Universitetet i Stavanger

FACULTY OF SCIENCE AND TECHNOLOGY

BACHELOR'S THESIS

Study program/specialization: Mechanical engineering	Spring semester, 2021 Open
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Course coordinator: Sheryl Josdal Supervisor: Ove Kjetil Mikkelsen	
Title of bachelor's thesis: Solar Tracker	
Study points: 20 ECTS	
Keywords: Solar tracker Solar panel Solar tracking system Sun's tracking	Number of pages: 34 + appendix/other: 15 Stavanger, 15.05.2021 date/year

Abstract

The global energy system is currently undergoing a significant change from fossil fuels to renewable energy. Depending on the country and its resources, one of the most efficient, reliable methods of producing energy is obtaining electricity from the sun. Going a step further, most typical solar farms are not using the full potential of solar panels. This study aims to determine why solar farms are widespread in some countries and some other countries do not use them at all. Specifically, it investigates whether and how much the geographical location affects the performance of the solar tracker. In this context, a solar tracker is defined as a device, which directs solar panels or modules toward the sun's radiation. By changing its orientation throughout the day, the solar tracker follows the sun's path on the horizon to maximize electricity production.

To test the hypothesis that how fast the costs of the self-designed solar tracker can be reimbursed, depending on its geographical location, first, the solar tracker was designed and tested against possible loads. For controlling the dual-axis solar tracker, a programmable logic controller with a self-programmed algorithm for tracking the sun was chosen. Next, the solar tracker's production costs were estimated, and with data about sun hours in two individual places, the reimbursement times were calculated. The results showed a significant difference in produced energy between these two chosen locations within Europe, which resulted in much deviated times needed to reimburse the solar tracker costs.

These results suggest that the performance of the solar tracker strictly depends on its geographical location. On this basis, it can be concluded that the solar tracker doesn't do good at all the destinations, and the potential future investor should consider all possible options before deciding on such a solution.

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Chapter 1

Introduction

1.1 Background

Nowadays people are becoming more and more aware of surrounded pollutions. Each of us wants to breathe clean air, drink fresh water and be eco-friendly. What is more, fossil fuels are running out at a quick pace. Therefore, humanity is facing an important decision, namely how to generate electricity in an ecological and renewable way. There are many different common ways to produce clean electricity. In this research, I have focused on solar energy, which any of us can produce via small, self-sufficient power plants in our gardens. The sizes of these solar power plants can reach as well hundreds of hectares. But in very densely populated areas, the price of land is worth its weight in gold. A solution for it is a solar tracker, which increases energy production without the need for extra space. In the solar tracking system, solar panels create more electricity, contributing savings in usable space and the number of photovoltaic panels.

1.2 Target of thesis

The primary purpose of the thesis is to estimate how fast the production costs of the self-designed solar tracker can be reimbursed, depending on its geographical location. For this aim, the performance of the solar tracker needs to be calculated for various places and then compared. The research should bring some light to the ordinary person over what is a solar tracker, what solar tracker's variances exist, how this technology works, and finally, how much it costs, and if it is worth or profitable to energize a household with solar energy.

1.3 Delimitation of thesis

The study consists of three main parts – literature review, analysis, and results. The literature review describes the idea behind the solar tracker and all needed background for further research. In the analysis section, the solar tracker is designed with all details, like materials used for the model, technology of the tracking system, components selection, and cost estimation. The solar tracker is as well simulated against possible loads. The results part describes the outcome of the research, with all necessary data needed. Also, the locations within Europe required for comparison are described together with insolation data, prices of electricity, and solar tracker's energy consumption at these locations.

Chapter 2

Literature review

2.1 Introduction

Before conducting the analysis part, it is interesting to understand first the theory behind a solar tracker. Therefore, the literature review is divided into two parts to show clearly what this device is and how it works. The first part focuses on the general idea about the solar tracker, its elements, available types, and some elementary information about solar panels. The second and last part of the literature review, called "Electrical and mechanical details of a solar tracker," concentrates on the mechanical and electrical aspects of the solar trackers and solar tracking methods. There are many ways to track the sun's position and control the solar tracker, and the most popular methods are briefly explained in this subchapter. As the study aims to use the most efficient solar tracking method, it was decided that a PLC will control the system. On this account, the more significant focus in this subchapter is placed on that kind of system.

2.2 Solar tracker

2.2.1 What is a solar tracker?

A solar tracker is a device, which directs solar photovoltaic panels toward the sun. The solar tracker follows the sun's path throughout the day to maximize produced energy captured from the sunlight. We distinguish two main types of solar trackers: single-axis and dual-axis.

Single-axis trackers follow the sun's path from east to west, rotating on a single point. In the dual-axis solution, the sun is chased in the x and y-axis. Therefore dual-axis trackers can position panels directly toward the sun at all sun locations. [28]

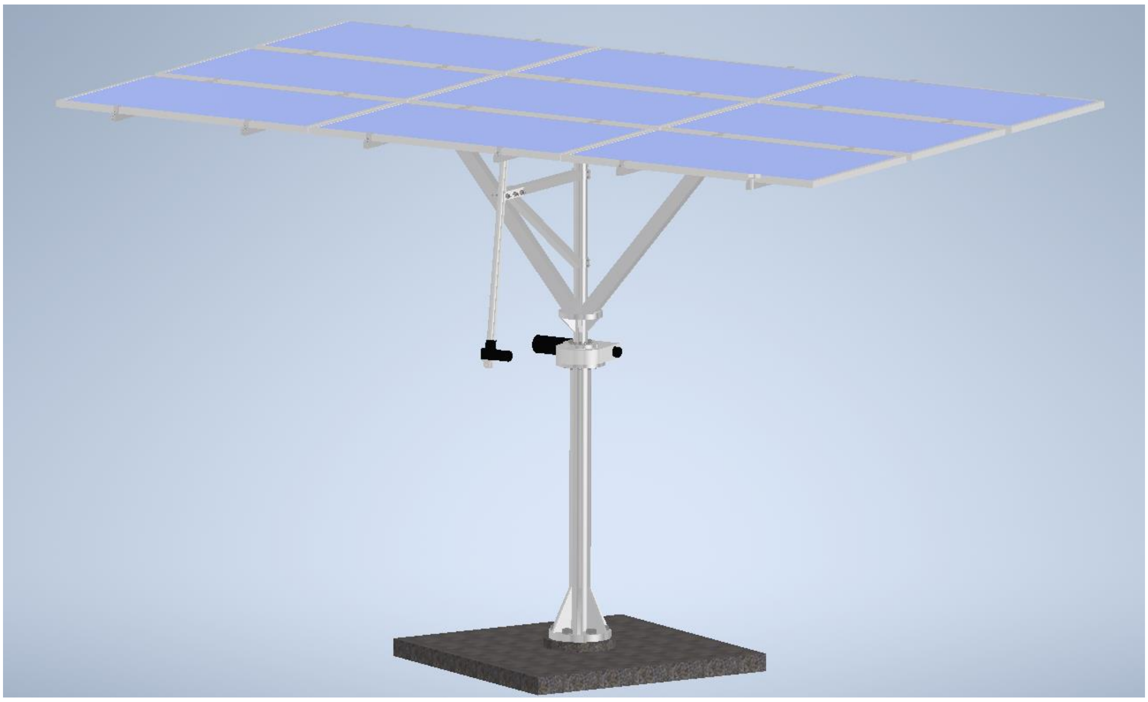

Figure 2.1 Example of a solar tracker

In static solutions, where solar panels remain in a fixed position, the full potential of solar cells is not used. Usually, panels in these solutions are faced to the south in Europe's latitudes. It gives the high efficiency throughout the year, as the sun is always in the south in summer and winter. To increase even more the energy output of the single solar panel unit, a solar tracker is filling up this gap. As the sun wanders from east to west during the day, adding a mechanism with a turret head would convert the incident east to west insolation into electric energy. It exists as well another single-axis tracking solution, which swivels horizontally around a vertical axis. However, the panels facing the south in the northern hemisphere swiveling vertically around a horizontal axis receive more incident insolation. Because of this, the previous type of single-axis trackers is not widely used. In single-axis vertical solar trackers, it is also necessary to face the surface of the panels at the most optimal tilt. This tilt varies depending on the different latitudes. For example, in Stavanger (Norway), the most optimal tilt angle would be 40°. But in more down south place like Aveiro (Portugal), it would be around 35°. [12]

The sun also changes its position during the seasons, from summer's position on the Tropic of Cancer sun wanders to the Tropic of Capricorn in the winter. To capture even these smaller motions of the sun, the solar tracker needs to use a dual-axis solution. In this solution, the single-axis vertical tracking capability is combined with a horizontal one. Panels in this configuration follow the sun perfectly during the day and exceed the efficiency of the optimally tilted panels in single-axis trackers.

The solar tracking systems with dual-axis configuration can produce approximately 40% more energy than a standard fixed-frame system. Depending on the used tracking method, the same number of solar panels can create up to 40% more power output, giving a shorter payback time. Fewer panels, frames, and so on would as well reduce the final project's costs. Unfortunately, there will come some extra expenses of elements needed for the tracking system. [21]

2.2.2 Structure of a solar tracker

The solar tracker usually consists of a dozen or so solar photovoltaic panels. It can be 9, 12, 16, or evermore depending on customer preferences, the desired energy output, an available space, a landform, or costs. Also, the shading and spacing between the units play a crucial role in their size. Solar panels are attached to the top part of the Unit's chassis and then the top part of the chassis swivel. Depending on the number of solar PV panels, the chassis needs to be designed to withstand the forces acting on the structure. Therefore, the most used material for this application is either aluminum or steel. The chassis base needs to be heavy and large-sized to keep up the whole construction against its weight and possible weather conditions. Usually, this base is buried to harden the stability of the top part of the chassis. To the solar tracker can be attached the electric box, which inner components are described in the second part of the literature review.

2.2.3 Solar photovoltaic panel

A solar cell consists of a p-n junction diode. This specific diode can convert the light energy from the sun, which can be called photons, into electricity. The energy produced in this way is in a direct current (DC). The idea behind this phenomenon adopted the name of the photovoltaic effect. The p-n junction is a connection between two different semiconductors. The electric field, created by connecting these two materials, moves the positively charged particles in one direction and negatively charged particles in the opposite direction. Photons get absorbed by the solar cell and transfer the photon's energy to the electrons of the p-n junction. While moving from the p-side to the n-side, electrons create an electric current in the cell. Photovoltaic cells are packed in an assembly and afterward form a solar panel. [15]

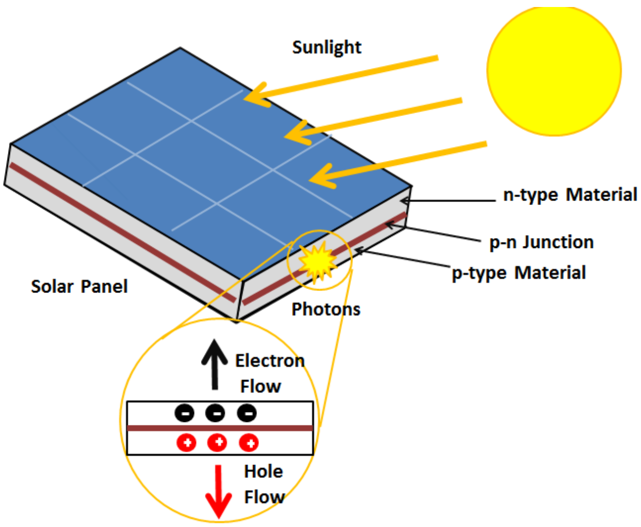

Figure 2.2 Photovoltaic effect [11]

2.2.4 Types of solar panels

Currently, on the market, there are plenty of different photovoltaic panels. They vary between different types, output power, and size. The first classification is the type.

We distinguish three major types of solar panels:

- Monocrystalline
- Polycrystalline
- Thin-film

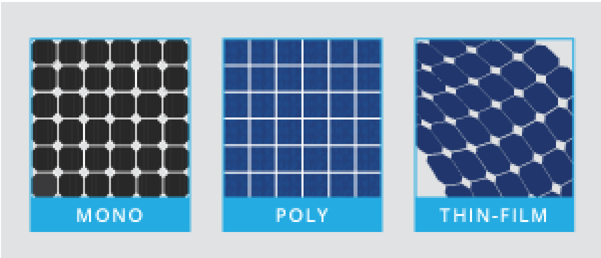

Figure 2.3 Types of solar panels [1]

These solar panels vary in the way they are made, costs, appearance, and destination, and because of the usage of semiconducting material, the sunlight gets converted into electricity. The most common material as a semiconductor is silicon. Silicon wafers are used in mono and polycrystalline cells. When it comes to thin-film panels, there are mostly made from 3 different materials: Cadmium Telluride (CdTe), Amorphous Silicon (a-Si), and Copper Indium Gallium Selenide (CIGS).

Each of these three types of panels has different advantages and disadvantages. The selection of the most suited types of solar panels depends on personal preferences and their destinations.

Type of solar panel	Pros	Cons
Monocrystalline	- Esthetics - High efficiency	- Highest costs
Polycrystalline	- Relatively lower costs	- Lower efficiency
Thin-film	- Esthetics - Lightweight - Flexible, portable - Lowest costs	- Lowest efficiency

Figure 2.4 Advantages and disadvantages of different types of solar panels

Differences between the above types of photovoltaic panels can also be visible in an appearance. In monocrystalline solar panels, pure silicon crystal interacts with sunlight appearing in black cells color. Unlike monocrystalline panels, polycrystalline solar panels don't contain pure silicon crystals. The silicon fragments in polycrystalline cells tend to have a blue color. Thin-film solar cells can be up to 350 times thinner than standard mono or polycrystalline cells. Sometimes thin-film cells are packed in thick frames, and this difference in thickness can be barely visible. This type of panels can have both black and blue hues, depending on the used cell's material. [1]

2.2.5 Size and power output of solar panels

The most common sizes of monocrystalline and polycrystalline panels are 60, 72, or 96 cells. Cells have two dimensions: five inches (125x125 mm) and six inches (156x156 mm). In mono- and polycrystalline panels bigger size usually mean larger power output.

Power output depends, in the most significant part, on insolation. More or less temperature doesn't affect that much electricity production. The most crucial factor is the clearness of the sky. Any fog on the panel's surface, clouds on the sky, or shade from the nearby tree can reduce power output. [10]

In most cases, the highest panel output is measured in temperatures between 1,5 - 25°C and when solar radiation is around 1000 W/m2 (at the clear sky).

For example, a monocrystalline panel in the 60 cells configuration produces around 305 W. [9]

2.3 Electrical and mechanical details of a solar tracker

2.3.1 Mechanics of a solar tracker

The solar tracker's head (the top part of the chassis, which consists of the panels and frame, to which they are attached) must be mounted on joints, allowing the unit's head to rotate about the x and y-axis. It can be controlled in most cases by linear actuators or slewing drives. A linear actuator is a device, which converts electric, hydraulic, or other types of energy into mechanical energy. In this research, the electric linear actuator is used. It plays the role of converting electrical energy into a straight-line movement. The piston moves forth and back and creates the movements such as pulling, pushing, blocking, etc. Usually, a 12V DC motor generates a high-speed rotational motion, and then the gearbox slows down this movement. This will, in turn, rotate the lead screw, which increases or decreases the length of the shaft. Depending on the different designs of the solar tracker's structures, the stroke length can vary from 500 mm up to 1000 mm. [23]

Figure 2.5 Example of electric linear actuator appearance [23]

A slewing drive is a gearbox, which transmits torque to rotation and holds the radial and axial loads of the whole structure. A DC motor converts the electric energy into the mechanical movement of a worm shaft. Then via a worm gear transmission, mechanical energy rotates the solar tracker's head. Below is placed a picture of a worm gear transmission operation. [27]

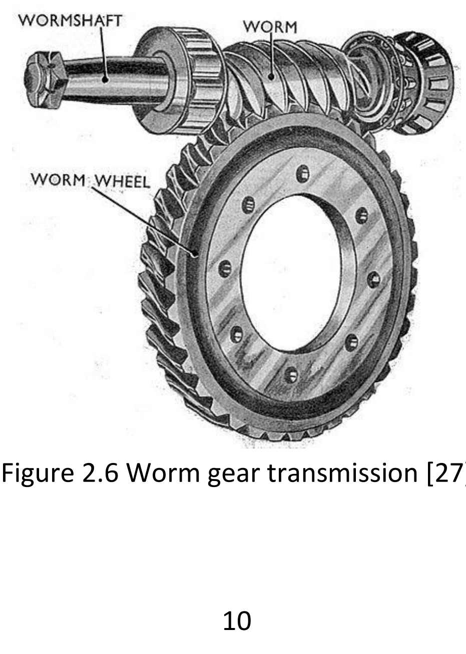

Figure 2.6 Worm gear transmission [27]

2.3.2 Electrics of a solar tracker

Electrical motors can be controlled by a programmable logic controller (PLC) or another micro-controller. A steering controller programmed in one of the sun-tracking techniques opens a DC or an AC circuit for the engines and thereby adjusts the head of a solar tracker towards the incident radiation.

