. Available: https://marketexmarine.net/en/. [Accessed 22 Dec 2022].

[3] Козловцев В.М., "Методические указания к выполнению лабораторных работ по дисциплине «проектирование сварных конструкций»," 2007 [Online]. Available: https://studfile.net/preview/7848746/page:12/. [Accessed 22 Dec 2022].

[4] KOWELD. *CS-251 I-BAR/ANGLE BAR Fillet Stitch and Continuous Dual side Welder.* [Online]. Available: http://www.koweld.co.kr/bbs/board.php?bo_table=eng_product2&wr_id=7. [Accessed 22 Dec 2022].

[5] Shanghai Huawei Welding & Cutting Machine Co., Ltd. *HK-6A-II Portable Wel-Twin Double Side Welding Tractor Carriage Two Torch.* [Online]. Available: https://www.huawei-cutting.com/hk-a-ii-portable-wel-twin-double-side-welding-tractor-carriage-two-torch-175.html. [Accessed 22 Dec 2022].

[6] ESAB. *Mechtrac 1730/2100/2500/3000.* [Online]. Available: https://esab.com/ee/eur_en/products-solutions/product/welding-automation-and-robotics/submerged-arc-welding-saw/carriers-and-manipulators/gantries/mechtrac-1730-2100-2500-3000/. [Accessed 22 Dec 2022].

[7] D. Lippert and J. Spektor, "Rolling Resistance and Industrial Wheels," Hamilton Caster, Hamilton, Ohio, USA, White Paper. [Online]. Available: https://www.mhi.org/media/members/14220/130101690137732025.pdf. [Accessed 22 Dec 2022].

[8] B. Lackey, "What's the Difference Between Servo and Stepper Motors?," MachineDesign, 25 June 2018. [Online]. Available: https://www.machinedesign.com/mechanical-motion-

systems/article/21836868/whats-the-difference-between-servo-and-stepper-motors. [Accessed 22 Dec 2022].

[9] Stepperonline. *Nema 17 Stepper Motor Bipolar L=38mm w/ Gear Ratio 5:1 Planetary Gearbox.* [Online]. Available: https://www.omc-stepperonline.com/nema-17-stepper-motor-bipolar-l-38mm-w-gear-ratio-5-1-planetary-gearbox-17hs15-1684s-pg5. [Accessed 22 Dec 2022].

[10] AliExpress. *SMC02 Stepper Motor Driver and Controller.* [Online]. Available: https://www.aliexpress.com/item/1005003590334407.html. [Accessed 22 Dec 2022].

[11] Stepperonline. *50W 12V 4.2A 115/230V Switching Power Supply.* [Online]. Available: https://www.omc-stepperonline.com/50w-12v-4-2a-115-230v-switching-power-supply-stepper-motor-cnc-router-kits-s-50-12. [Accessed 22 Dec 2022].

[12] Canadian Centre for Occupational Health and Safety. OSH Answers fact sheets. *Welding – Ergonomics.* [Online]. Available: https://www.ccohs.ca//oshanswers/safety_haz/welding/ergonomics.html. [Accessed 22 Dec 2022].

[13] TYMA CZ, s.r.o. [Online]. Available: https://www.tyma.eu/products/. [Accessed 22 Dec 2022].

[14] MISUMI Europa GmbH. [Online]. Available: https://uk.misumi-ec.com/en/products/. [Accessed 22 Dec 2022].

[15] European Commision. CE marking. *Manufacturers.* [Online]. Available: https://single-market-economy.ec.europa.eu/single-market/ce-marking/manufacturers_en. [Accessed 22 Dec 2022].

[16] *EVS-EN ISO 12100:2010. Safety of machinery - General principles for design - Risk assessment and risk reduction.*

[17] *Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC.* 9 June 2006. Article 12. L 157/31. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32006L0042&from=EN. [Accessed 22 Dec 2022].