Solar panels produce the direct current. After the photons are turned into electric energy, the current flows to the electric box. The electric current needs to pass first a circuit breaker and then arrive in the power inverter, where the direct current is inverted to the 230 V, 50 Hz alternating current. Using two 12 V DC motors for the solar tracking system, the 230 V AC must be transformed into a constant 12 V DC. Therefore, a transformer needs to be used. Sometimes, when the sun falls on the back of solar panels, the tracking system doesn't have enough energy to rotate the head towards the radiation. In this case, it is recommended to use a battery. Therefore, the motors and the controllers would receive a steady current.

2.3.3 Solar tracking techniques

We distinguish two main classes of solar trackers:

- Active trackers
- Passive trackers

Active trackers are running on an external power source or on harvested by the photovoltaic panels' electricity. Usually, these trackers consist of single or dual-axis systems with motors and other elaborate mechanical devices.

Passive trackers are as well tracking the sun like active trackers but without an external power source. These trackers don't need to harvest and use their own produced energy too. They are based on the thermal expansion of matter. The sun's heat is used to cause an expansion of a fixed mass of a substance. It can be a gas with a low boiling point, which creates a mechanical movement of an actuator while expanding. Different expansions at different actuators cause the tracker to move closer to the sun's direction. Passive trackers can be sufficient for a small solar tracking system, where high accuracy is not needed. This particular system faces some problems. In cold temperatures, actuators move very slowly, especially in the mornings, when the expanding liquids are still cold. [15]

A microcontroller or a PLC controls active trackers. There are a couple of different ways of driving the unit to increase the efficiency of a solar system. One of the options is to use a coordinate system. The tracker uses a predetermined astronomical database to determine a sun's position at any given time and based on the tracker's coordinate location. In this method, the microcontroller or PLC calculates the best possible tilt of the panels and adjusts it with the engines. The controller uses an astronomical equation for calculating the angle of light. This method requires a complex program for the controller, extra workforce, and higher costs for setup and installation. However, it gives one of the highest efficiency in solar tracking systems. The tracker using the coordinate system does not depend on the weather or ambient temperatures. [25]

Another method to track the sun is by use Light Dependent Resistors (LDR). These sensors are used to detect the light intensity falling on the photovoltaic panels, placed at different angles around the panel, usually on the east, west, north, and south side. When the sunlight falls on one particular sensor, its electric voltage increases, and the microcontroller can verify in this matter from which side sunlight falls and face the solar tracker's head straight into the falling photons. [15]

2.3.4 PLC

A Programmable Logic Controller, or just PLC, is a ruggedized computer used for automation purposes. Specific processes, machine functions, or production lines can be automated with these controllers. PLC consists of input and output devices or sensors, which can monitor, operate and record runtime data. Basically, the PLCs are adaptable to almost every application.

2.3.5 Backtracking

If the big solar trackers were placed next to each other, one solar tracker would create a shadow over another, especially when the sun is in lower locations over the horizon. That would affect the amount of energy output. Below is placed a graphic of a shading effect of the trackers.

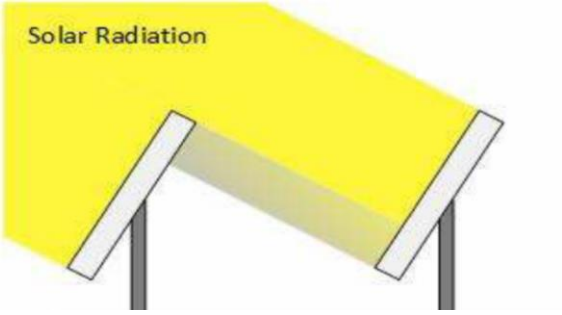

Figure 2.7 Shading effect of the solar trackers [2]

This effect can be prevented by applying the safe distance between the panels or by using a unique algorithm for the PLC. The backtracking algorithm is used to avoid the shadowing effect. Especially in early mornings or late afternoons, when the shading effect occurs, the microcontroller can adjust the tracker's head to eliminate the shading effect with minor losses of energy output. In this algorithm, the trackers are not faced directly to the sun's light, but by changing a little bit the tilt of the panels, they can create even more electric energy than by direct solar radiation with a shading effect. [2]

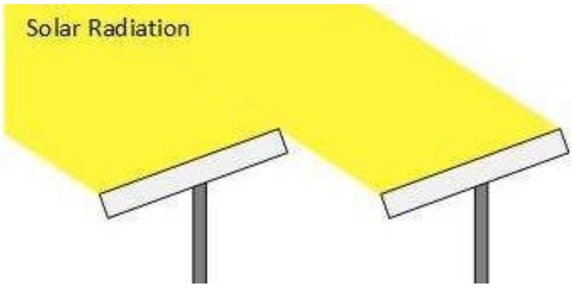

Figure 2.8 Backtracking algorithm [2]

Chapter 3

Analysis

3.1 Introduction

In this chapter is done the prototype analysis of the self-designed and programmed dual-axis solar tracker. The first part of this chapter presents the solar tracker's design, together with a strength analysis of its parts. Description of the tracker starts with the top components and goes to the bottoms ones. The prototype's design and strength simulations are done in a Cad software called "Inventor" from Autodesk.

The second part of this chapter, called "Tracking system", focuses on the electronic aspects of the solar tracker. For controlling the tracking system, a PLC is used. The program for the controller is described together with all the needed electric components for the fully functional solar tracker.

In the third part of the analysis chapter, the cost analysis of the prototype is done. The costs of off-the-shelf products are given, and the costs of the custom-made elements are estimated. Finally, the total price of the solar tracker is calculated.

3.2 Design of the solar tracker

3.2.1 Presentation of the solar tracker

For presenting the design of the solar tracker is used an exploded view (see Appendix 1). The solar panels and their fixtures are invisible for a more transparent look over the solar tracker. Figure 3.1 presents a clipping from Appendix 1. In the text below, all the items from the Appendix 1 are described.

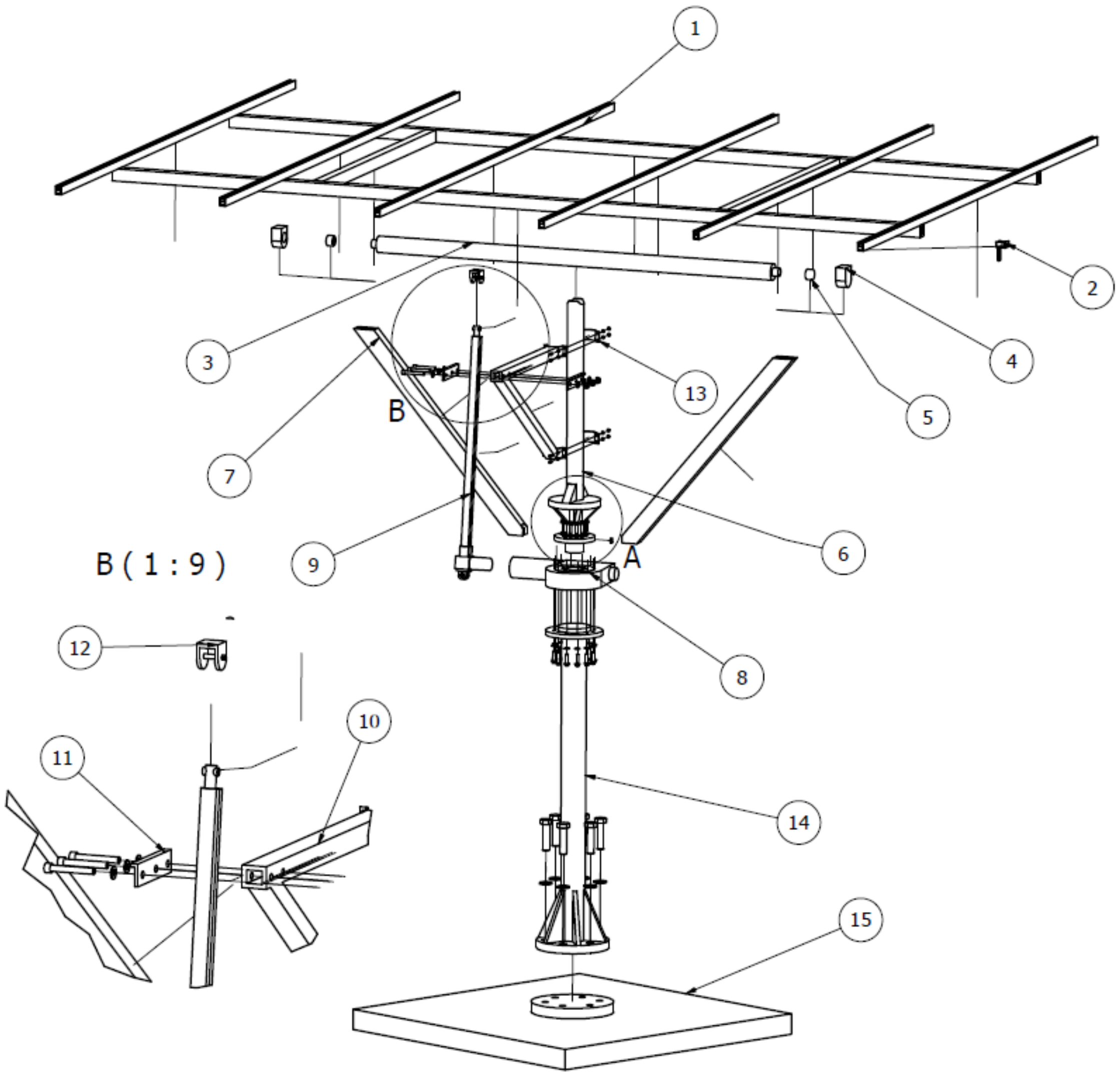

Figure 3.1 Clipping from Appendix 1

For the prototype, it is used the most common type of solar photovoltaic panels. It is a monocrystalline solar panel. It distinguishes itself with high efficiency, durability, and good power output.

The project consists of nine monocrystalline solar panels. Each with 60 photovoltaic cells and with nominal power of 305 W 20 V. PV panels has 1640 x 992 x 35 mm dimensions, and each weighs 18 kg. [9]

The total nominal power of the whole structure is 2745 W, which is adequate for the needs of a small/medium size contemporary house, assuming that the solar tracker will be exposed for 8-9 hours per day of solar radiation on average of a year. It would produce around 7000 kWh per year, which is a standard household electricity consumption. [26]

Solar panels are placed in three rows and three columns on the supporting frame. Each column consists of three panels, which are braced on two aluminum special designed for this purpose beams. And each panel is mounted on four fixtures to the supporting beams (see Figure 3.2). Appendix 3 shows the drawing of the solar panel's fixture.

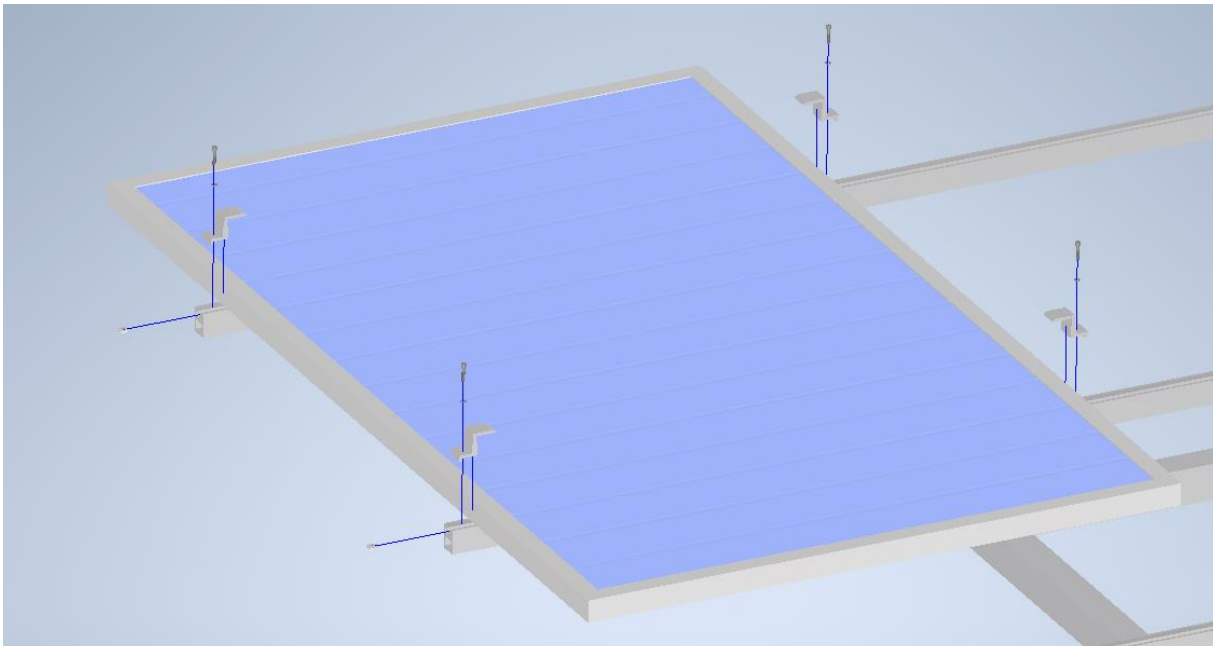

Figure 3.2 Fixing of the solar panel

These fixtures are custom-made for this application to give a firm grip on the panels. They hold the top and the side edge of the solar panel's frame. Fixtures are made of aluminum 6061 and are attached by screws (M5x25) and special nuts to the supporting beams.

Six supporting beams are fillet welded to the bottom part of the frame. Everything is made of aluminum 6061, including welds. For the drawing of the frame, see Appendix 4. The whole frame (see Appendix 1, Item no 1) is welded to the bearing cases (see Appendix 1, Item no 4), which hold the entire upper section of the solar tracker. Inside bearing cases are bearings (see Appendix 1, Item no 3), which allow the panels to vertical tilt. For the model are used needle roller bearings, which give a circular motion of the upper section. Appendix 5 shows the drawing of the bearing case.

Between these two bearings is placed an aluminum circular beam (see Appendix 1, Item no 3). For the drawing of the circular beam, see Appendix 6. This circular beam is then welded to the middle base (see Appendix 1, Item no 6), and for better stability, the side supports are used (see Appendix 1, Item no 7). Appendix 7 and 8 show respectively drawings of middle base and side support.

For rotating the solar tracker's head from east to west and changing the panels' tilt, the prototype uses a slewing drive (see Appendix 1, Item no 8) and a linear actuator (see Appendix 1, Item no 7). Both the drive and actuator are using 12 V DC motors. The actuator generates a 6 kN pushing force, 4 kN pulling force, and a stroke length of 1 m, allows vertical tilt of the panels to 71°. (distance from the central axis of rotation of the tracker's head to the axis of rotation of actuator's top fixture is 804mm, the stroke length is 1000 mm, which gives a $((1000\,mm \times 360°) \div (2 \times \pi \times 804\,mm) = 71° -$ using the formula for arc sector). Also, the actuator has a function of a lock to hold the tilted upper section of the solar tracker. [19]

The linear actuator is placed on a unique bearer (see Appendix 1, Item no 11), which is bolt connected to the actuator's support (see Appendix 1, Item no 10). This connection is made in such a manner to allow the actuator free rotation while working. The actuator's support is mounted to the middle base using an aluminum band around the column (see Appendix 1, Item no 13). Appendix 9, 10, and 11 show respectively drawings of the actuator's fixture to support, the actuator's support, and the middle base's band.

The top end of the actuator is connected to the solar panel's frame via a fixture with a pin inside to allow the upper section to free rotate (see Appendix 1, Item no 12). This fixture also uses aluminum 6061 and is fillet welded to the upper frame. Appendix 12 shows the drawing of the actuator's fixture to the solar panel's frame.

The model uses a slewing drive for the east to west sun's tracking (see Appendix 1, Item no 8). The drive is mounted to the bottom base and the middle base. For the mounting are used 12 bolts M12 from each side. The motor used for slewing drive makes one whole spin in five minutes with maximal torque of 3280 Nm. This configuration gives the solar tracker strong torque with precise adjusting toward the solar radiation.

The bottom part of the solar tracker consists of an aluminum bottom base (see Appendix 1, Item no 14) attached from the top side to the slewing drive and from the underside to the concrete base (see Appendix 1, Item no 15). The bottom base has six bearers for better stability and is connected to the concrete base with six bolts M36. This concrete base, which weighs 550 kg, is intended to be buried in the ground. This solution gives a strong resistance against wind or rain. Appendix 13 and 14 show the bottom base and concrete base.

3.2.2 Strength analysis

The strength calculations are carried out to verify if the solar tracker can withstand the possible loads acting on it. Based on the European windstorm data, the average horizontal severe wind speed, which the prototype is expected to resist, is 35 m/s wind. [20]

The strength simulations are done in Inventor. Von Mises Stress and displacement are considered as the criteria for affirming the strength of the components. First analyzed is the solar panels' frame and then the base, to which the upper section is attached.

The strength analysis assumes that the tracker's head is positioned at its maximal tilted position with 71°. Figure 3.3 shows the direction of the wind acting on the solar tracker.

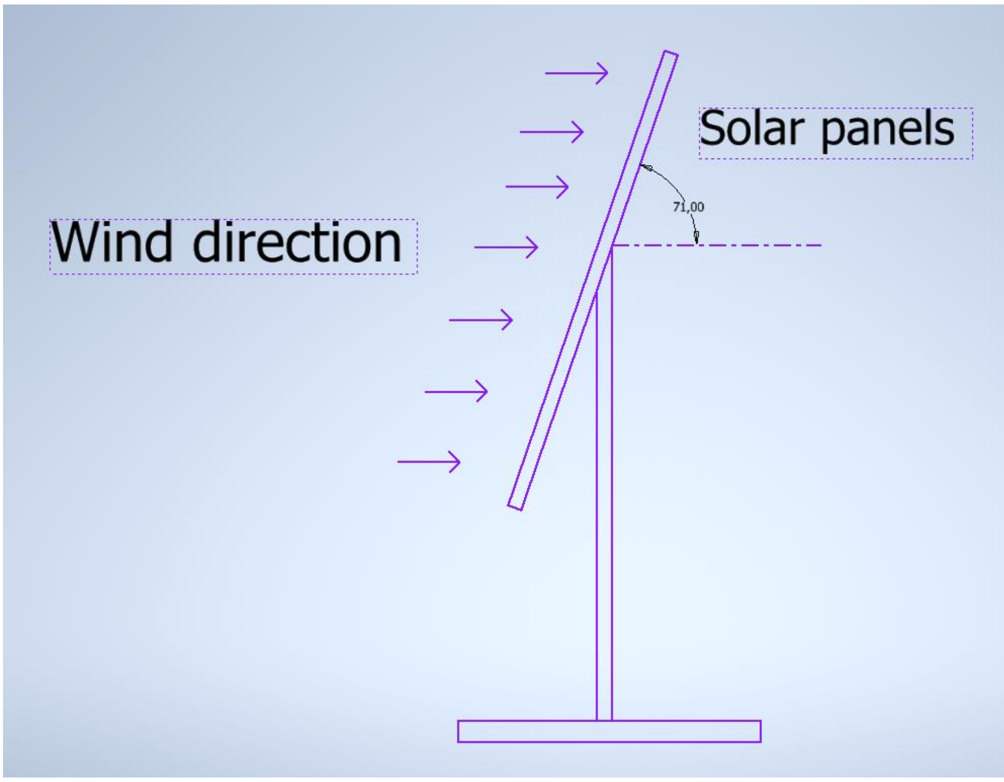

Figure 3.3 Wind direction acting on the solar tracker (side view)

For calculating the force created by the wind, the below formula for wind force is used.

$Fw = \frac{1}{2} \times \rho \times v^2 \times A \times \sin{(angle)}$,

A = area of the solar panel ($1{,}64\ m \times 0{,}992\ m = 1{,}63\ m^2$),

ρ = density of air ($1{,}2\ \frac{kg}{m^3}$),

v = simulated wind speed ($35\ \frac{m}{s}$),

Fw = wind force, acting perpendicular to solar panels ($\frac{1}{2} \times 1{,}2\ \frac{kg}{m^3} \times (35\ \frac{m}{s})^2 \times 1{,}63\ m^{\ 2} \times \sin(71°) \approx 1\ 133\ N$).

Substituting values, we get the final wind force equals 1 133 N, acting perpendicular on each solar panel.

First analyzed is the solar panel's frame (see Appendix 1, Item no 1). The element consists of six supporting beams, to which the panels are attached. The wind load acting on panels is equal to 1 133 N, and the weight of each panel is 18 kg. For strength analysis of the frame, it is assumed that the load created by solar panels' mass is acting in the same direction as the wind force. The final load on each beam equals 1 965 N, $(3 \times (1\,133\ N + 177\ N) \div 2 = 1\,965\ N)$. This load is acting on the entire top surface of the supporting beams as solar panels lay on them. The frame is fixed at two bottom points, where it is welded to the bearing cases.

This element is made from Aluminum 6061 with a yield strength equals to 275 MPa. Figures 3.4 and 3.5 show the strength analysis results. Maximum stresses are much below the yield strength, and displacements are minor. The frame has passed the strength analysis.

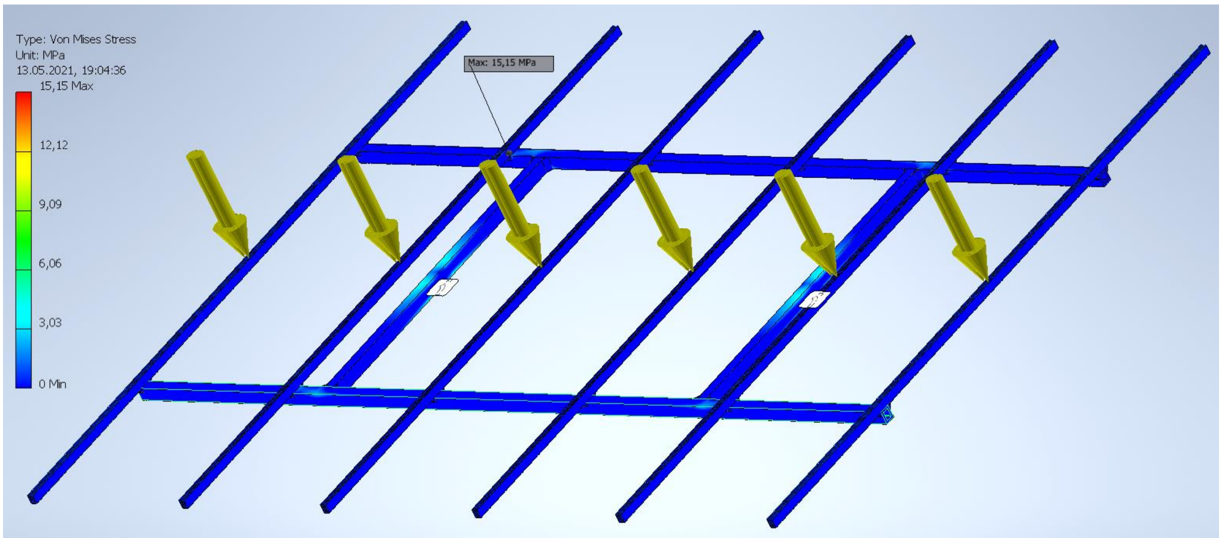

Figure 3.4 Von Mises Stress analysis of the frame

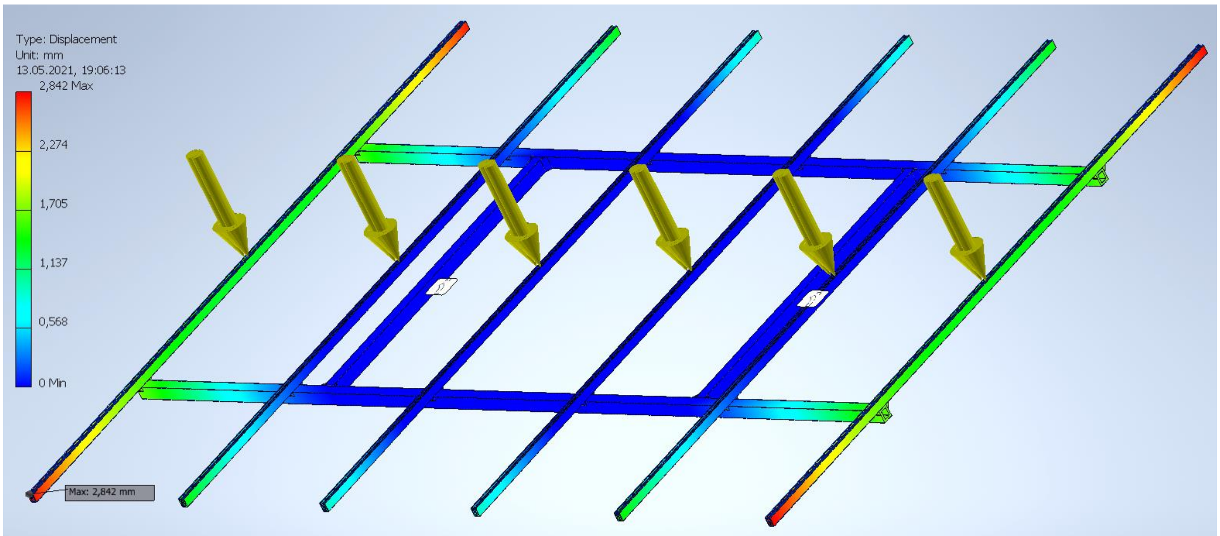

Figure 3.5 Displacement analysis of the frame

Next analyzed is the solar tracker's base, consisting of bearing cases, bearings, circular beam, side supports, middle base, and bottom base. In this simulation, the loads are applied to bearing cases. As the actuator and its fixings hold the tilt, it is assumed that only the tracker's base is exposed to all the loads.

The upper section weighs 230 kg (2 256 N), and the wind load acting on all of the solar panels is equal to 10 197 N ($1\ 133\ N \times 9 = 10\ 197\ N$). The weight load acts vertically downward, and the wind load is tilted at 71°. Therefore, the wind load is divided into vertical and horizontal forces. The horizontal load acting on the tracker's base equals 9 641 N ($10\ 197\ N \times \sin(71°) = 9\ 641\ N$), and the vertical load equals 5 576 N ($2\ 256\ N + (10\ 197 \times \cos(71°)) = 5\ 576\ N$). As the solar tracker's frame is welded on two bearing cases, the loads are divided by two. For simulating, the concrete base is fixed, as it is supposed to be buried.

Figures 3.6 and 3.7 show respectively results of Von Mises Stress and displacement analysis. The maximum stresses occur at the bearing joints and the column above the slewing drive. As the stresses do not exceed the yield points of the materials and the displacements are not large, it can be assumed that the base has passed the strength analysis.

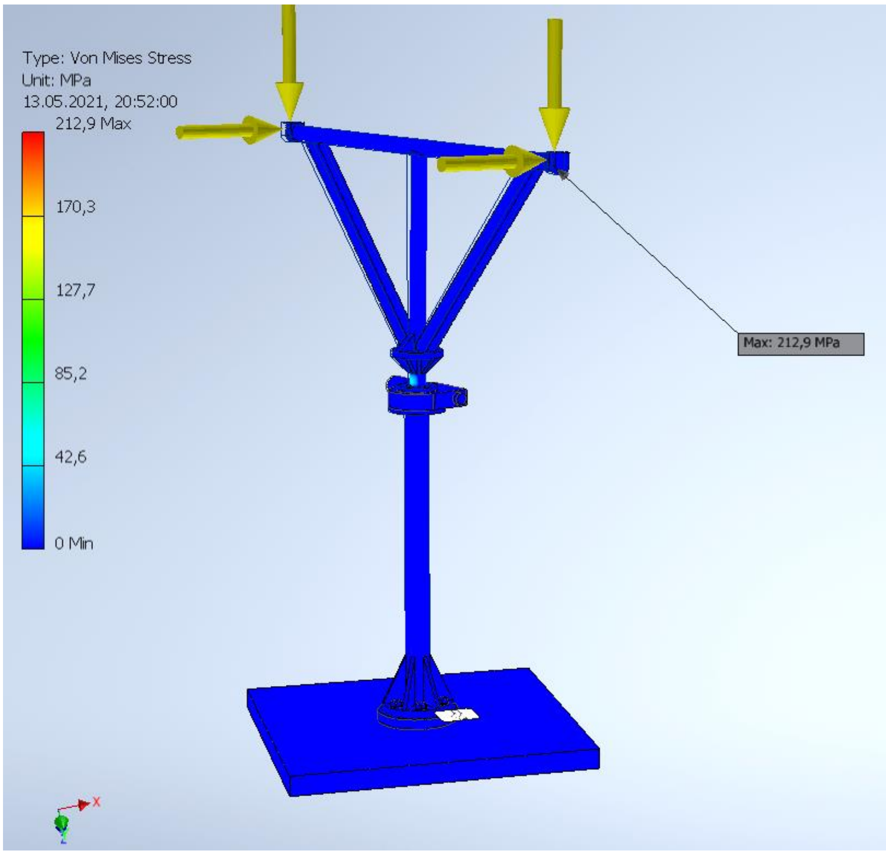

Figure 3.6 Von Mises Stress analysis of the solar tracker's base

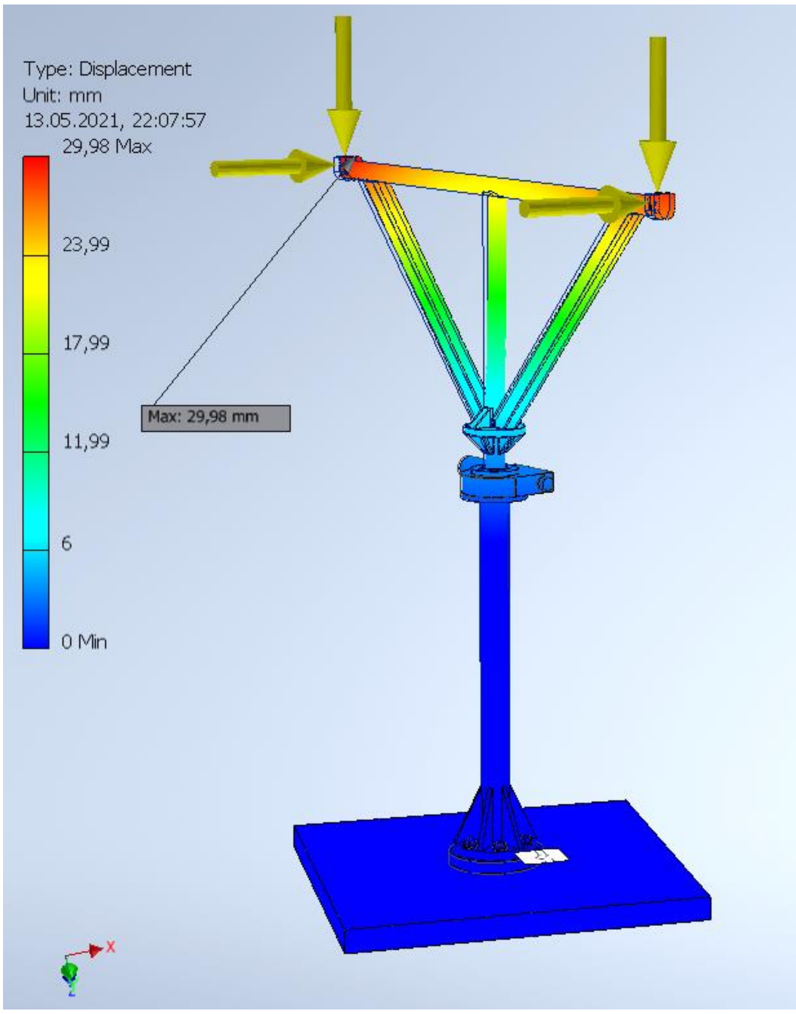

Figure 3.7 Displacement analysis of the solar tracker's base

3.3 Tracking system

3.3.1 Functioning of the solar tracker

The tracking system consists of one linear actuator and one slewing drive controlled by a PLC to obtain the highest electricity production efficiency. Before analyzing the controller's program, the PLC's power supply is described.