APPENDICES

Appendix 1. Workstation bill of materials

Pos.	Part name	Type	Dimensions	Pcs. per assembly	Total quantity	Supplier	Price per piece, €	Product code
AT-1211-101_Frame sub-assembly					**1**			
1	Aluminium extrusion	40x40, slot 8	470	3	3	Elme Metall OÜ		
2	Aluminium extrusion	40x40, slot 8	290	4	4	Elme Metall OÜ		
3	Aluminium extrusion	40x40, slot 8	500	4	4	Elme Metall OÜ		
4	Corner bracket	Reversal	43x43	20	20	Misumi	0,94	HBLFSN8
5	Bolt	DIN 933	M6x16	40	40	Elme AS	0,10	
6	T-nut	DIN 508	M6x8	40	40	Elme AS	1,95	
AT-1211-102_Non-drive side wheel hub sub-assembly					**2**			
1	Plate	PL 3	144x59	1	2	Elme Metall OÜ		
2	Plate	PL 3	72x72	2	4	Elme Metall OÜ		
3	Plate	PL 3	83x75	1	2	Elme Metall OÜ		
4	Wheel	w/roller bearing	ø80/ø12	1	2	Misumi	7,56	B61.080
5	Set collar	w/set screws	ø12x5	2	4	Misumi	1,46	SCCJ12-5
6	Set screw	DIN 553	M3x3	4	8	Elme AS	0,10	
7	Shoulder bolt	ext. thread	M10, ø12x65	1	2	Elme AS	7,08	
8	Washer	DIN 125	M12	2	4	Elme AS	0,08	
9	Nut	DIN 934	M10	1	2	Elme AS	0,07	
AT-1211-103_Drive side wheel hub sub-assembly					**2**			
1	Plate	PL 3	144x59	1	2	Elme Metall OÜ		
2	Plate	PL 3	72x72	2	4	Elme Metall OÜ		
3	Plate	PL 3	83x75	1	2	Elme Metall OÜ		
4	Wheel	w/roller bearing	ø80/ø12	1	2	Misumi	7,56	B61.080
5	Bearing	flanged	ø12	2	4	Misumi	10,24	HBT12
6	Set screw	DIN 553	M3x3	6	12	Elme AS	0,10	
7	Shaft	keyed	ø12x95	1	2	Masinaehitus OÜ	25,00	Custom
8	Parallel key	DIN 6885	A4x4x10	1	2	Elme AS	0,40	
9	Sprocket 06B-1	15-teeth, keyway	12H7 bore	1	2	TYMA CZ, s.r.o.	7,37	06B-1-15-NKZ/D12
10	Plate	PL 1,5	70x20	1	2	Elme Metall OÜ		