For this reason, the external power source isn't used, but the PLC is energized by a small accumulator, which is charged by the tracker's panels. When the solar panels produce electric energy, it flows through the circuit breaker to the inverter. From the inverter, electricity is sent to the household usage and the transformer. As PLC and the motors are energized by 12 V DC, the prototype uses a transformer, which transforms 230 V AC to 12 V DC. When the electricity is already converted, it flows to the 12 V accumulator, which capacity is equal to 50 Ah. This capacitance is enough for energizing the PLC and the motors after the sunset when the solar tracker's head rotates to the initial position or during the day when the sun hides behind the clouds. The inverter, wiring, PLC, and other electronic devices usually need to be placed in an electric box. As the electronic devices do not need to be very close to the solar tracker, the electric box isn't attached to the tracker's column in this prototype. Because in the case of having two units of the solar tracker, there needs to be just one electric box. Therefore the box isn't included in the design.

In the following subchapter, the PLC program is described.

3.3.2 PLC program of the solar tracker

The solar tracking system uses the Light Dependent Resistors (LDRs) with an output voltage of 0-10 V. For this purpose, a unique small platform (see Appendix 2) is designed and welded to one of the frame beams at the top of the solar tracker (see Appendix 1, Item no 2). On each side of the platform is placed an LDR sensor, in total four LDRs. Depending on which side of the platform the LDR is attached to, they are named after the cardinal direction.

The LDR's platform is made in such a matter that when the sun radiates from one cardinal direction, a sensor from that side has a higher output voltage than the opposite sensor, which would be covered in shadow from the dividing them wall. As the solar tracker is dual-axis, the sun's radiation is checked simultaneously horizontal and vertical. So, for example, in the morning, when the sun rises in the east, the east and south LDR will have the highest voltage. In this way, the PLC will know how to adjust the solar tracker's head to direct the panels toward the incident insolation.

To process the information from the LDRs and thereby control the actuator and the slewing drive, the PLC has an uploaded program. For this purpose, the 12 V PLC is programmed via OMRON's CX-Programmer. It is a well-known program, which is used for the programming of controllers. This program accepts programming in Ladder structure, Sequential Function Chart (SFC), and Structured Text (ST). For better illustration of the solar tracker's code, an SFC programming language is used, and for controlling the analog I/O unit inputs, the CJ1W-MAD42 card is used. First, the input entries and types of them need to be defined. As the tracking system consists of four LDRs, the PLC has to have four analog inputs. Figure 3.8 shows activating these inputs and choosing the type of them.

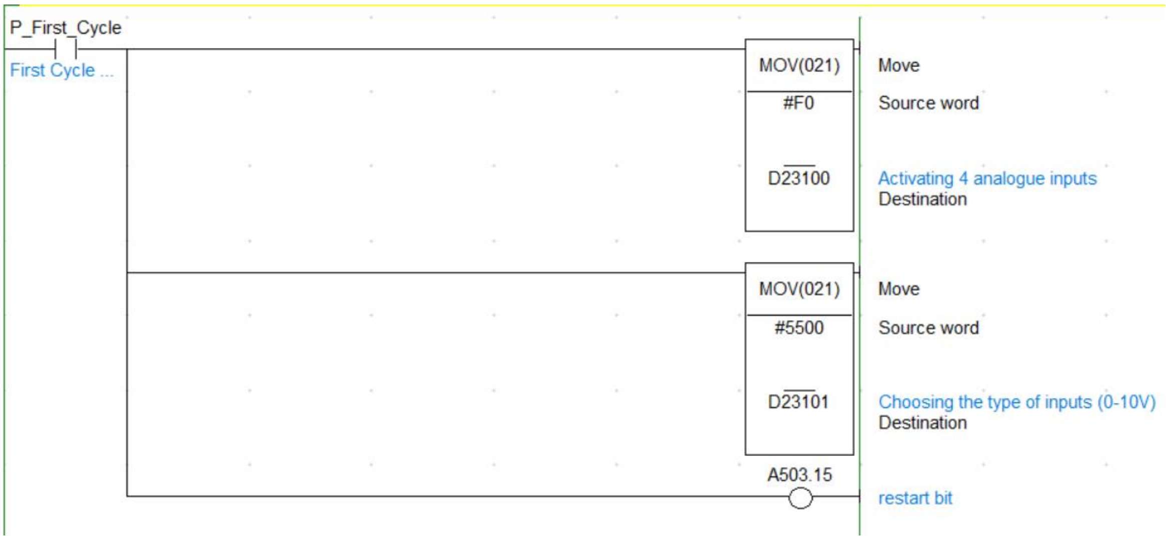

Figure 3.8 Activating analog inputs and choosing their type

Analysis of the idea behind the code starts at the dawn when the solar tracker's head is initially facing the east. The PLC program is checking for daytime by analyzing the voltages from LDRs. When one of the sensors exceeds the limit of 100 mV, the first transition opens, and the algorithm of adjusting the tracker's head starts. Figure 3.9 shows the SFC main program. Figure 3.10 shows the first transition in the ladder structure, which checks for the greater than 100 mV voltages on all LDRs (number 40 in hexadecimal represents 0,1 V). This method of 100 mV gives savings on cloudy days. When the sun's radiation is minimal, the tracker doesn't consume any energy to rotate the unit's head. Only when radiation is considerable and worth tracking motors operate.

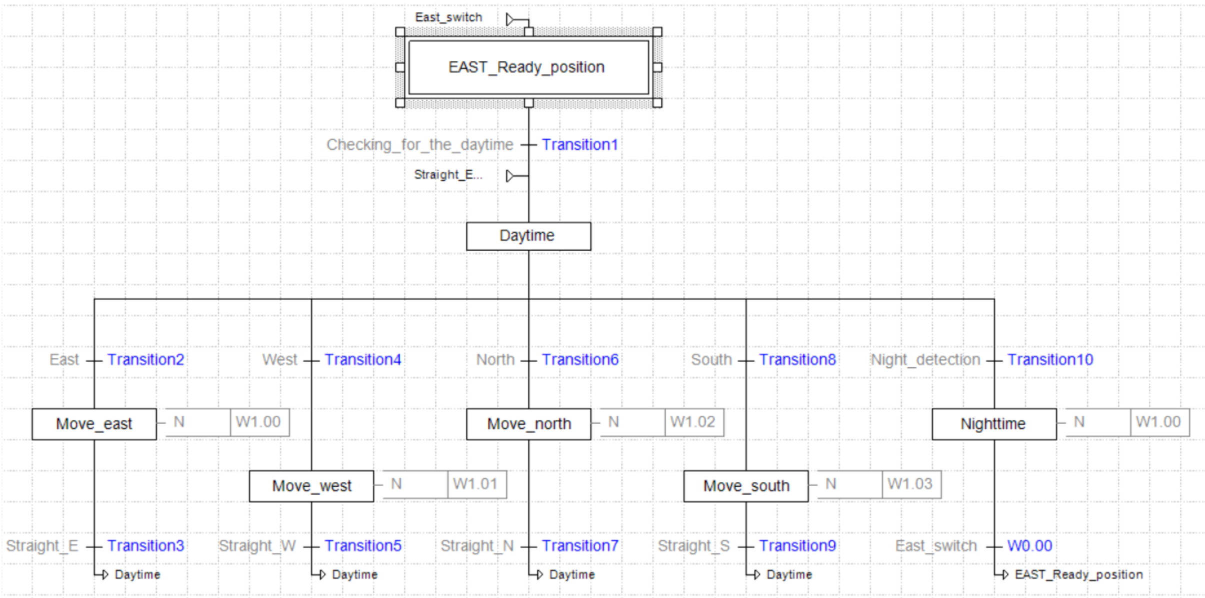

Figure 3.9 SFC main program

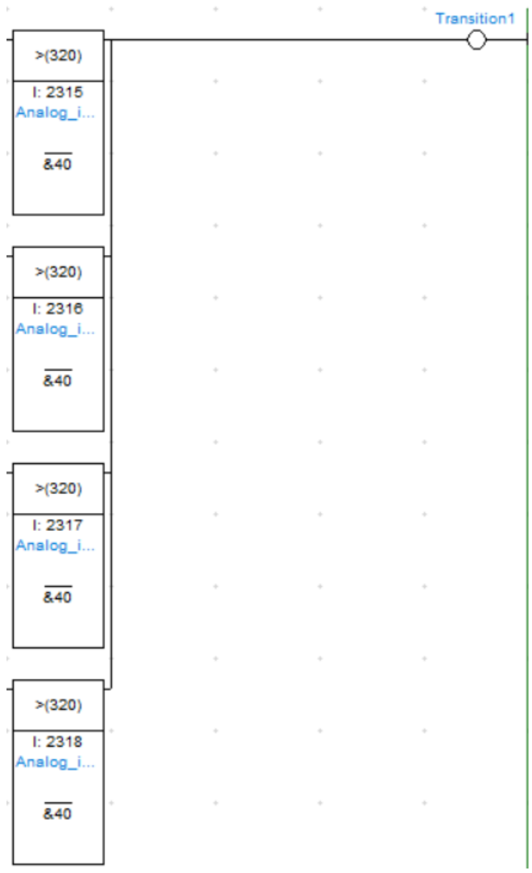

Figure 3.10 Transition 1

The main algorithm is based on five different possible scenarios. The first four move the upper section of the solar tracker to the east, west, south, north, and the fifth one checks for the nighttime. The idea behind the first four transitions is similar; therefore, only one is described. For this reason, the path to move the unit's head to the east is considered. When the east LDR voltage is greater than 100 mV from the west LDR voltage, then the Move_west field is activated and turns on the W1.00 output, which rotates clockwise the slewing drive until the difference in voltage between these two sensors is less than 100 mV. Then the W1.00 output turns off, and the algorithm comes back to the daytime field, which checks again for the differences in voltage between the sensors and the whole cycle repeats.

For this purpose, an extra ladder structure calculates the voltage differences in real-time and places them in the W-memory. Figure 3.11 shows the calculating of voltage differences and setting them in the W-memory.

Figure 3.12 presents transition 2, which checks if the east sensor is larger by 100 mV than the west sensor by analyzing the W-memory. When the voltage difference is a negative number, which in hexadecimal turns into a large number, the second comparison needs to be used. As the maximum output voltage of the LDR is 10 V (4000 in hexadecimal) and the negative numbers are much larger, the second comparison rejects the numbers, which are larger than 10 V.

When one of the differences is greater than 100 mV, the signal goes in the path, where the sensors detect the difference. After adjusting the panels, the sun falls straight at the top of the LDR's platform. At that time, the shadow made by the dividing wall doesn't shadow any of the sensors, meaning that the voltage difference between the sensors is less than 100 mV.

Figure 3.13 presents Transition 3's ladder structure, which checks whether the difference is less than 100 mV.

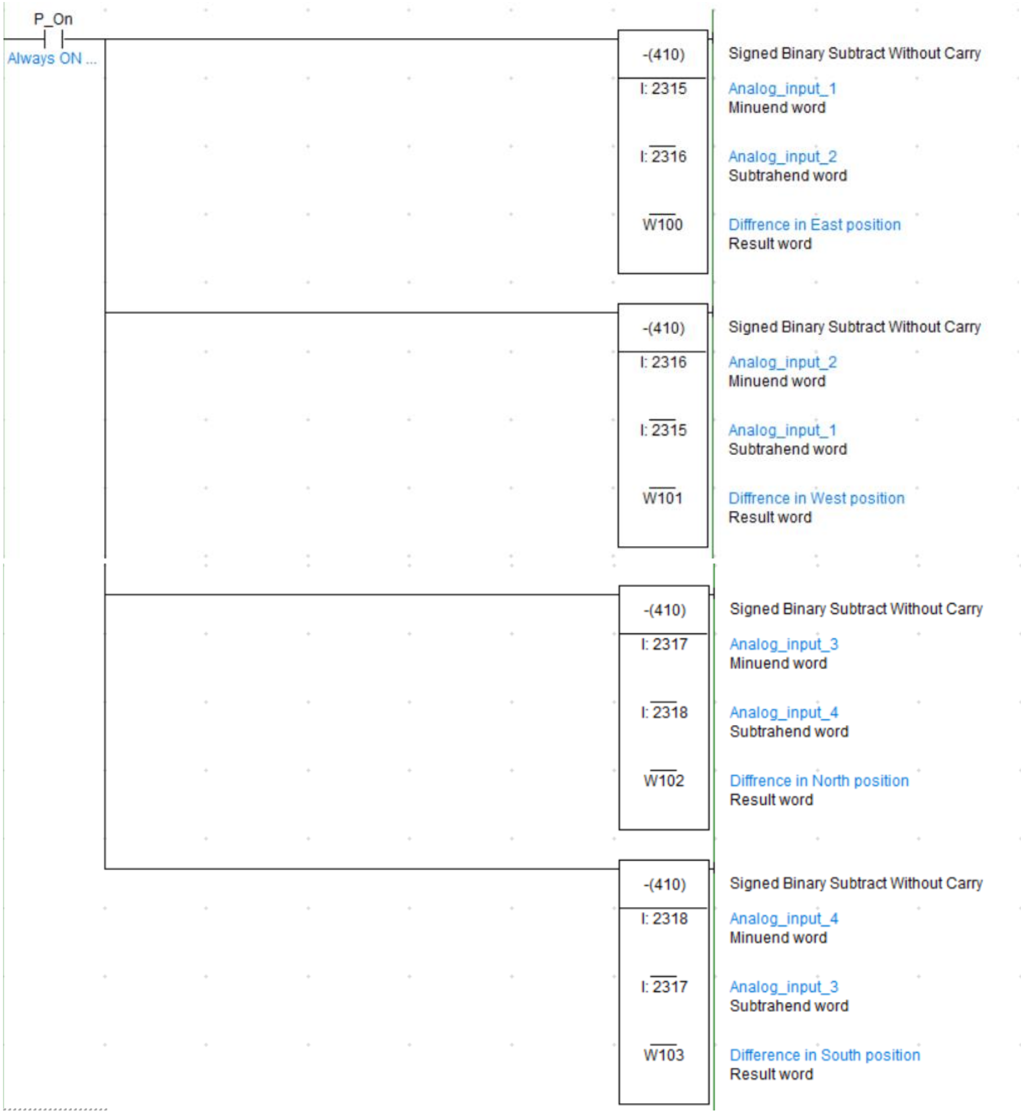

Figure 3.11 Calculations of voltage differences and placing them to the W-memory

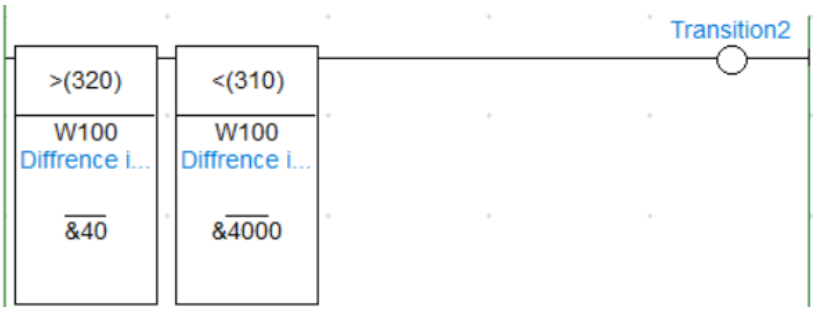

Figure 3.12 Transition 2

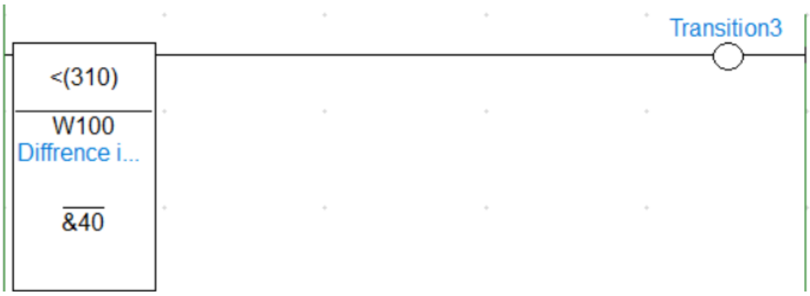

Figure 3.13 Transition 3

When the daytime is over and the solar panels face the west, the solar tracker comes to the initial state. If all the sensors are smaller than 100 mV, meaning that the nighttime came, the solar tracker's head starts rotating to the east position. When the unit's head reaches the east limit switch, the motor turns off, and the algorithm comes to the east ready position. The next day the whole cycle repeats, starting with checking for radiations greater than 100 mV on all sensors. Figure 3.14 shows Transition 10, which verifies if it is dark outside.

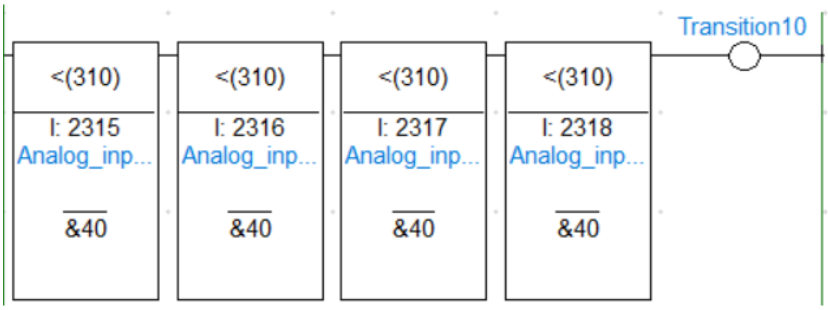

Figure 3.14 Transition 10

For checking if the unit's head has already reached the east position, the limit switch needs to be added to the design (see Appendix 1, Item no 16). It is a regular limit switch, which closes the circuit while reaching the initial east state.

In the end, outputs are connected to coils. Figure 3.15 shows the outputs ladder section. W1.00 rotates the tracker's head clockwise, W1.01 rotates the tracker's head counterclockwise, W1.02 tilt north the tracker's head by pulling in the stroke of the actuator, W1.03 tilt south the tracker's head by pushing out the stroke of the actuator.

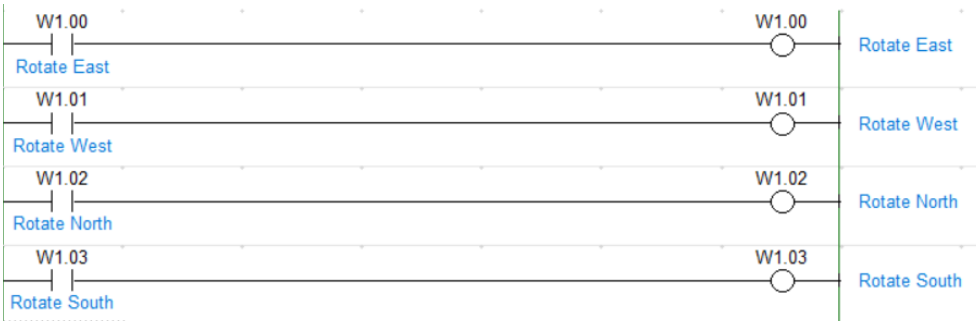

Figure 3.15 Outputs ladder section

The program was tested in CX-programmer simulation, and the algorithm was working as described above with no errors found.

3.4 Cost analysis

3.4.1 Introduction

In this phase of the design, it is almost impossible to acquire the exact costs of the whole project. Many parts of the solar tracker are custom-made, especially aluminum elements, shown in the "design of the solar tracker" subchapter. Due to the unplanned building of the prototype, they can be just estimated. The labor costs for welding and assembling are considered as a part of custom-made elements costs. Components, which are off-the-shelf products used in the design, have been given exact prices, which are summed up in the following subchapter. In this manner, a rough estimation of the production costs can be obtained. Each off-the-shelf product is priced in euros, based on information found on the suppliers' websites. First are analyzed the most expensive elements and followingly the cheaper ones.

3.4.2 Cost analysis of the solar tracker

The prototype consists of nine monocrystalline solar panels. The "farco.no" provides them with the price of 305 € each, giving in total 2745 €. [9] In the solar tracker is used both the linear actuator and the slewing drive. The 12 V actuator found on "ebay.com" costs 144 €. [19] For the slewing drive is chosen a product of "imo.de", which costs 993 €. [22] All the screws, washers, nuts used for the prototype can be bought for around 50 €. As most of these elements come in big packages, and many different variances can be used, the exact price per unit can't be obtained. Two bearings, which hold the upper section of the solar tracker, cost 10 € in total. [4]

For a better look over final costs, the electric components need to be cost analyzed as well. The most significant price fell on the inverter (5 500 W, DC to AC), which can be provided by "Alibaba.com" for 320 €. [16] The transformer (AC to 12 V DC) costs 60 € on "Amazon.com". [24] The battery with a 50 Ah 12 V capacity costs 120 € on the website "Battery-direct.com". [3] Programmable Logic Controller powered by 12 V DC with four analog inputs costs 78 € on "buy.eescodist.com". [18] The set of five LDRs cost 2 € on the "opencircuit.shop" website. [17] The rest of the electric elements like wires, fuses, circuit breakers can be estimated at 200 €.

The final cost of all off-the-shelf elements can be set for around 4722 €.

For the final price of the prototype estimation, the costs of the custom-made elements need to be assessed. On "Alibaba.com", a solar tracker with a similar power output costs 3 000 €. This tracker doesn't include solar panels, electric components like inverter and is mass-produced. As proposed above, the self-designed solar tracker is not mass-produced; the cost of custom-made elements is estimated at 5 000 €. [7]

Due to unexpected costs during the production, the final price of the solar tracker is assessed at 10 000 €.

Chapter 4

Discussion

4.1 Introduction

The primary purpose of this study is to show the difference in how fast costs of the solar tracker can be reimbursed, depending on its latitude. To evaluate the difference, I chose two locations wherefrom data are collected. For the first location, Aveiro in Portugal is selected, as this bachelor thesis is written during the Erasmus semester there. Stavanger in Norway is the second place for this comparison, where I am doing the full degree. The process of estimating the reimbursement time needs data about the number of sun hours at each location, the electricity price at both places, and the costs of the solar tracker production, which the analysis chapter presents. For more precise answers, the energy consumption of the solar tracking system is subtracted from the annual energy production. As the sun hours in each location might differ and the tracking system is programmed to do not operate on cloudy days, the power consumption wouldn't be the same everywhere. Therefore, the data about the number of annual rainy days are taken into consideration for each place. For this reason, it is assumed that the system doesn't operate and doesn't consume electricity during rainy days. In the following subsection, the data and all necessary calculations are presented. In the third and the last subchapter, the results are discussed.

4.2 Data and calculations

Based on the organization "Climates to travel" in Aveiro, there are around 2750 sunshine hours per year, and in Stavanger, there are around 1540 sunshine hours annually. [5][6] To estimate the energy consumption of the solar tracker, I assume that all these sunshine hours take place on not rainy days. Respectively, there are 125 rainy days per year in Aveiro and 210 rainy days in Stavanger. [13][14] The solar tracking system consists of three devices: a PLC, an actuator, and a slewing drive. The inverter power usage is not considered, as it uses the external power source and its performance strictly depends on an amount of inverting energy. The PLC operates nonstop during the whole year, checking the solar radiation and facing the panels towards the incident radiation. Therefore, irrespectively of the geographical location, the PLC with the power of 3 W consumes 26,28 kWh annually ($3\ W \times 24\ h \times 365\ days = 26\ 280\ Wh$). The actuator with the power of 114 W and with 5 minutes to push out or pull in the entire length of the stroke consumes 0,0184 kWh per working day with no rain, assuming that the stroke is fully pushed out and pulled in ($114\ W\ \times 2\ cycles \times (1\ 000\ mm \div 3{,}5\ \frac{mm}{s}) = 18{,}4\ Wh$). The slewing drive with the same power of 114 W and similar gear ratio of 5 min for an entire revolution consumes 0,00912 kWh per working day with no rain, assuming that the unit's head makes one complete revolution ($114\ W \times 0{,}08\ h = 9{,}12\ Wh$). During the whole year, the tracking system in Aveiro consumes 33 kWh ($26{,}28\ kWh + (365\ days - 125\ days) \times 0{,}0184\ kWh + (365\ days - 125\ days) \times 0{,}00912\ kWh \approx 33\ kWh$), and in Stavanger 31 kWh ($26{,}28\ kWh + (365\ days - 210\ days) \times 0{,}0184\ kWh + (365\ days - 210\ days) \times 0{,}00912\ kWh \approx 31\ kWh$). [18][19][22]

The electricity costs in Portugal 0,232 € per one kWh and in Norway one kWh costs 0,087 €. [8]

Based on the price assessment from the previous thesis section, the solar tracker production costs 10 000 €. With all these necessary data, it is possible to determine the amount of annual power production and afterward the time needed to reimburse the solar tracker costs. As the research aims to track every bit of sun radiation, it is assumed that the solar tracker has 100% efficiency during sun hours. The solar tracker model, which consists of nine photovoltaic panels with a power of 305 W, produces in Aveiro 7 549 kWh annually ($305\ W \times 9\ panels \times 2750\ hours = 7\ 548\ 750\ Wh$), and in Stavanger, it is 4 227 kWh ($305\ W \times 9\ panels \times 1540\ hours = 4\ 227\ 300\ Wh$).

The solar tracker operating in Aveiro needs six years to reimburse its costs ($10\ 000\ € \div \left((7\ 549\ kWh - 33\ kWh) \times 0{,}232\ €\right) \approx 6\ years$). The same tracker in Stavanger needs twenty-seven years ($10\ 000\ € \div \left((4\ 227\ kWh - 31\ kWh) \times 0{,}087\ €\right) \approx 27\ years$).

4.3 Discussion of the results

The data suggests that there is a significant difference in reimbursement time. The result from Stavanger is almost five times bigger than the result from Aveiro, meaning that the average owner of the solar tracker in Stavanger needs to wait five times longer than the solar tracker owner from Aveiro to get a profit from the investment. Twenty-seven years in Stavanger is relatively a long time when the whole electricity market can change. New power production technologies can be created at this time, for instance, hydrogen power plants, which can have much higher efficiencies. Therefore, it isn't a very profitable investment. On the other hand, in Aveiro, it is only six years to start earning a profit, which is a pretty short time. The statement that arose from the research is that the two most affecting factors in solar energy production are the number of sun hours and the price of electricity.

The power production is as well surprisingly distinct. The solar tracker in Stavanger produces just 4 227 kWh per year, which would be enough to energize a small house or a cabin. At the same time, the same solar tracker produces 7 549 kWh annually in Aveiro, which can energize a medium or even a massive contemporary house. To generate a similar amount of energy, the consumer in Stavanger needs to invest double the price of the single solar tracker.

Even if the results aren't mightily prospering for the northern countries, solar energy production can affect the climate positively. Instead of generating electricity via fossil fuel power plants, solar energy is ecological and not harmful to the environment—the solar tracker proposed in the analysis chapter tracks the sun's position to obtain the highest possible efficiency of panels without wasting unnecessary energy. As it results from the research, the power consumption of the solar tracking system is inconsiderable and doesn't affect the annual power output that much. What is more, the solar tracker can withstand the wind of 125 km/h, which makes it worthwhile even in very windy areas. Maybe in Norway, where solar energy is not very popular, as the hydropower plants can generate electricity cheaper and in more significant amounts, it is not the best option to use such a solution. Still, in Portugal, where there are many sunny days during the year, and the electricity is expensive, it would be worth considering using a proposed solar tracker model.

It is beyond the scope of this study to build and test the actual model of the solar tracker. Therefore, the price of the solar tracker, which is just estimated, might differ from the final costs of production, which would slightly affect the results of the reimbursement time. The absolute efficiency of the solar tracking system might as well differ a little from the assumed 100% due to unexpected complications. Most of the solar tracker's producents customize the size and power of the used motors, depending on the number of solar panels. In this case, the solar tracker uses 114 W motors to change the tilt and rotate the unit's head. Thus, depending on used components, the energy consumption can vary slightly afterward. Despite all these possible variances and uncertainties, the final results of this study are reliable and can be used for further works as the probable errors of the assumptions are minor.

Chapter 5

Conclusion and further work

This research aimed to identify a difference in the performance of a self-designed solar tracker, depending on its geographical location. There were two chosen places on the opposite sides of Europe to show differences between them. The first place is Aveiro in Portugal and the second is Stavanger in Norway. Based on the literature review, design of the solar tracker, its tracking system, the cost analysis, and the profitability analysis, it can be concluded that the solar tracker location plays a significant role in the further performance of the solar tracker. The results indicate that the model in Aveiro would generate twice the power output of the model placed in Stavanger with five times fewer costs reimbursement time.

It may be concluded that the essential factors, which resulted from this statement, are the amount of the sun hours at the particular place and the electricity price. What surprised me was the energy consumption of the solar tracker, which was relatively low. The tracking system aims to use a PLC to control the solar tracker's head. With the use of four LDRs, the sun's position can be accurately estimated. After analyzing the data from LDRs, the PLC can precisely direct the panels toward the solar radiation. This method consists of a simple tracking system with a short PLC program, which saves a significant amount of energy during the year.

The research clearly illustrates all needed data for the solar tracker production and its expected performance depending on its destination location. However, the tricky part of the project was to estimate the final costs of the solar tracker. As most of the solar tracker components are custom-made, it is hard to obtain the exact values. Therefore, for more accurate data and a better understanding of the implications of the results, future studies are needed. The next step could be building the solar tracker and testing it in the natural environment to confirm the tracking system's functioning and its efficiency.

In closing, the whole research contributed to the final product's design, which can be widely used worldwide. The obtained results answered the primary purpose of the thesis. Hopefully, the results can bring some light to the solar tracking idea and help decide on such a solution to the average consumer unsure about using the solar tracker.

Chapter 7

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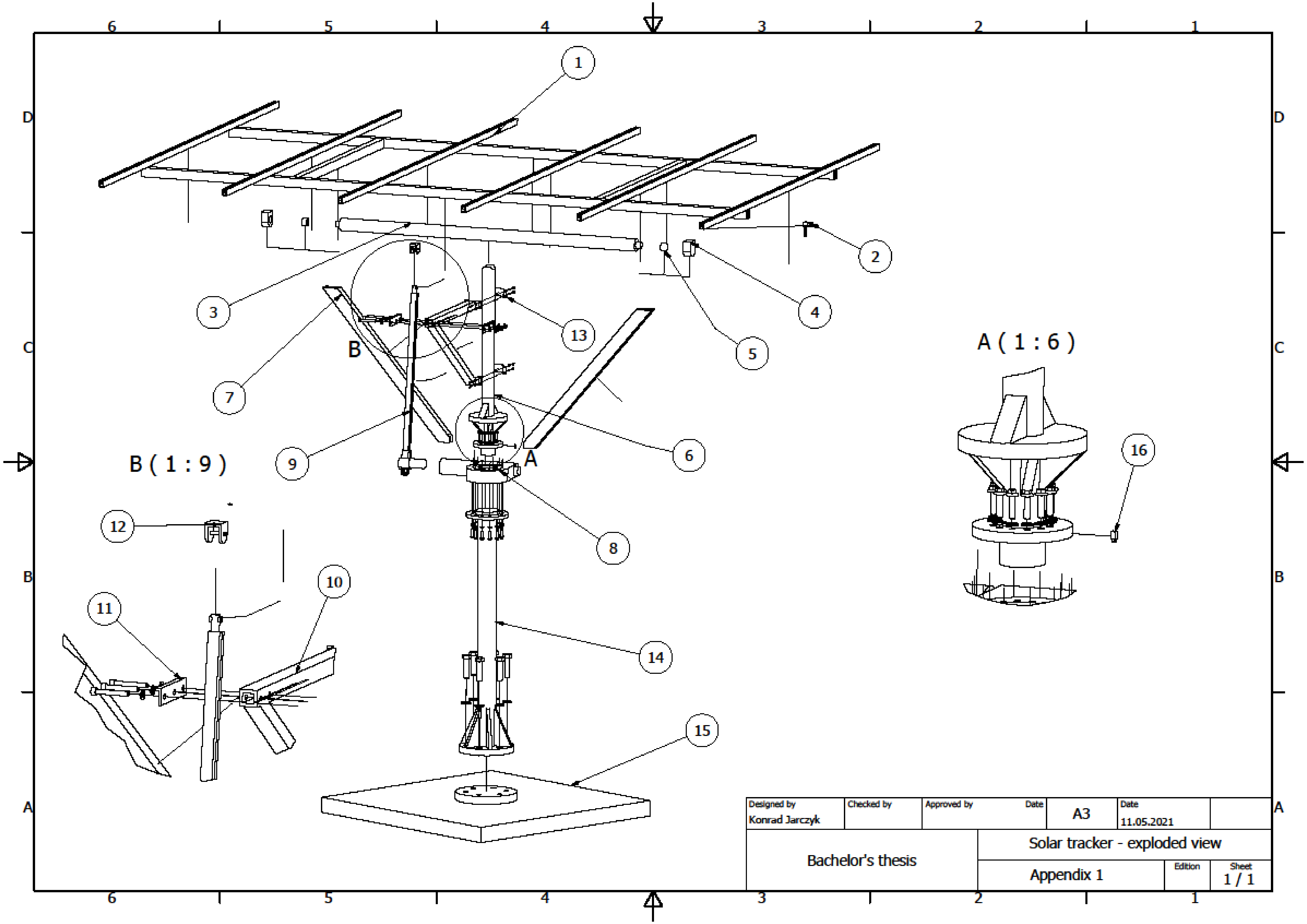
Chapter 6