11	Hex bolt	DIN 933	M6x16	4	8	Elme AS	0,10	
12	Nut	DIN 934	M6	4	8	Elme AS	0,07	
13	Hex bolt	DIN 933	M3x20	2	4	Elme AS	0,05	
14	Nut	DIN 934	M3	2	4	Elme AS	0,05	
AT-1211-104_Guiding roller sub-assembly					**2**			
1	Plate	PL 3	124x50	1	2	Elme Metall OÜ		
2	Plate	PL 3	88x56	2	4	Elme Metall OÜ		
3	Plate	PL 3	70x60	1	2	Elme Metall OÜ		
4	Plate	PL 3	54x25	1	2	Elme Metall OÜ		
5	Plate	PL 3	35x20	1	2	Elme Metall OÜ		
6	Round bar	RB12	300	2	4	Elme Metall OÜ		
7	Flat bar	FB20x10	25	2	4	Elme Metall OÜ		
8	Plate	PL 8	15x10	2	4	Elme Metall OÜ		
9	Knob	threaded shaft	M6x16	1	2	Misumi	1,37	NKSM6-16
10	Clamp lever	threaded shaft	M4x16	2	4	Misumi	3,45	300-30-M4-16-OS
11	Ball bearing	threaded shaft	ø30x12	2	4	Misumi	6,45	NTBGT30-12
12	Nut	DIN 934	M6	2	4	Elme AS	0,07	
13	T-nut	DIN 508	M6x8	1	2	Elme AS	1,95	
AT-1211-105_Gripping jig sub-assembly					**4**			
1	Plate	PL 3	65x36	1	4	Elme Metall OÜ		
2	Plate	PL 3	27x23	3	12	Elme Metall OÜ		
3	Plate	PL 3	100x54	1	4	Elme Metall OÜ		
4	Square tube	SHS30x30 x3	325	1	4	Elme Metall OÜ		
5	Square tube	SHS30x30 x3	200	1	4	Elme Metall OÜ		
6	Square bar	SB24x24	300	1	4	Elme Metall OÜ		
7	Square bar	SB20x20	43	1	4	Elme Metall OÜ		
8	Round bar	RB12	25	1	4	Elme Metall OÜ		
9	Square bar	SB20x20	30	1	4	Elme Metall OÜ		
10	Flat bar	FB30x10	30	1	4	Elme Metall OÜ		
11	Threaded rod	M6	360	1	4	Elme AS	1,26	3,50 €/m
12	Threaded rod	M6	235	1	4	Elme AS	0,82	3,50 €/m
13	Threaded rod	M6	45	1	4	Elme AS	0,15	3,50 €/m
14	Knob	tapped	M6	2	8	Misumi	1,54	NKSF6
15	Knob	through thread	M6	1	4	Misumi	3,62	STK-30-NT
16	Clamp lever	threaded shaft	M4x16	1	4	Misumi	3,45	300-30-M4-16-OS
17	Nut	DIN 934	M6	8	32	Elme AS	0,07	

18	Washer	DIN 125	M6	4	16	Elme AS	0,02	
AT-1211-106_Drivetrain sub-assembly					**1**			
1	Plate	PL 3	118x50	1	1	Elme Metall OÜ		
2	Plate	PL 3	35x35	1	1	Elme Metall OÜ		
3	Plate	PL 3	75x30	1	1	Elme Metall OÜ		
4	Motor frame	Nema 17	53x50x51	1	1	Stepperonline	1,60	ST-M1
5	Stepper motor	w/gearbox 5:1	ø8 shaft	1	1	Stepperonline	28,80	17HS15-1684S-PG5
6	Hex bolt	DIN 933	M4x12	2	2	Elme AS	0,12	
7	Nut	DIN 934	M4	2	2	Elme AS	0,05	
8	Bolt cross recessed	DIN7985	M3x5	4	4	Elme AS	0,11	
9	Sprocket 06B-1	11-teeth	8H7 bore	1	1	TYMA CZ, s.r.o.	2,75	06B-1-11-NK
10	Set screw	DIN 553	M3x3	2	2	Elme AS	0,10	
11	Guide roller	single flanged	ø30x18	2	2	Misumi	24,41	GRL30S2-L
12	Hex bolt	DIN 933	M6x30	2	2	Elme AS	0,13	
13	Nut	DIN 934	M6	2	2	Elme AS	0,07	
14	T-nut	DIN 508	M6x8	5	5	Elme AS	1,95	
15	Hex bolt	DIN 933	M6x16	3	3	Elme AS	0,10	
16	Roller chain 06B-1	Simplex	1075	1	1	TYMA CZ, s.r.o.	8,10	06B-1 DIN 8187
AT-1211-100_Welding carriage assembly					**1**			
1	Plate	PL 1	490x280	1	1	Elme Metall OÜ		
2	Plate	PL 1	410x280	1	1	Elme Metall OÜ		
3	Plate	PL 1	330x175	1	1	Elme Metall OÜ		
4	Plate	PL 1	35x20	2	2	Elme Metall OÜ		
5	Plate	PL 1	70x52	1	1	Elme Metall OÜ		
6	Plate	PL 1	200x59	1	1	Elme Metall OÜ		
7	Plate	PL 1	490x360	1	1	Elme Metall OÜ		
8	Power supply	Sw. 12V DC 4.2A		1	1	Stepperonline	6,34	S-50-12
9	Controller+ driver	Single axis 4A		1	1	Aliexpress	16,56	ZK-SMC02
10	T-nut	DIN 508	M6x8	50	50	Elme AS	1,95	
11	Hex bolt	DIN 933	M6x16	29	29	Elme AS	0,10	
12	Bolt cross recessed	DIN7985	M6x16	19	19	Elme AS	0,08	
AT-1211-200_Workbench assembly					**1**			
1	Plate	PL 10	7300x1000	1	1	Elme Metall OÜ		
2	Flat bar	FB50x10	880	6	6	Elme Metall OÜ		