Appendices

List of Appendices

Appendix 1



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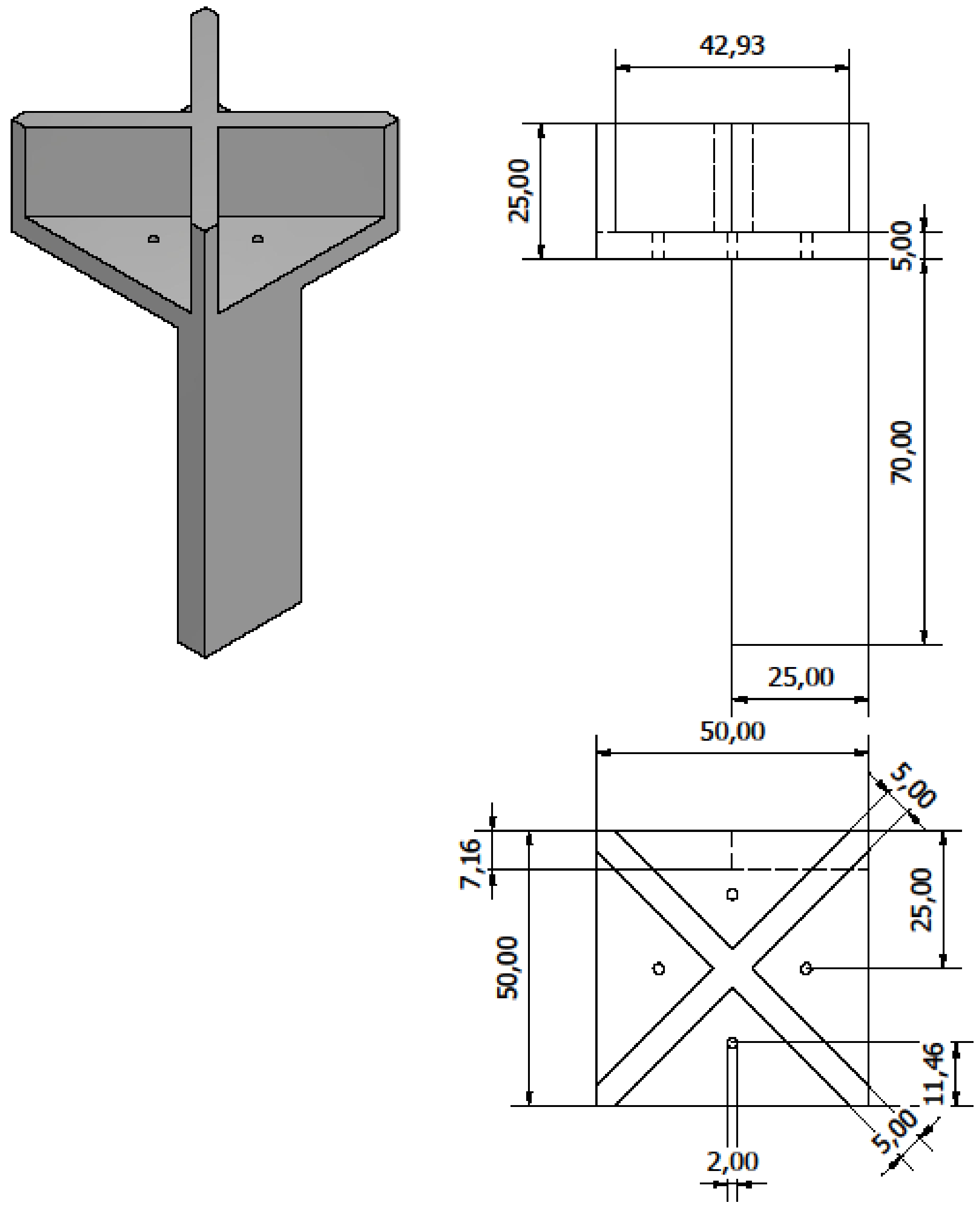
Appendix 2



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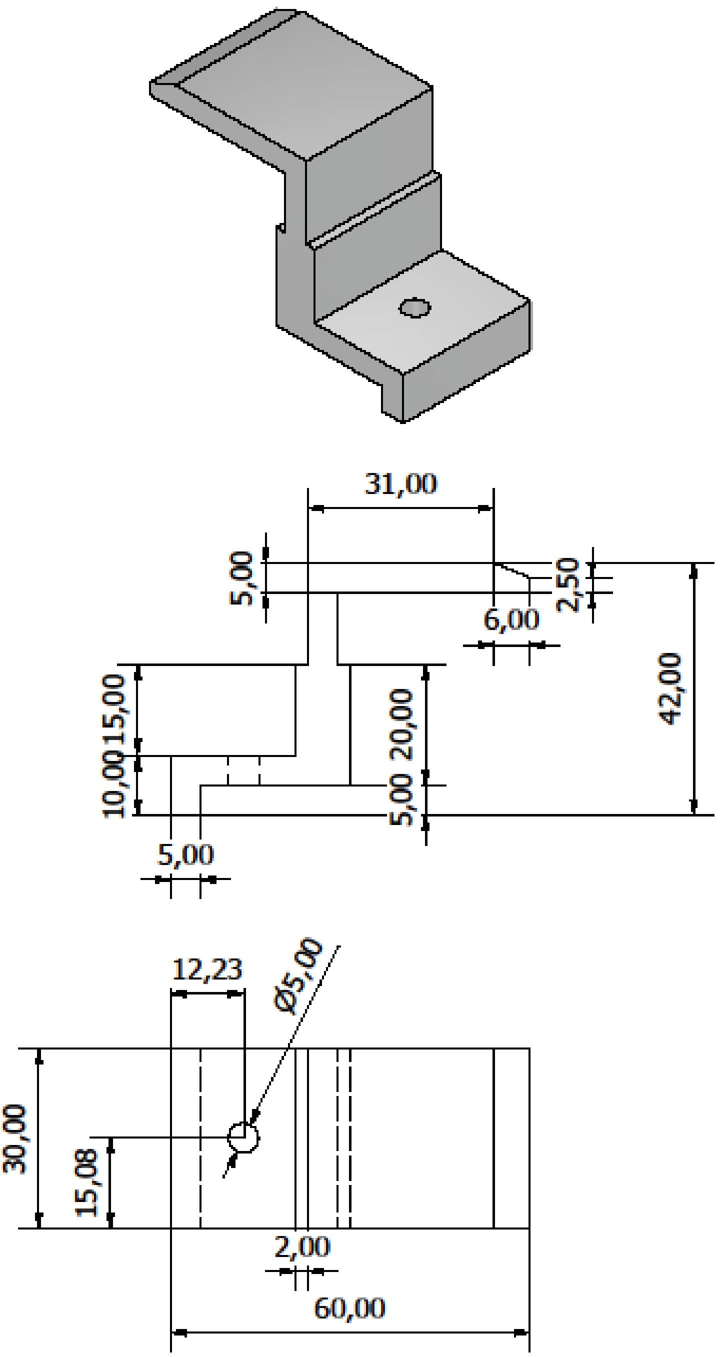
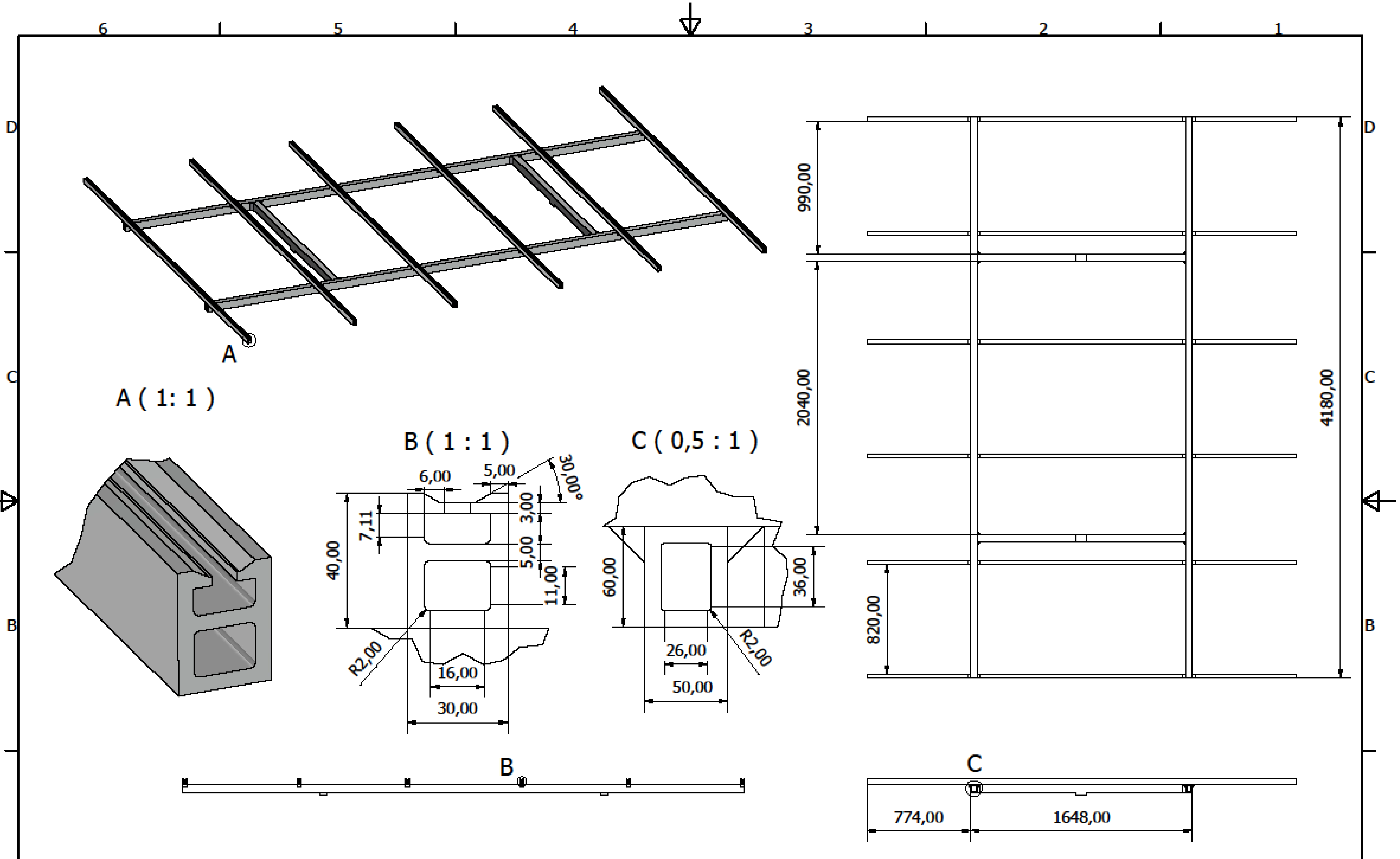
Konrad Jarczyk					12.05.2021	
Bachelor's thesis	LDR's platform					
	Appendix 2				Edition	Sheet 1 / 1

Appendix 3



Designed by Konrad Jarczyk	Checked by	Approved by	Date	A4	Date 12.05.2021	
Bachelor's thesis				Solar panel's fixture		
				Appendix 3	Edition	Sheet 1 / 1

Appendix 4



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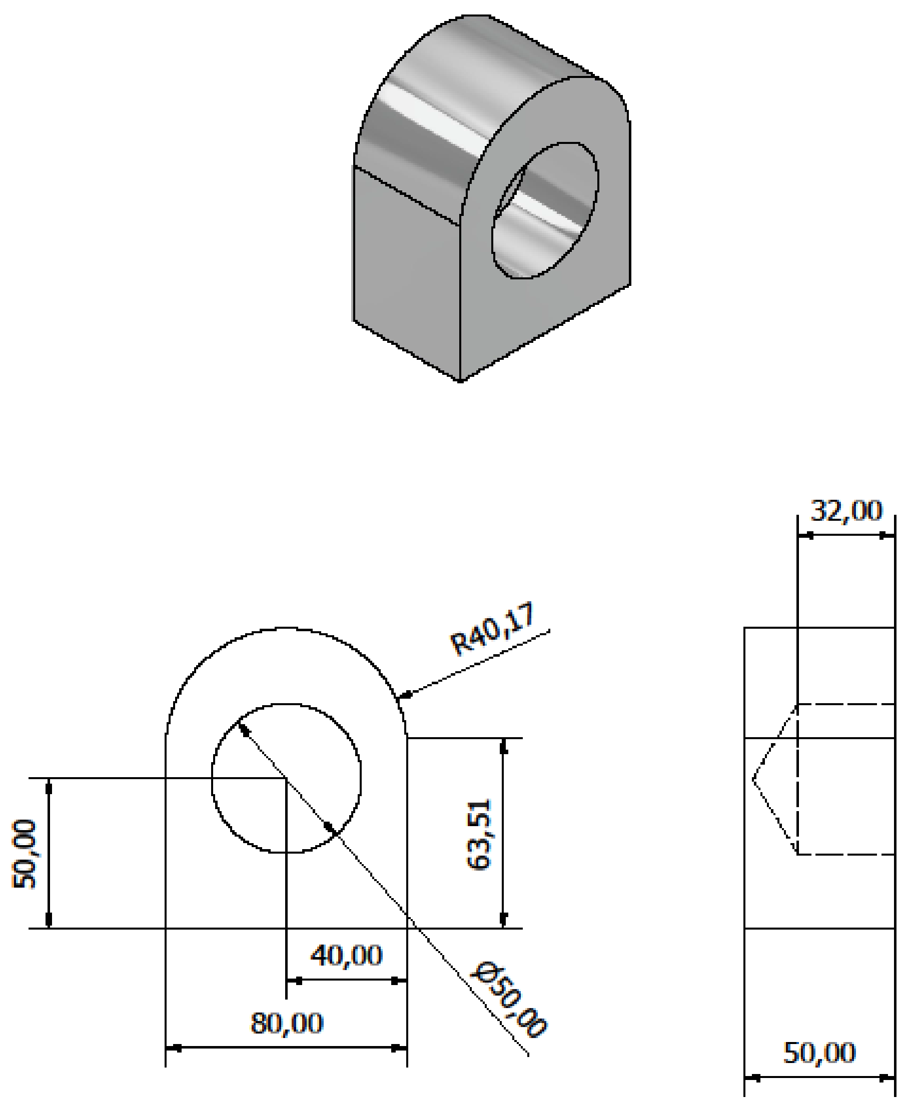
Konrad Jarczyk					12.05.2021