3	Flat bar	FB50x10	7200	2	2	Elme Metall OÜ		
4	Flat bar	FB50x10	890	2	2	Elme Metall OÜ		
5	Flat bar	FB50x10	1490	2	2	Elme Metall OÜ		
6	Flat bar	FB50x10	2390	1	1	Elme Metall OÜ		
7	Square tube	SHS50x50 x5	920	8	8	Elme Metall OÜ		
8	Plate	PL 10	45x45	8	8	Elme Metall OÜ		
9	Plate	PL 10	80x80	8	8	Elme Metall OÜ		
10	Flat bar	FB50x10	220	14	14	Elme Metall OÜ		
11	Flat bar	FB50x5	200	14	14	Elme Metall OÜ		
12	Plate	PL 8	80x80	7	7	Elme Metall OÜ		
13	Flat bar	FB70x30	60	7	7	Elme Metall OÜ		
14	Flat bar	FB70x30	60	7	7	Elme Metall OÜ		
15	Angle bar	AB50x50x5	780	4	4	Elme Metall OÜ		
16	Angle bar	AB50x50x5	2290	4	4	Elme Metall OÜ		
17	Angle bar	AB50x50x5	2400	1	1	Elme Metall OÜ		
18	Hex bolt	DIN 933	M20x80	15	15	Elme AS	1,87	
19	Nut	DIN 934	M20	15	15	Elme AS	0,26	
20	Washer	DIN 125	M20	7	7	Elme AS	0,22	
21	Angle bar	AB50x50x5	600	2	2	Elme Metall OÜ		
22	Hex bolt	DIN 933	M6x25	4	4	Elme AS	0,07	
23	Nut	DIN 934	M6	4	4	Elme AS	0,07	

Fasteners
Components
Plates
Profiles

Welding carriage			
	Total amount, kg (m)*	**Price, €/kg (€/m)***	**Cost, €**
Fasteners	N/A	N/A	230,19
Components	N/A	N/A	356,49
Plates	7,30	2,40	17,52
Profiles	6,10	1,40	8,54
Alu. extrusion 40x40*	4,57	19,10	87,29
Total			**700,03**

Workbench			
	Total amount, kg	**Price, €/kg**	**Cost, €**
Fasteners	N/A	N/A	34,05
Plates	577,20	2,40	1385,28
Profiles	230,80	1,40	323,12
Total			**1742,45**

GRAPHICAL MATERIAL

1. **AT-1211-101_Frame sub-assembly (A3)**
2. **AT-1211-102_Non-drive side wheel hub sub-assembly (A3)**
3. **AT-1211-103_Drive side wheel hub sub-assembly (A3)**
4. **AT-1211-104_Guiding roller sub-assembly (A3)**
5. **AT-1211-105_Gripping jig sub-assembly (A3)**
6. **AT-1211-106_Drivetrain sub-assembly (A2)**
7. **AT-1211-100_Welding carriage assembly (A2)**
8. **AT-1211-200_Workbench assembly (A2)**