Bachelor's thesis	Frame		
	Appendix 4	Edition	Sheet 1 / 1

Appendix 5



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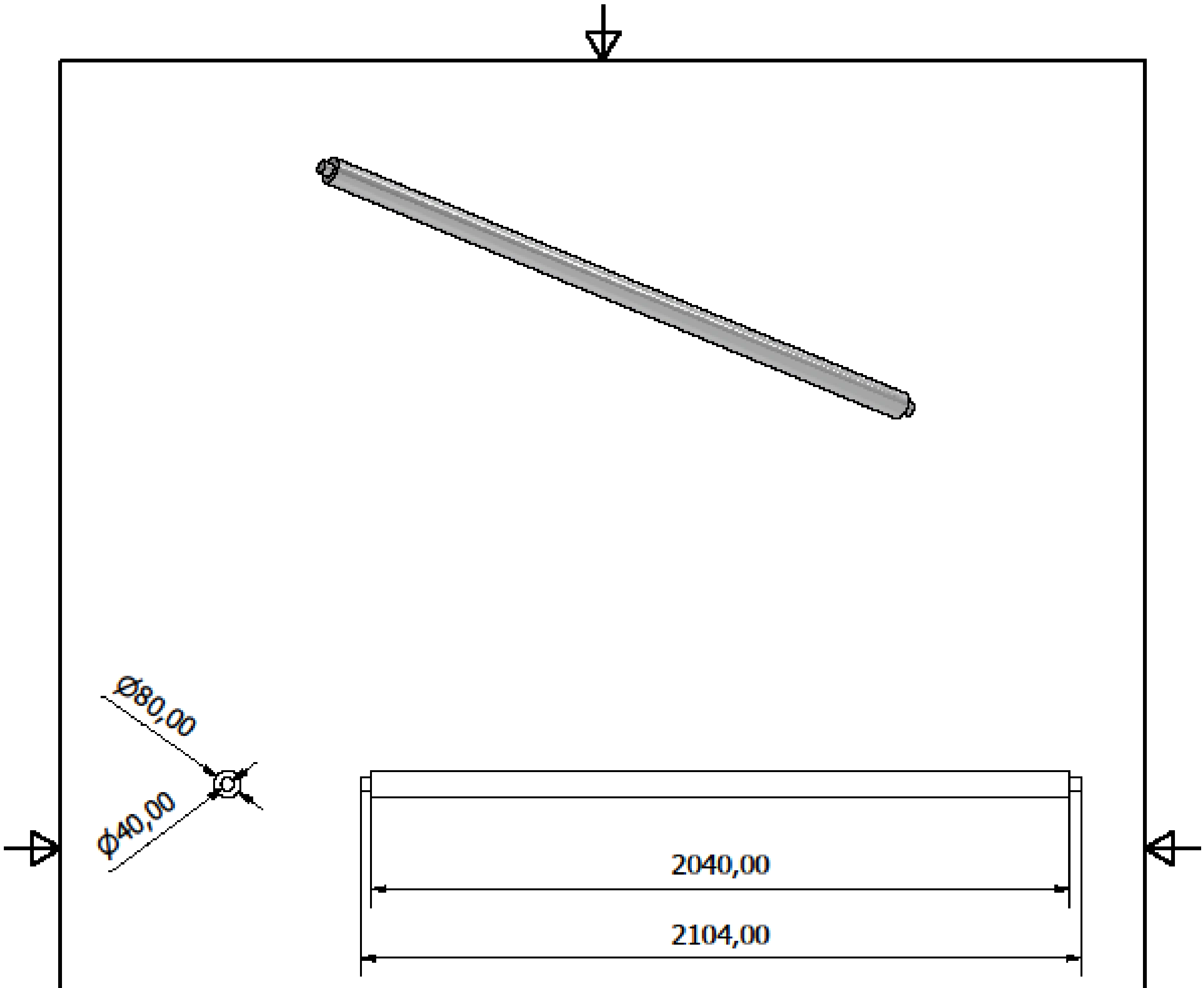
Bechelor's thesis			Bearing case			
			Appendix 5		Edition	Sheet 1 / 1

Appendix 6



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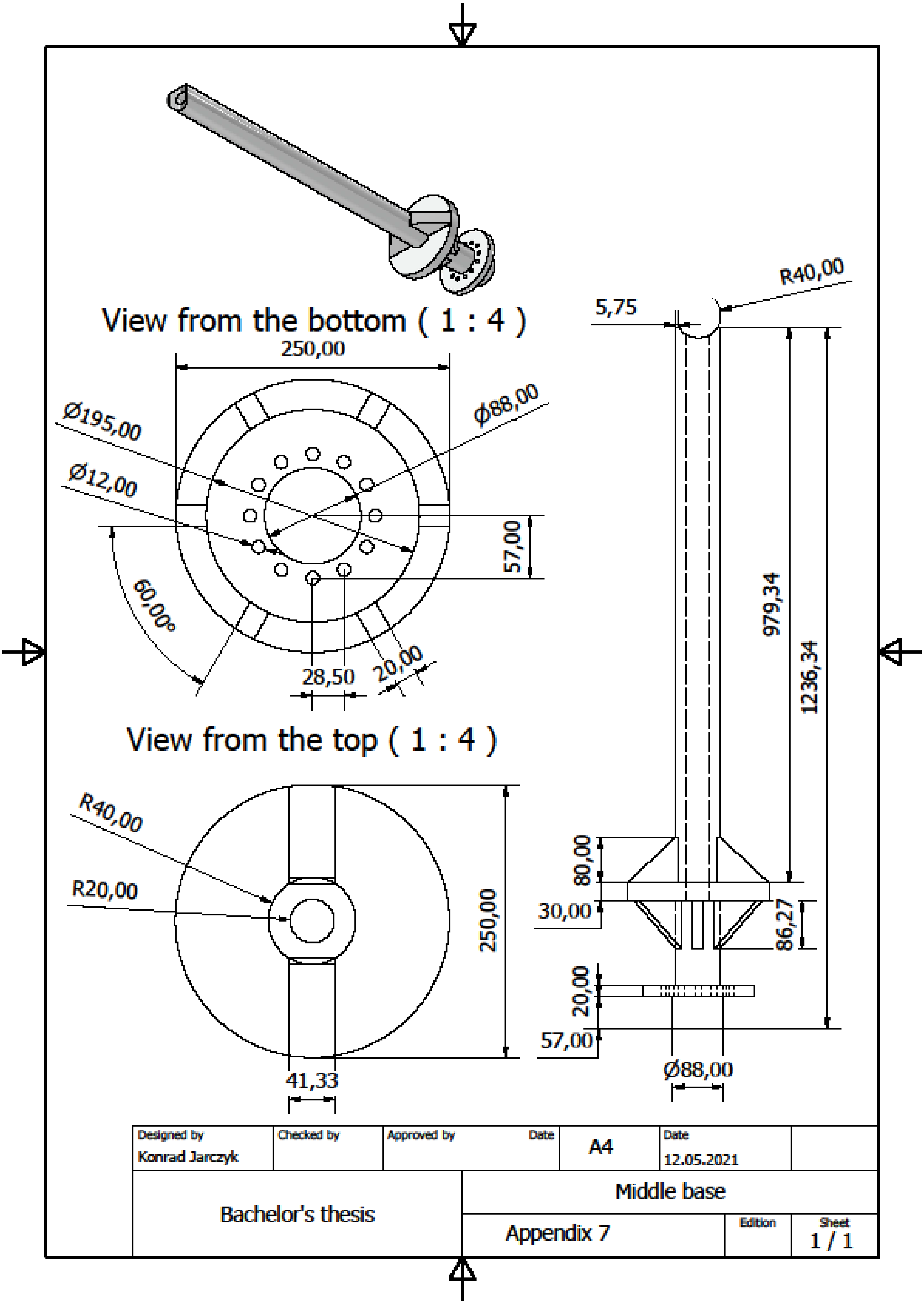
Konrad Jarczyk					12.05.2021	
Bachelor's thesis	Circular beam					
	Appendix 6				Edition	Sheet 1 / 1

Appendix 7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R20,00
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5,75
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1236,34
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30,00
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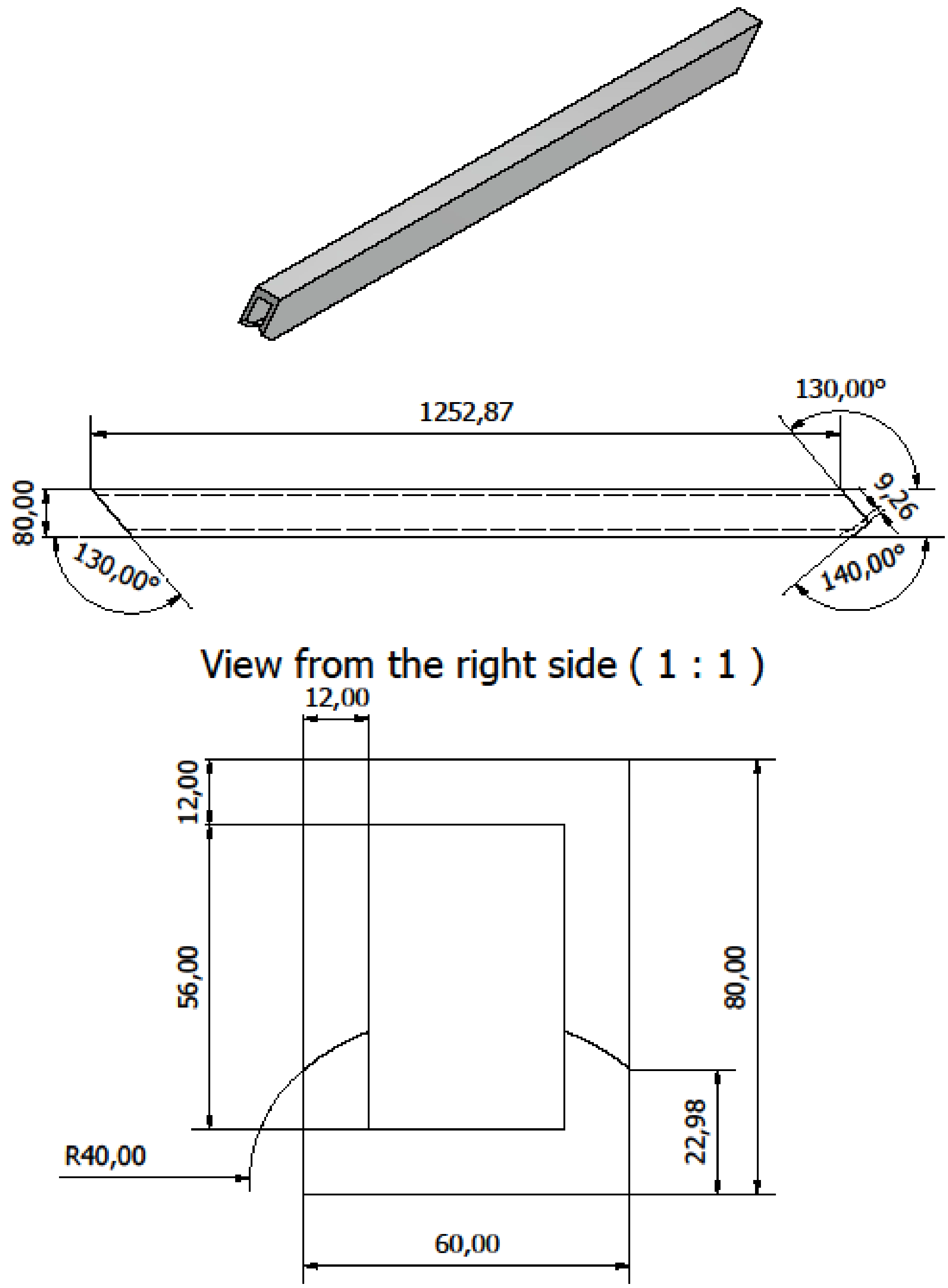
20,00
57,00
Ø88,00
Designed by
Konrad Jarczyk
Checked by
Approved by
Date
A4
Date
12.05.2021
Bachelor's thesis
Middle base
Appendix 7
Edition
Sheet
1 / 1

Appendix 8



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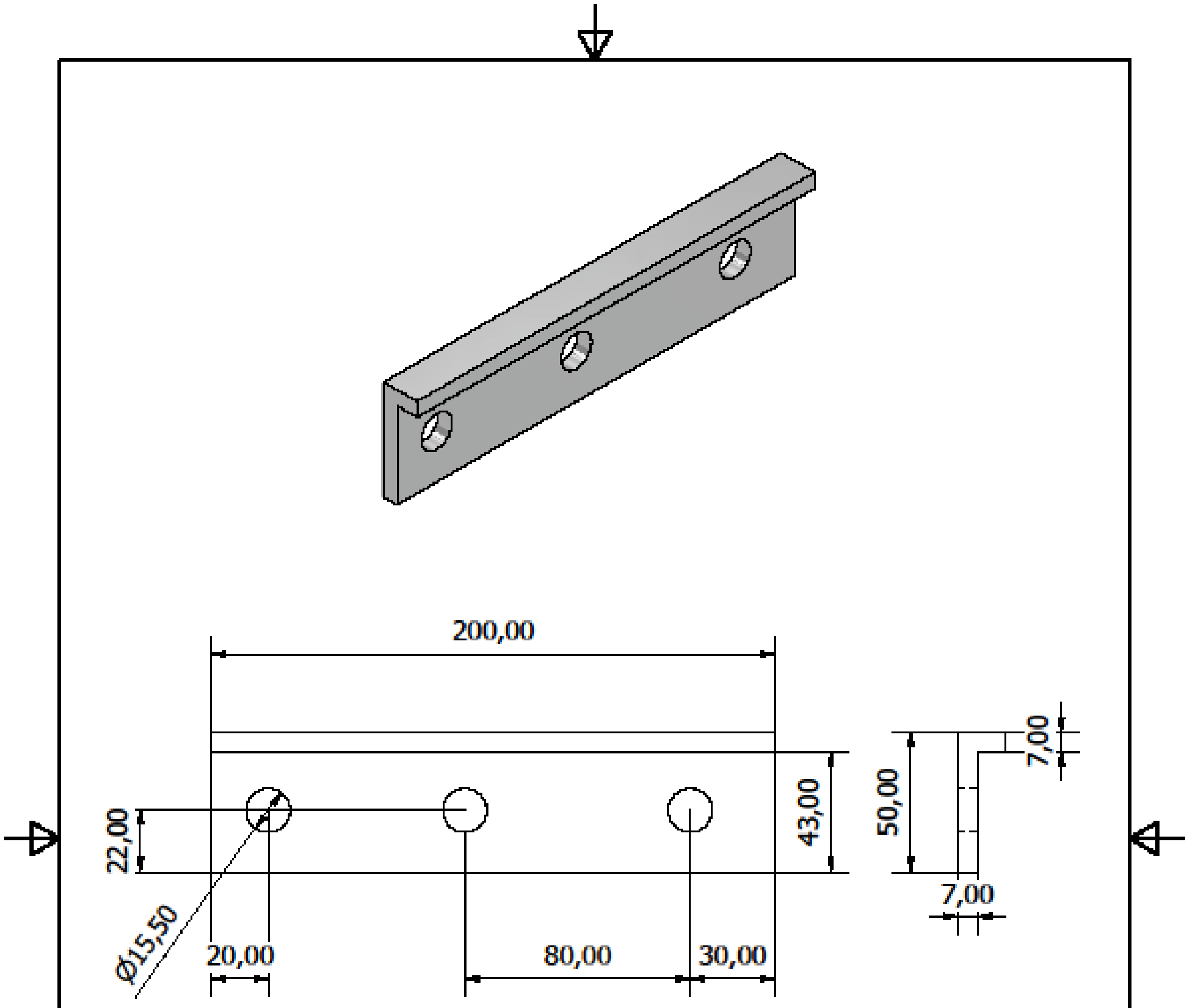
Bachelor's thesis			Side support			
			Appendix 8		Edition	Sheet 1 / 1

Appendix 9



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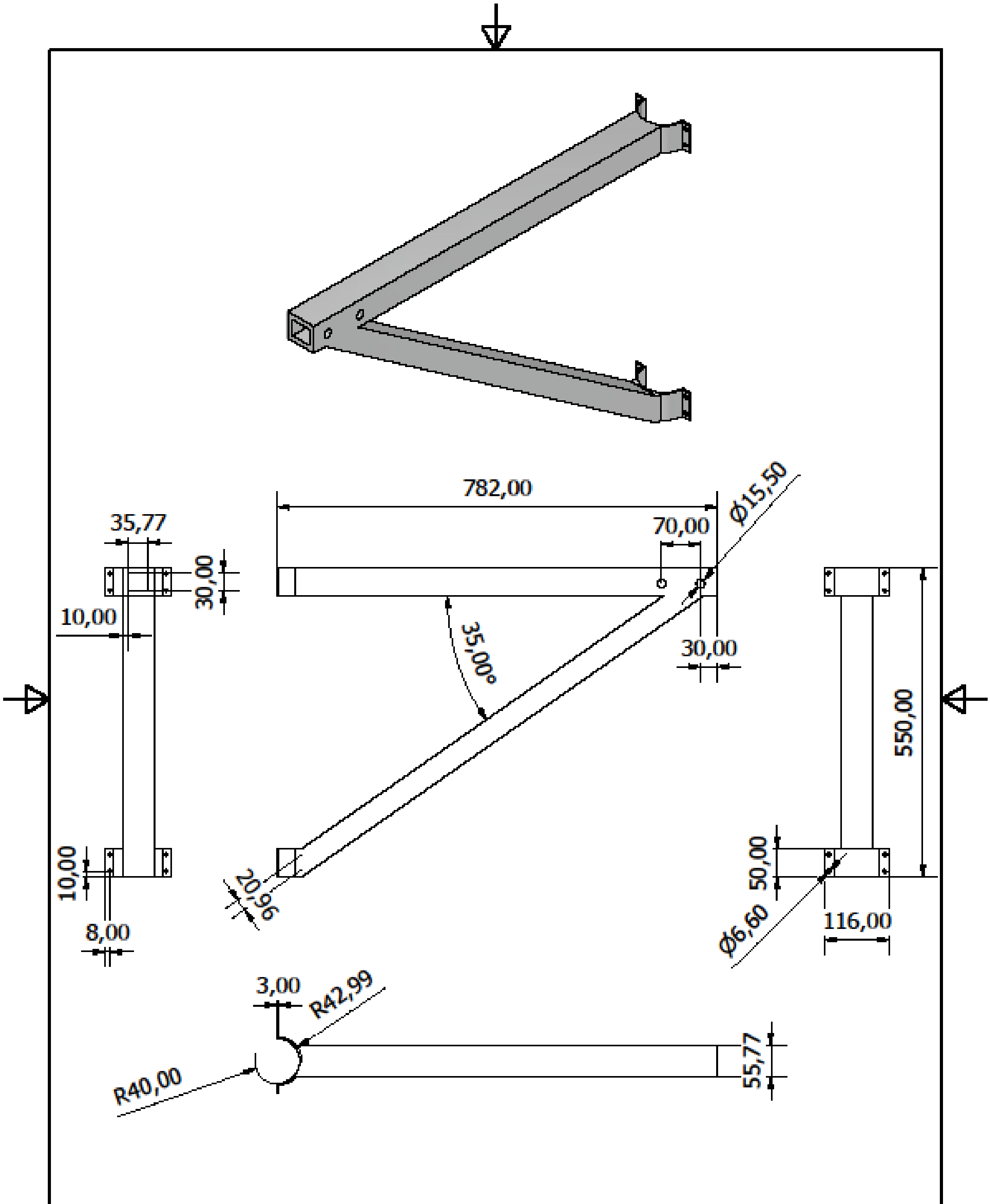
Konrad Jarczyk					12.05.2021	
Bachelor's thesis				Actuator's fixture to support		
				Appendix 9	Edition	Sheet 1 / 1

Appendix 10



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Bachelor's thesis		Actuator's support			
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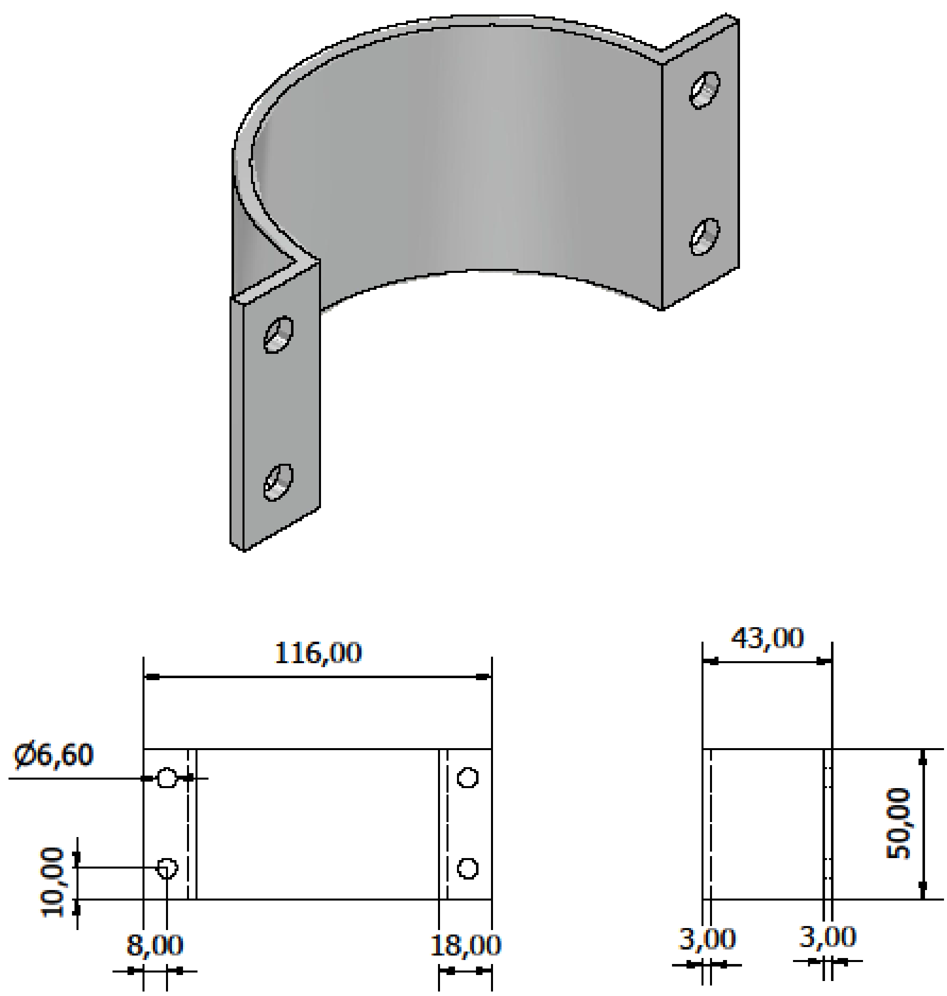
Appendix 11



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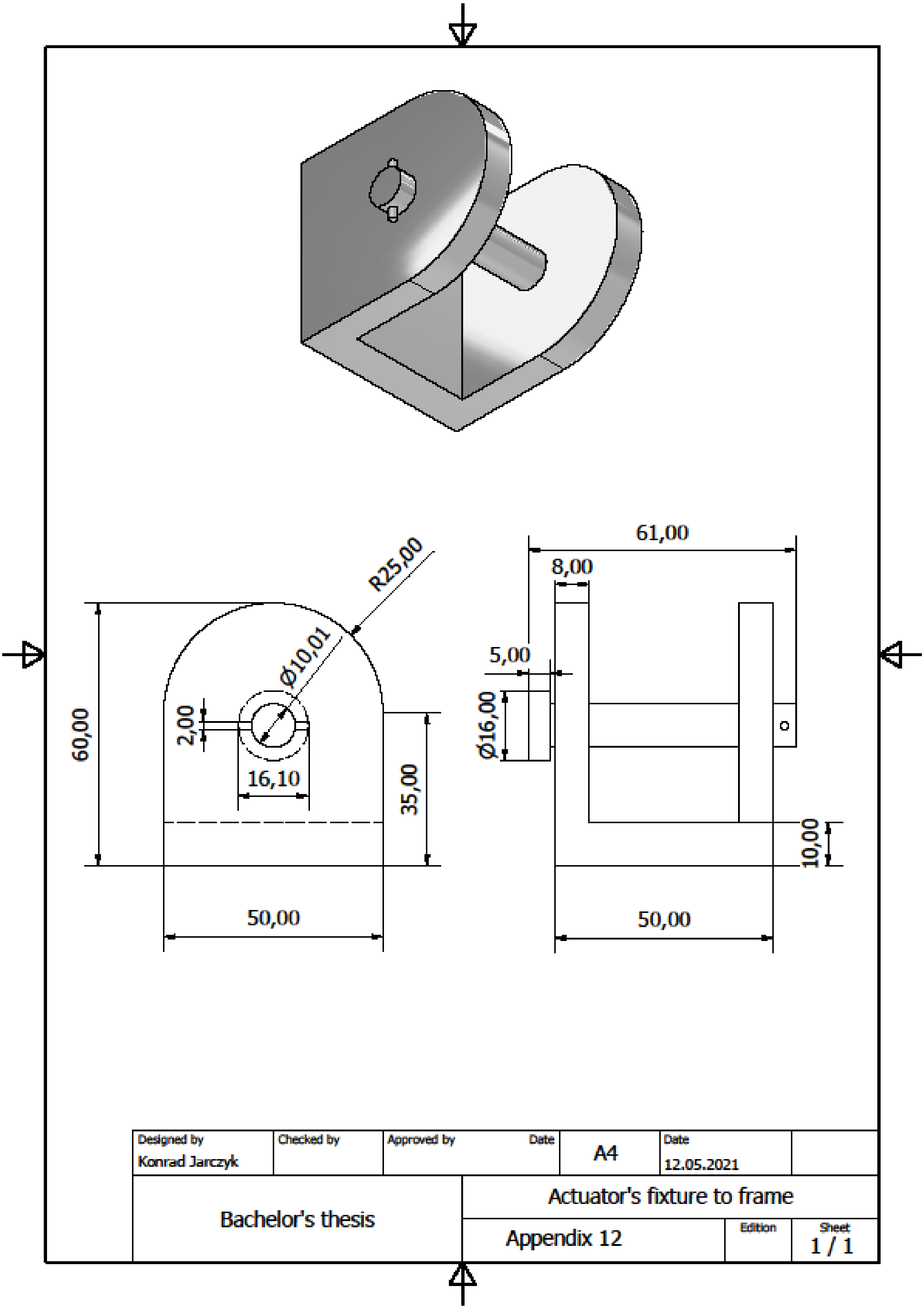
Bachelor's thesis	Middle base's band					
	Appendix 11				Edition	Sheet 1 / 1

Appendix 12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Designed by
Konrad Jarczyk
Checked by
Approved by
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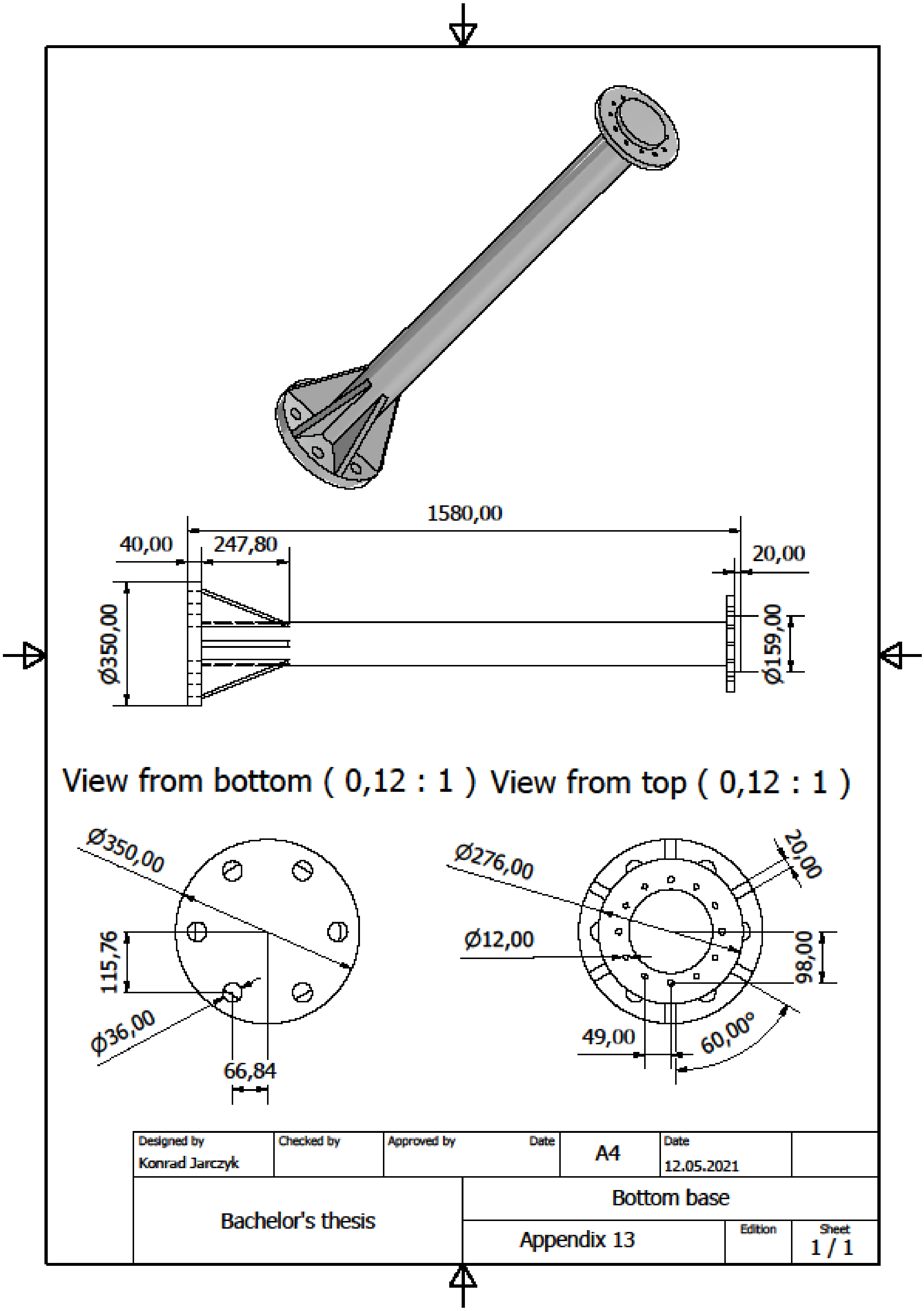
12.05.2021
Bachelor's thesis
Actuator's fixture to frame
Appendix 12
Edition
Sheet
1 / 1

Appendix 13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Designed by
Konrad Jarczyk
Checked by
Approved by
Date
A4
Date
12.05.2021
Bottom base
Bachelor's thesis
Appendix 13
Edition
Sheet
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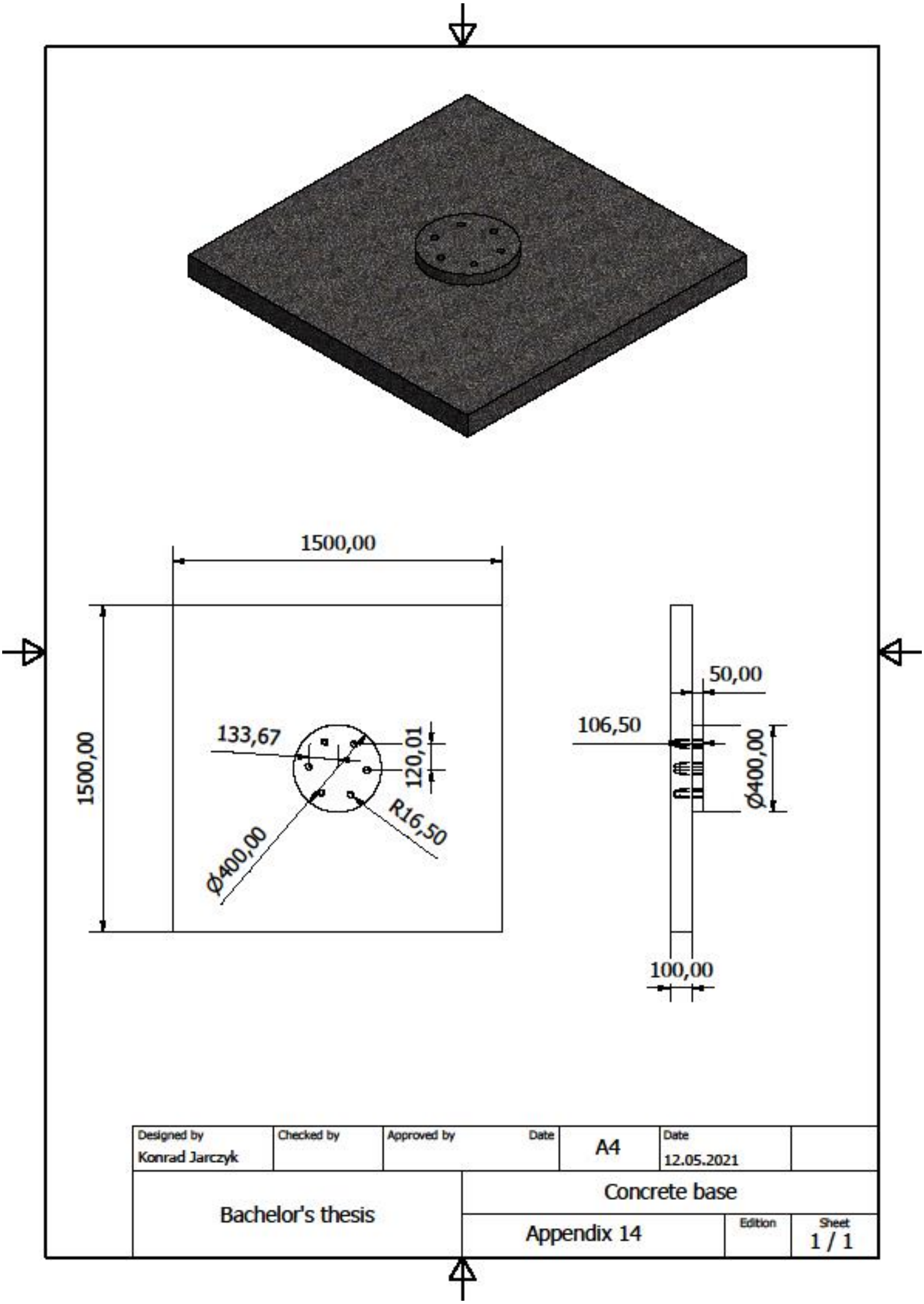
Appendix 14



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Checked by
Approved by
Date
A4
Date
12.05.2021
Bachelor's thesis
Concrete base
Appendix 14
Edition
Sheet
1 / 1